Nonlinear applications of step-index and microstructured soft-glass fibres
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This thesis focuses on the potential of compound-glass, highly nonlinear, small-core fibres for use in nonlinear applications. Both fibres with a conventional step-index design and small-core holey fibres are considered. While the former technology is more mature, the latter represents the ultimate candidate, since it offers the flexibility of combining novel dispersion properties with a very high nonlinearity. With regard to holey fibre designs, small-core, compound-glass holey fibres with different core diameters and designs are considered for two different background materials: a commercially available lead-silicate glass and a bismuth-oxide based glass. Firstly, characterization measurements are performed on the fabricated holey fibres. The measurements reveal the advantages of each glass type and each fibre design, the ultra-high nonlinearity that can be achieved in such fibres and the potential of achieving simultaneously a novel dispersion profile and high nonlinearity. Nonlinear applications are then demonstrated for some of the fibres presented. In particular, the use of a lead-silicate holey fibre, having a dispersion-shifted profile, with a zero-dispersion wavelength lying close to the C-band is demonstrated in cross-phase modulation based wavelength conversion and switching applications in the 1.55 µm window. Both a co-polarized pump and probe scheme and a Kerr-shutter configuration are considered. For the same fibre, the stimulated four-wave mixing process for amplification and wavelength conversion applications in the C-band is thoroughly studied. Numerical simulations and experimental findings are combined to study the fibre performance, demonstrate its applicability to nonlinear wavelength conversion applications and identify future improvement objectives. The suitability of compound-glass holey fibres is also examined for the generation of correlated photons, through spontaneous four-wave mixing, and the generation of a broad supercontinuum by pumping at the convenient in terms of high power laser availability wavelength regions of 1.0 µm and 1.5 µm. The experiments presented in this thesis constitute the first nonlinear applications ever reported for dispersion-tailored, compound-glass holey fibres, clearly revealing their potential in fibre-based nonlinear applications. Nonlinear applications are also demonstrated for a commercially available, fibreised, bismuth-oxide based fibre with a step-index design. Using this fibre, an all-optical regenerator of Return-to-Zero picosecond pulses is realized at repetition rates of 10 and 40 Gb/s. The same fibre is also employed in an all-fibreised pulse compression scheme, which relies on nonlinear pulse propagation in the normal dispersion regime and enables the compression of picosecond pulses down to the femtosecond scale. In both applications, the ultra high nonlinearity of the compound-glass, step-index fibre results in reduced fibre-length and peak power requirements. The thesis concludes by addressing the issues concerning the practicality of compound-glass fibres and proposing potential future directions.
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Declaration of Authorship

I, Symeon Asimakis, declare that the thesis entitled “Nonlinear applications of step-index and microstructured soft-glass fibres” and the work presented in it are my own.

I confirm that:

- this work was done wholly while in candidature for a research degree at this university;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published, see List of Publications.

Symeon Asimakis
September 2008
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For someone who has always thought that there is a ‘patience’ gene, a gene somewhere on the chromosome map responsible for patience that some people do not possess, Ph.D. studies can come as a surprise. For, although no formal dictionary mentions it, Ph.D. studies are equivalent to ‘patience studies’. In my ‘trip to the world of patience’, several people were always there to assist me. This part of the thesis is dedicated to all of them.

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### Abbreviations

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<tbody>
<tr>
<td>AR</td>
<td>Anti-Reflection</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
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<td>ASR</td>
<td>Air-Suspended Rod</td>
</tr>
<tr>
<td>BER</td>
<td>Bit-Error Rate</td>
</tr>
<tr>
<td>Bi-HNLF</td>
<td>Bismuth-Oxide Highly Nonlinear Fibre</td>
</tr>
<tr>
<td>BPF</td>
<td>Bandpass Filter</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion-Compensating Fibre</td>
</tr>
<tr>
<td>DDF</td>
<td>Dispersion-Decreasing Fibre</td>
</tr>
<tr>
<td>DFG</td>
<td>Difference-Frequency Generation</td>
</tr>
<tr>
<td>DGD</td>
<td>Differential Group-delay</td>
</tr>
<tr>
<td>DSF</td>
<td>Dispersion-Shifted Fibre</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>EAM</td>
<td>Electro-Absorption Modulator</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-doped Fibre Amplifier</td>
</tr>
<tr>
<td>EFRL</td>
<td>Erbium Fibre Ring Laser</td>
</tr>
<tr>
<td>FBG</td>
<td>Fibre Bragg Grating</td>
</tr>
<tr>
<td>FOM</td>
<td>Figure-of-Merit</td>
</tr>
<tr>
<td>FROG</td>
<td>Frequency-Resolved Optical Gating</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full-Width at Half-Maximum</td>
</tr>
<tr>
<td>FWM</td>
<td>Four-Wave Mixing</td>
</tr>
<tr>
<td>GVD</td>
<td>Group-velocity Dispersion</td>
</tr>
<tr>
<td>HF</td>
<td>Holey Fibre</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>HNLF</td>
<td>Highly Nonlinear Fibre</td>
</tr>
<tr>
<td>KS</td>
<td>Kerr-shutter</td>
</tr>
<tr>
<td>L-FROG</td>
<td>Linear Frequency-Resolved Optical Gating</td>
</tr>
<tr>
<td>MOF</td>
<td>Microstructured Optical Fibre</td>
</tr>
<tr>
<td>MZM</td>
<td>Mach-Zehnder Modulator</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>Neodymium-doped Yttrium Aluminum Garnet</td>
</tr>
<tr>
<td>Nd:YLF</td>
<td>Neodymium-doped Yttrium Lithium Fluoride</td>
</tr>
<tr>
<td>NLSE</td>
<td>Nonlinear Schrödinger Equation</td>
</tr>
<tr>
<td>NOLM</td>
<td>Nonlinear Optical Loop Mirror</td>
</tr>
<tr>
<td>NRZ</td>
<td>Nonreturn-to-Zero</td>
</tr>
<tr>
<td>OEO</td>
<td>Optical-Electronic-Optical</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>OPO</td>
<td>Optical Parametric Oscillator</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical Spectrum Analyzer</td>
</tr>
<tr>
<td>OTDM</td>
<td>Optical Time-Division Multiplexing</td>
</tr>
<tr>
<td>PBGF</td>
<td>Photonic Bandgap Fibre</td>
</tr>
<tr>
<td>PMD</td>
<td>Polarization Mode Dispersion</td>
</tr>
<tr>
<td>PRBS</td>
<td>Pseudo-Random Bit Sequence</td>
</tr>
<tr>
<td>RZ</td>
<td>Return-to-Zero</td>
</tr>
<tr>
<td>SBS</td>
<td>Stimulated Brillouin Scattering</td>
</tr>
<tr>
<td>SC</td>
<td>Supercontinuum</td>
</tr>
<tr>
<td>SEST</td>
<td>Structured Element Stacking</td>
</tr>
<tr>
<td>SFG</td>
<td>Sum-Frequency Generation</td>
</tr>
<tr>
<td>SHG</td>
<td>Second-Harmonic Generation</td>
</tr>
<tr>
<td>SMF</td>
<td>Single-Mode Fibre</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>SPM</td>
<td>Self-Phase Modulation</td>
</tr>
<tr>
<td>SRS</td>
<td>Stimulated Raman Scattering</td>
</tr>
<tr>
<td>SSF</td>
<td>Split-Step Fourier</td>
</tr>
<tr>
<td>SSFS</td>
<td>Soliton Self-Frequency Shift</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength-Division Multiplexing</td>
</tr>
<tr>
<td>XGM</td>
<td>Cross-Gain Modulation</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross-Phase Modulation</td>
</tr>
<tr>
<td>ZDW</td>
<td>Zero-Dispersion Wavelength</td>
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</table>
Introduction

All components that are currently in use for switching and regeneration of optically transmitted signals have electronic cores. The light pulses at the input of the processing systems are converted back into electronic signals so that their route is handled by conventional Application Specific Integrated Circuits. The advantages of this process stem from the fact that the technology concerning optical-electronic-optical (OEO) conversion is well developed, therefore several high performance products of this type are already available in the market.

However, due to the relatively low bandwidth of electronics, the associated optoelectronic interfaces and the electronics for routing control present an obstacle to fully utilizing the large bandwidth offered by optical fibres. This problem can be eliminated if signals remain in an optical form during switching, address recognition and signal processing. Thus, all-optical signal processing solutions are strenuously sought.

A range of important functions in telecommunication systems that can be performed directly in the optical domain, without the need for a conversion to the electronic domain, are based on nonlinear effects. There are three main candidates for nonlinear devices: semiconductor optical amplifiers (SOAs), passive waveguides formed in nonlinear crystals, like LiNbO$_3$ or AlGaAs, and highly nonlinear optical fibres (HNLFs). This thesis relates to the investigation of fibre-based nonlinear devices. However, below I attempt a brief outline of all three of these technologies, and identify the strong and weak points of each solution.

SOAs are electrically pumped active devices that offer the great advantage of integrated circuit compatibility. They are based on the same technology as semiconductor lasers, with an active region imparting gain via stimulated emission, but their facets are anti-reflection (AR) coated, so that self-oscillations, which would lead to lasing, are avoided. Initially designed for linear amplification in point-to-point systems, SOAs have been out-competed by erbium-doped fibre amplifiers (EDFAs),
which exhibit superior performance. However, the nonlinear behaviour of SOAs, a major drawback in linear amplification applications, makes them attractive for use as optically controlled logic gates [1].

When used in nonlinear applications, SOAs usually exploit either the cross-gain modulation (XGM) or the cross-phase modulation (XPM) effect. In a XGM scheme, an amplitude-modulated strong pump signal at wavelength $\lambda_s$ is simultaneously injected into the SOA together with a weak probe, continuous-wave (CW) signal, at wavelength $\lambda_{pr}$. When the pump is at a low power state, the probe experiences unsaturated gain. On the other hand, at the high power state of the pump, saturation of the gain occurs due to carrier density depletion and the probe signal experiences a lower gain. Hence, an inverted replica of the signal, at wavelength $\lambda_s$, is created at a wavelength $\lambda_{pr}$. The extent of this gain decrease due to carrier density depletion depends on the injection current in the amplifier and the pump power. However, the XGM scheme, although relatively simple to realize and potentially insensitive to polarization, suffers from serious disadvantages. The greatest disadvantage of XGM is the degradation of the extinction ratio of the switched signal, especially at high bit rates. It is worth noting that this extinction ratio degradation is greater when the probe signal is chosen to be towards longer wavelengths compared to the pump signal [2]. This poses serious limitations to the cascadability of SOAs in optical networks. Additionally, significant signal-to-noise ratio (SNR) degradation is caused by the SOA due to amplified spontaneous emission (ASE). Typical noise figures of SOAs are ~ 7-8 dB [3]. Furthermore, the received wavelength converted signal is inverted compared to the input pump signal and heavily chirped due to simultaneous modulation of the refractive index of the SOA [1, 4]. It should be noted that, although it was initially thought that the speed of a XGM scheme in SOAs would be determined by the relatively slow intrinsic carrier lifetime of 0.5 ns, under high optical injection conditions (gain saturation) the effective carrier lifetime can be decreased down to a few picoseconds, hence enabling operation over 80 Gb/s [1, 4].

Better nonlinear performance is achieved when SOAs are used in an interferometric configuration, so as to utilize the XPM effect. XPM schemes are based on the modulation of the refractive index of the SOAs that accompanies the gain modulation induced by carrier density changes. Devices that utilize XPM typically have a Mach-
Zehnder interferometric arrangement. SOAs are placed in both arms of the interferometer and a CW probe signal, at a wavelength $\lambda_{pr}$, is allowed to propagate through both arms. A strong modulated pump signal at a wavelength $\lambda_s$, entering one of the two paths, can cause depletion of the carrier density at the corresponding SOA and induce a relative phase difference between the two paths. The interferometric configuration translates this phase difference between the paths of the interferometer into intensity modulation of the probe signal. Thus, the optical input signal controls the phase difference between the arms of the interferometer. By proper adjustment of the injection currents into the two SOAs, the state of the interferometer can be chosen so that the probe signal undergoes constructive or destructive interference without the presence of the pump signal. Hence, it becomes apparent that the XPM scheme provides the opportunity for both inverting and non-inverting operation [4]. Moreover, even small input signal modulation levels are sufficient to introduce a $\pi$ phase shift between the two arms of the interferometers, due to the very steep transfer function of the XPM based interferometric device. As a result, the extinction ratio of the output signal can be as high as the input signal, the wavelength of operation can lie almost anywhere in the gain region of the SOA and the frequency chirp characteristics of the output signal can be small compared to the XGM converter [1, 2, 4]. Furthermore, if the probe signal is relatively strong and especially for a non-inverting mode of operation, the noise due to spontaneous emission can be greatly reduced [3]. For these reasons, XPM schemes exhibit superior performance compared to XGM schemes. In fact, their highly nonlinear behaviour can result in regenerative operation, hence they can be cascaded [1]. However, XPM-based schemes have the major drawback of strict operational requirements. As for every interferometric scheme, the XPM interferometric configurations are very sensitive to even slight changes in temperature and power. In particular, the input power control requirements are very strict in XPM techniques, due to the sharp dependence of the transfer function of the interferometric device on the carrier density of the SOAs. The dynamic range of the input power is therefore extremely restricted and the input power levels should be constantly monitored and adjusted with extreme accuracy, much better than 3 dB [3].

Nonlinear crystals have been primarily employed in wavelength conversion applications [5, 6, 7]. Utilizing principally difference-frequency generation (DFG) and second-harmonic generation (SHG), they offer transparent wavelength conversion,
Introduction

potentially with quantum-noise limited operation [3]. In order for a crystal to be of practical importance, requirements such as high material nonlinearity, low transmission loss, good thermal properties and phase-matching at the wavelengths of interest should be simultaneously satisfied. From all the above requirements, phase-matching is the most restrictive. While traditionally the birefringence in nonlinear crystals was used for phase-matching, quasi-phasematching conditions are now readily achieved in ferroelectric materials such as LiNbO$_3$ by electric-field poling [8]. Hence, periodically poled LiNbO$_3$ waveguides are most commonly used in applications based on second-order nonlinearity. On the other hand, in non-ferroelectric material, such as AlGaAs, the periodic domain inversion necessary for quasi-phasematching is achieved using wafer bonding, selective etching and chemical vapour deposition [5]. However, the technique of wafer bonding usually results in large scattering losses, due to waveguide corrugations.

A three-wave mixing process that is based on second-order nonlinearity and is commonly utilized by nonlinear crystals is DFG. A strong pump at wavelength $\lambda_p$ is mixed with a weak signal at wavelength $\lambda_s$ and generates an output (idler) at wavelength $\lambda_{idl}$, with $1/\lambda_p = 1/\lambda_s + 1/\lambda_{idl}$. For wavelength conversion within the 1.5 µm telecommunications band using DFG, a single-mode strong pump laser operating in the 750-800 nm range is commonly used, together with a weak signal at a wavelength $\lambda_s$ inside the 1.5 µm band [6]. However, the required operation with laser sources and optical components outside the communication spectral window (i.e. in the 750-800 nm range) is considered inconvenient, and more importantly it is hard to ensure simultaneous launching of a 1.5 µm-band signal and a ~750 nm pump into the fundamental mode of a waveguide. An approach that is commonly used relies on cascaded second-order nonlinearity, where both the pump and signal are in the 1.5 µm band [7, 9]. Provided that phase-matching is achieved for both SHG and DFG by selection of an appropriate quasi-phase-matching grating period, a pump at a frequency $\omega_p$, corresponding to a wavelength $\lambda_p$ lying inside the 1.5 µm band, is up-converted to a signal at a frequency $2\omega_p$ due to SHG. Combining the generated $2\omega_p$ wave with a signal at frequency $\omega_s$, such that $\lambda_s$ is inside the 1.5 µm band, a wavelength converted output is generated at a frequency $2\omega_p - \omega_s$ due to DFG. Using this technique with LiNbO$_3$ waveguides, conversion efficiencies as high as −5 dB and conversion bandwidths over ~80 nm have been realised [7, 9]. Moreover, by the use of
cascaded second-order nonlinearity in a periodically poled LiNbO$_3$ waveguide, simultaneous wavelength conversion, from the C-band to the L-band, of a dense wavelength-division multiplexed (DWDM) signal, consisting of up to 103, 25 GHz-spaced channels of 10 Gb/s rate each, has been reported [10].

Waveguides made from nonlinear crystals, that utilize DFG, enable wide conversion bandwidths to be achieved; hence they can easily accommodate THz modulation bandwidths. They have negligible spontaneous emission noise and offer transparent wavelength conversion. However, the strict requirements for phase-matching pose limitations to the effective realization of devices based on them [11]. Moreover, difficulties in the fabrication of low loss, passive crystal waveguides restrict the achievable conversion efficiencies [3, 5, 7]. Furthermore, the performance of such waveguides is greatly dependent on the temperature, and normally operation at a high temperature is required [6, 7].

A promising nonlinear medium for the realisation of all-optical signal processing devices is the optical fibre itself. Optical fibres owe their nonlinear behaviour to the third-order nonlinearity, which manifests itself as a variation of the refractive index with the light intensity. When used in nonlinear applications, optical fibres do not cause any degradation of the SNR or of the extinction ratio. They combine high-power density with long interaction lengths, hence they can exhibit very strong nonlinearities. Moreover, the time response of the third-order nonlinearity can be very fast, as fast as 1-10 fs, hence THz modulation bandwidths can be accommodated by optical fibres [12]. Nevertheless, standard telecommunications single-mode fibres (SMFs) and standard dispersion-shifted fibres (DSFs) are made of silica, which is not a particularly nonlinear material. Therefore, the utilization of nonlinear effects in these fibres requires relatively high light intensities or very long fibre lengths [13, 14, 15]. An enhanced nonlinear behaviour can be achieved by combining a reduction in the core diameter with the addition of a high concentration of dopants, such as germanium, in the core. However, even using highly nonlinear DSFs, long lengths of the order of several hundred meters to a few kilometres are required for nonlinear applications [16, 17, 18, 19]. Hence, even though optical fibres can achieve superior nonlinear operation compared to SOAs and semiconductor waveguides, they are impractical for real applications, due to issues of compactness and stability. Issues such as accumulated
dispersion and latency associated with long propagation lengths can also compromise the performance of fibre-based nonlinear devices.

From an application point of view, the use of highly nonlinear compound glasses, which can have material indices orders of magnitude higher than silica, for the fabrication of fibres with small effective core areas is a particularly desirable approach. The very high nonlinearity per unit length of such fibres would drastically reduce the length or the power requirements of nonlinear fibre-based devices, greatly increasing their practicality. It is in general hard to obtain suitably matched glasses, both optically and thermally for the core and the cladding, hence it is difficult to fabricate step-index fibres from a large range of compound glasses. Nevertheless, several fabrication attempts with different compound glasses have been made and very high nonlinearities per unit length have been reported [20, 21, 22, 23, 24]. However, it is difficult to tailor the dispersion properties of such fibres. The zero-dispersion wavelength (ZDW) normally lies far from the C-band and a large dispersion at the 1550 nm telecommunications window has to be tolerated [22, 24].

A novel approach that can take full advantage of the potential of compound glasses, without suffering the limitations of conventional step-index design, is holey fibre (HF) technology. HFs have generated great interest over the past few years, growing from a research-oriented field to a commercially available technology in little over five years. Some of the most impressive properties of HFs are the endlessly single-mode guidance [25], the unique dispersion properties, ranging from ultra-flattened behaviour to anomalous dispersion down to the visible wavelength region [26, 27, 28], and the extreme values of Numerical Aperture (NA) [29] and fibre nonlinearity [29, 30].

HFs comprise a solid core and an arrangement of air holes along their length that surrounds the core and which acts as the cladding region, hence they can be fabricated from a single material. The presence of the holes results in an effective refractive index of the cladding region that is strongly dependent on wavelength and is lower than the core refractive index. Therefore, light can be effectively confined in the core. HFs with very small core dimensions and relatively large holes, hence a very large NA, can confine light tightly in the core and exhibit a very high effective nonlinearity per unit length. For pure silica HFs, a value of \(~70 \text{ W}^{-1}\text{km}^{-1}\) [30] has been reported.
A range of important applications in telecommunication systems that can utilize the strong nonlinear effects within highly nonlinear, small-core HFs have already been demonstrated. Wavelength conversion [31, 32], demultiplexing [33] and 2R regeneration [34] represent just a few of the successful applications of small-core HFs that have been reported.

To date, most applications have been based on pure silica HFs. However, the use of compound glasses with high nonlinear refractive indices can lead to a further drastic increase in the achieved nonlinearity per unit length, as mentioned previously, making the prospect of compact devices operating at very low power realisable [35]. Moreover, such glasses also have a high linear refractive index, which leads to an increased index contrast between the core and the holey cladding, hence providing even tighter mode confinement and a smaller effective mode area. Furthermore, compound glasses have, in general, lower softening temperatures compared to silica, thus allowing different approaches to be used for the fabrication of HFs, for example the extrusion technique, which can be used for designs that cannot be created with stacking techniques [29, 35]. Ultimately, the enhanced nonlinear behaviour offered by compound-glass HF technology aims at the realisation of nonlinear devices employing just a meter of fibre and operating at powers of the order of a few milliwatts.

This thesis focuses on the great potential of compound-glass, small-core fibres with regard to nonlinear device applications. Both fibres with a conventional step-index design and small-core HFs are considered. While the first technology is more mature and can readily be used in practical applications, the latter represents the ultimate candidate due to the flexibility it offers to combine novel dispersion properties with a very high nonlinearity. The structure of this thesis is outlined below.

In Chapter One, the main nonlinear phenomena taking place in optical fibres are discussed. The basic properties and the major issues concerning HF technology are explained and some recent applications of silica-based HFs are presented.

In Chapter Two, the results from the thorough characterisation of small-core, compound-glass HFs, which have been fabricated at the Optoelectronics Research
Centre, are presented. HFs with different core diameters and designs are characterised in terms of optical properties for two different compound glasses: the commercially available lead-silicate Schott glass SF57 and a bismuth-oxide based glass. The characterization reveals the relative advantages of each compound glass type and each fibre design, showing a route to future fabrication attempts.

In Chapter Three, the use of a lead-silicate HF, with a ZDW near the C-band, is demonstrated in wavelength conversion and switching applications in the 1.55 µm region. Both a co-polarized pump and probe scheme and a Kerr-shutter (KS) configuration are examined and the relative advantages of each configuration in terms of performance and robustness are examined.

In Chapter Four, the stimulated four-wave mixing (FWM) process for amplification and wavelength conversion applications in the C-band is studied in a short piece of a lead-silicate HF. The HF has a dispersion-shifted profile, with a ZDW lying close to the C-band. Numerical simulations and experimental findings are combined to study the fibre performance, demonstrate its applicability to nonlinear wavelength conversion applications and identify future improvement objectives. Furthermore, the results from an experiment regarding the generation of correlated photons through spontaneous FWM in a lead-silicate HF are presented. The suitability of small-core compound-glass HFs for such applications is discussed and various issues affecting the performance of the scheme are examined.

In Chapter Five, the generation of a broad continuum, widely known as a supercontinuum (SC), stemming from the interplay of several nonlinear phenomena, is examined for various fabricated compound-glass HFs. Different fibres are used for pumping at different wavelength regions, mainly on the basis of the position of the ZDW. The process of the formation of the SC is explained and numerical simulations are used to support the experimentally acquired spectra.

In Chapter Six, the great potential of compound glasses in nonlinear applications is revealed from a demonstration of an all-optical regenerator using a step-index bismuth-oxide based fibre. It is shown that a very small fibre-length and relatively low peak powers are required for the effective regeneration of Return-to-Zero (RZ) pulses.
of the order of a few picoseconds. The operation of the regenerator is examined both at 10 and 40 Gb/s and the issues regarding its applicability are discussed.

In Chapter Seven, the pulse compression performance of an all-fiberised pulse compression scheme, incorporating a bismuth-oxide based fibre of a step-index profile, is presented. It is shown that the combination of the very high nonlinearity offered by the fibre with pulse propagation in the normal dispersion regime can enable the compression of picosecond pulses down to the femtosecond scale, using very short fibre lengths and relatively low peak powers.

In Chapter Eight, the main results stemming from the experimental work are discussed and some useful conclusions are drawn. The issues regarding compound-glass fibres are summarised and future objectives are proposed.
References


Chapter 1

Small-core, highly nonlinear fibres

The attractive prospect of combining HF technology with high nonlinearity compound glasses is thoroughly discussed in this Chapter. It is shown that such an approach can potentially lead to extraordinarily high values of effective nonlinearity, enabling the realization of compact devices with low-power requirements. First, a descriptive analysis of the various nonlinear phenomena in optical fibres is provided. Parameters such as the NA, the effective mode area, the nonlinear refractive index and the effective nonlinearity are introduced and their contribution in achieving a high effective nonlinearity is outlined. Particular emphasis is given on the unique advantages offered by HF technology. The ability of HFs to exhibit broadband single-mode guidance, novel dispersive behaviour and very tight mode confinement is described. Issues such as the propagation loss and the birefringence of small-core HFs are also discussed. Finally, a review of a range of telecommunication applications, which have been demonstrated for small-core HFs, is provided. Since the vast majority of these applications concern pure silica HFs, this overview is indicative of the applications that can be realized and potentially be enhanced with the use of compound-glass, small-core HFs.

1.1 Nonlinear effects in optical fibres and their applications

All dielectrics exhibit a nonlinear behaviour when they are subject to sufficiently intense electromagnetic fields. In particular, when a strong field $\bar{E}$ is applied to a dielectric, the total polarization $\bar{P}$ is given by [1]

$$\bar{P} = \varepsilon_0 \left( \chi_{(1)} \cdot \bar{E} + \chi_{(2)} \cdot \bar{E}\bar{E} + \chi_{(3)} \cdot \bar{E}\bar{E}\bar{E} + \ldots \right)$$

(1.1)

where $\varepsilon_0$ is the permittivity of the vacuum and $\chi_{(i)}$ is the $i$-th order dielectric susceptibility, corresponding to an $i+1$ rank tensor. The first order susceptibility is
related to the refractive index and the attenuation coefficient of the dielectric medium. The second order susceptibility is responsible for effects such as SHG, sum-frequency generation (SFG) and DFG. However, for non-crystalline isotropic media such as optical fibres, the second order susceptibility is zero. Thus, the lowest order term causing nonlinear effects in optical fibres is the third order susceptibility, $\chi^{(3)}$ [2].

The most important nonlinear processes originating from $\chi^{(3)}$ are third-harmonic generation, four-wave mixing (FWM) and nonlinear refraction. In optical fibres, third-harmonic generation requires special efforts to achieve phase-matching and it is rather inefficient, therefore it is not going to be considered further in this thesis. On the other hand, FWM is by far the most dominant parametric process in optical fibres, although it also requires phase-matching conditions to be met. Nonlinear refraction refers to the dependence of the refractive index of the fibre core on the intensity of a propagating electric field, and is usually referred to as the Kerr effect. The most important Kerr-induced nonlinear processes are self-phase modulation (SPM) and cross-phase modulation (XPM).

The nonlinear effects governed by the third-order susceptibility are elastic, in the sense that there is no energy exchange between the propagating electric field and the dielectric medium. A second category of nonlinear effects relates to stimulated inelastic scattering processes, in which case energy is exchanged between the electromagnetic field passing through the fibre and the fibre itself. Effects falling in this category are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), both of which relate to the vibrational excitation modes of the glass material used for the fabrication of the fibre. The fundamental difference between SBS and SRS results from the participation of optical phonons in the case of SRS and acoustic phonons in SBS. In particular, acoustic phonons correspond to sound waves propagating within the medium and, due to their acoustic nature, they have much lower energies than optical phonons. As a result, Brillouin scattering gives rise to a scattered photon that is only slightly shifted in frequency (~11 GHz in SMFs at 1.55 µm), as opposed to Raman scattering, where the corresponding frequency shift can be very large (up to ~40 THz) [1]. Moreover, due to the finite damping time of the acoustic waves causing Brillouin scattering, the resulting gain bandwidth is very
narrow (up to a few tens of MHz at 1.55 µm). In contrast, the gain bandwidth of Raman scattering can be as wide as several THz in silica fibres, owing to the amorphous nature of silica that leads to the formation of a continuum of available molecular vibrational energy levels [1].

In this section, a brief introduction to the most important nonlinear phenomena in optical fibres is provided. Both elastic, Kerr-induced processes and inelastic, scattering processes are considered.

### 1.1.1 Elastic nonlinear processes

Nonlinear effects in optical fibres usually concern the use of short pulses ranging from a few nanoseconds down to the picosecond range. The propagation of an electromagnetic field in nonlinear dispersive optical fibres is governed by the general wave equation

\[
\nabla^2 \tilde{E} - \frac{1}{c^2} \frac{\partial^2 \tilde{E}}{\partial t^2} - \mu_0 \frac{\partial^2 \tilde{P}}{\partial t^2} = 0
\]

(1.2)

which can be derived from the well-known set of Maxwell’s equations [3]. To solve Eq. 1.2, a relation between the electric field and the polarization is required. A usual approach is to separate the polarization into a linear \( P_L \) and a nonlinear \( P_{NL} \) part [1]

\[
\tilde{P}(\vec{r},t) = \tilde{P}_L(\vec{r},t) + \tilde{P}_{NL}(\vec{r},t)
\]

(1.3)

The linear polarization term is related to the first order susceptibility through the relation

\[
\tilde{P}_L(\vec{r},t) = \int_{-\infty}^{\infty} \varepsilon_0 \chi_1(t-t') \tilde{E}(\vec{r},t')dt'
\]

(1.4)

Since in optical fibres the lowest order term responsible for nonlinear effects is the third order susceptibility, the nonlinear polarization term can be written as [1]

\[
\tilde{P}_{NL}(\vec{r},t) = \int \int \int_{-\infty}^{\infty} \varepsilon_0 \chi_3(t-t_3,t-t_2,t-t_1) \tilde{E}(\vec{r},t_3) \tilde{E}(\vec{r},t_2) \tilde{E}(\vec{r},t_1) dt_3 dt_2 dt_1
\]

(1.5)

Due to the complexity of Eqs 1.2-1.5 several approximations have to be made. First of all, it is assumed that the applied electric field has a linear polarization, which is maintained during propagation through the fibre. Moreover, the approximation of a slowly varying pulse envelope is applied. Under this assumption, the spectral width
\( \Delta \omega \) of a pulse centred around a frequency \( \omega_0 \) is considered to be greatly smaller than \( \omega_0 \), i.e. \( \Delta \omega \ll \omega_0 \). In this way, it is convenient to write the electric field in the form

\[
\tilde{E}(\mathbf{r}, t) = \frac{1}{2} \left( E(\mathbf{r}, t) e^{-i \omega t} + E(\mathbf{r}, t) e^{i \omega t} \right) \hat{x}
\]  

(1.6)

where \( E(\mathbf{r}, t) \) is assumed to be a slowly varying function of time, \( \hat{x} \) is the polarization unit vector. The polarization components can also be expressed in a similar form

\[
\tilde{P}_L(\mathbf{r}, t) = \frac{1}{2} \left( P_L(\mathbf{r}, t) e^{-i \omega_0 t} + P_L(\mathbf{r}, t) e^{i \omega_0 t} \right) \hat{x}
\]  

(1.7)

\[
\tilde{P}_{NL}(\mathbf{r}, t) = \frac{1}{2} \left( P_{NL}(\mathbf{r}, t) e^{-i \omega_0 t} + P_{NL}(\mathbf{r}, t) e^{i \omega_0 t} \right) \hat{x}
\]  

(1.8)

A third approximation is that the nonlinear response of the medium to the applied electric field is instantaneous. In this way, the time dependence of \( \chi^{(3)} \) can be written in the form of three delta functions. This approximation essentially implies that only the response of the electrons to the applied electric field is considered for the calculation of the nonlinear response, while the effect of molecular vibrations due to Raman effects, which has a slower time response of several tens of femtoseconds, is disregarded. By substituting Eq.1.6 in 1.5 and considering an instantaneous nonlinear response, it turns out that \( P_{NL} \) has a term oscillating at a frequency \( \omega \) as well as a term oscillating at a frequency of \( 3\omega_0 \). The latter term corresponds to the effect of third harmonic generation, which is normally negligible in optical fibres unless specific phase-matching conditions are applied. Therefore, it can be disregarded. Under all these approximations, \( P_{NL} \) takes the approximate form

\[
\tilde{P}_{NL}(\mathbf{r}, t) = \varepsilon_{NL} \tilde{E}(\mathbf{r}, t)
\]  

(1.9)

where \( \varepsilon_{NL} \) is given by [1]

\[
\varepsilon_{NL} = \frac{3}{4} \chi^{(3)} |\tilde{E}(\mathbf{r}, t)|^2
\]  

(1.10)

If \( P_{NL} \) is treated as a small perturbation to \( P_L \), so that perturbation theory can be applied, and by writing the electric field in the form

\[
\tilde{E}(\mathbf{r}, t) = \frac{1}{2} \left( F(x,y) A(z,t) e^{-i \omega_0 t + \beta_0 z} + c.c. \right) \hat{x}
\]  

(1.11)

where \( A(z,t) \) represents the slowly varying pulse envelope, \( F(x,y) \) is the modal distribution and \( \beta_0 \) is the propagation constant at \( \omega = \omega_0 \), it can be shown, after some algebra, that the equation governing the propagation of \( A(z,t) \) is [1]
\[
\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} + \frac{\alpha}{2} A - i \gamma |A|^2 = 0
\] (1.12)

In Eq. 1.12, $\beta_1$, $\beta_2$, $\beta_3$ are the first, second and third derivatives respectively of the propagation constant $\beta$ with respect to $\omega$ at the point $\omega=\omega_0$. The nonlinear parameter $\gamma$ is a measure of the fibre’s nonlinearity and is defined as

\[
\gamma = \frac{2m_2}{\lambda A_{eff}}
\] (1.13)

where $n_2$ is the nonlinear refractive index coefficient, related to the third-order susceptibility and the linear refractive index $n(\omega)$ through the relation [2]

\[
n_2 = \frac{3}{8 \cdot n(\omega)} \cdot \text{Re}(\chi^{(3)})
\] (1.14)

The parameter $A_{eff}$ plays the role of an effective mode area and is defined as [1]

\[
A_{eff} = \left[\frac{\iiint \left|F(x,y)\right|^2 \, dx \, dy}{\iiint \left|F(x,y)\right| \, dx \, dy}\right]^2
\] (1.15)

For a SMF, $F(x,y)$ corresponds to the modal distribution of the fundamental mode and is approximately considered unaffected by the nonlinearity-induced refractive index change. The parameter $F(x,y)$ is usually approximated by a Gaussian distribution, in which case $A_{eff}$ is provided by the simple relation [2]

\[
A_{eff} = \pi w^2
\] (1.16)

where $w$ is the width parameter, dependent on the fibre core dimensions and the refractive index of both the core and the cladding.

It is common to apply the transformation

\[
T = t - \beta_1 z
\] (1.17)

to Eq. 1.12, so as to study the evolution of the slowly varying envelope under a frame of reference that moves with the group-velocity $v_g$ of the propagating pulse, since $\beta_1=1/v_g$. Under the transformation of Eq. 1.17, Eq. 1.12 takes the form

\[
\frac{\partial A}{\partial z} + \frac{\beta_2}{2} \frac{\partial^2 A}{\partial T^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial T^3} + \frac{\alpha}{2} A - i \gamma |A|^2 = 0
\] (1.18)

This equation is normally used to approximate the propagation of light pulses in an optical fibre under the combined effects of propagation loss, dispersion and nonlinearity. It is usually referred to as the nonlinear Schrödinger equation (NLSE).
[4], due to its resemblance to the Schrödinger equation, with the addition of a nonlinear term and the third-order dispersion term.

It has to be noted that, although Eq. 1.18 has been successfully used in the study of nonlinear effects in optical fibres, it might require modifications to account for the actual experimental conditions. For example, if the peak power of the incident optical pulse is above a threshold level, SBS or SRS might be triggered, giving rise to a new pulse that can propagate in the same or the opposite direction with reference to the input pulse. In this case, the interaction between the two pulses has to be considered and modifications, so as to include the contributions of XPM and Raman or Brillouin gain, are required. Moreover, in the case of an ultrashort optical pulse of the order of ~1 ps, the spectral width of the pulse is such that the Raman effect has to be considered, since it gives rise to the phenomenon of intra-pulse Raman scattering, as it will be explained in section 1.1.2.1. Another higher-order nonlinear effect that might become important in the case of ultra-short optical pulses (shorter than 100 fs) is self-steepening. Self-steepening results from the intensity dependence of the group velocity. Due to this dependency, the peak of the pulse moves at a lower speed compared to the wings, leading to pulse distortion in the time domain and an asymmetric SPM-broadened spectra in the frequency domain [1].

1.1.1.1 Self-phase modulation

The SPM effect occurs when intense beams pass through a nonlinear medium. The beam causes a nonlinear change of the medium’s refractive index, which in turn induces an intensity dependent phase modulation on the propagating beam. To study the SPM effect in optical fibres, the NLSE can be used as a starting point. In the limit of dispersion-free propagation, $\beta_2, \beta_3 = 0$, Eq. 1.18 takes the simplified form

$$\frac{\partial A(z,T)}{\partial z} + \frac{a}{2} A - i\gamma |A(z,T)|^2 A(z,T) = 0$$  \hspace{1cm} (1.19)

Considering a solution in the form

$$A(z,T) = V(z,T)e^{i\phi_{NL}(z,T)}$$  \hspace{1cm} (1.20)

Eq. 1.19 becomes
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\[
\frac{\partial}{\partial z} \left( e^{i \phi_{NL}(z, T)} V(z, T) \right) + \frac{a}{2} V(z, T) e^{i \phi_{NL}(z, T)} = i \gamma |V(z, T)|^2 V(z, T) e^{i \phi_{NL}(z, T)} \tag{1.21}
\]

\[
e^{i \phi_{NL}(z, T)} \frac{\partial V(z, T)}{\partial z} + i V(z, T) e^{i \phi_{NL}(z, T)} \frac{\partial \phi_{NL}(z, T)}{\partial z} + \frac{a}{2} V(z, T) e^{i \phi_{NL}(z, T)} =
\]

\[
= i \gamma |V(z, T)|^2 V(z, T) e^{i \phi_{NL}(z, T)} \tag{1.22}
\]

\[
\frac{\partial (V(z, T))}{\partial z} + i V(z, T) \frac{\partial \phi_{NL}(z, T)}{\partial z} + \frac{a}{2} V(z, T) = i \gamma |V(z, T)|^2 V(z, T) \tag{1.23}
\]

Equating the real part of the left and right hand side of equality 1.23,

\[
\frac{\partial (V(z, T))}{\partial z} = -\frac{a}{2} V(z, T) \tag{1.24}
\]

\[
\frac{\partial (V(z, T))}{V(z, T)} = -\frac{a}{2} \frac{\partial z}{z} \tag{1.25}
\]

\[
\frac{\partial (\ln(V(z, T)))}{\partial z} = -\frac{a}{2} \ln(V(z, T)) \tag{1.26}
\]

\[
\int_{(L, T)}^{(0, T)} \frac{\partial (\ln(V(z, T)))}{\partial z} = \int_{0}^{L} -\frac{a}{2} \partial z \tag{1.27}
\]

\[
\ln \left( \frac{V(L, T)}{V(0, T)} \right) = -\frac{aL}{2} \tag{1.28}
\]

and finally

\[
V(L, T) = V(0, T) e^{-\frac{aL}{2}} \tag{1.29}
\]

Combining Eqs. 1.20 and 1.29,

\[
|A(L, T)| = \left| V(L, T) - V(0, T) \right| e^{-\frac{aL}{2}} = |A(0, T)| e^{-\frac{aL}{2}} \tag{1.30}
\]

The physical meaning of Eq. 1.30 is that the pulse shape does not change under the effect of SPM alone; the pulse is just attenuated due to the propagation loss of the fibre. Equating the imaginary part of the left and right hand side of equality 1.23,

\[
V(z, T) \frac{\partial \phi_{NL}(z, T)}{\partial z} = \gamma |V(z, T)|^2 V(z, T) \tag{1.31}
\]

\[
\frac{\partial \phi_{NL}(z, T)}{\partial z} = \gamma |V(z, T)|^2 \tag{1.32}
\]
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and by integration

\[ \phi_{NL}(L,T) = \gamma \int_0^L |V(z,T)|^2 \, dz \]  

(1.33)

\[ \phi_{NL}(L,T) = \gamma \cdot |V(0,T)|^2 \cdot \int_0^L e^{-a z} \, dz \]  

(1.34)

and finally

\[ \phi_{NL}(L,T) = \gamma \cdot |V(0,T)|^2 \cdot L_{eff} = \gamma \cdot |A(0,T)|^2 \cdot L_{eff} \]  

(1.35)

where the parameter \( L_{eff} \) is called effective length and is provided by the relation

\[ L_{eff} = \left[ \frac{1 - e^{-a L}}{L} \right] \]  

(1.36)

The effective length takes into account the loss of the fibre, it is always smaller than the actual fibre length, \( L \), due to the fibre propagation loss and it approaches the actual fibre length as the loss parameter \( a \) approaches zero. If \( P_o \) is the peak power of the incident pulse, then the maximum phase shift, occurring at the pulse centre located at \( T=0 \), is given by

\[ \phi_{max} = \gamma P_o L_{eff} = L_{eff} / L_{NL} \]  

(1.37)

where the parameter \( L_{NL} \) is referred to as the nonlinear length and is provided by the relation

\[ L_{NL} = \frac{1}{\gamma P_0} \]  

(1.38)

Eq. 1.35 shows that, in the absence of dispersion, the SPM effect in optical fibres gives rise to an intensity dependent phase shift, while it does not affect the pulse shape. The acquired phase shift increases with the fibre length and is dependent on the fibre nonlinear parameter \( \gamma \) and the power of the applied electromagnetic wave. The time dependence of the phase shift (Eq. 1.35) gives rise to a change in the instantaneous frequency along the pulse compared to its central value of \( \omega_0 \). This frequency change induced by SPM increases with the fibre length and leads to the generation of new frequency components as the pulse propagates through the fibre. In Fig. 1.1, the SPM-induced change in the instantaneous frequency \( \delta \omega \) and the resulting spectral broadening are presented for the case of an unchirped Gaussian pulse and conditions corresponding to a maximum nonlinear phase shift \( \phi_{max} \) of 2.5\( \pi \). It can be
seen that $\delta\omega$ is negative near the leading edge of the pump, while it becomes positive near the trailing edge. In the central part of the pulse, $\delta\omega$ changes linearly over time. The SPM-induced frequency chirp leads to spectral broadening. The resulting spectrum exhibits an oscillatory structure that comprises of many peaks, with the outermost peaks being the most intense. The number of peaks depends linearly on $\phi_{\text{max}}$.

![Figure 1.1: SPM-induced (a) spectral broadening and (b) instantaneous frequency change for an initially unchirped Gaussian pulse when $\phi_{\text{max}}=2.5\pi$. In (a), the dashed line corresponds to the spectrum of the input Gaussian pulse.](image)

The above analysis considers solely the effect of SPM, while pulse dispersion is ignored. However, as the input pulse becomes shorter, dispersion starts to affect the pulse evolution. The combined effects of dispersion and SPM give rise to interesting features. To study the temporal and spectral evolution of a pulse under the effects of
dispersion and SPM, it is common to define a time scale normalized to the input pulse width $T_0$

$$\tau = \frac{T}{T_0} = \frac{t - \beta_1 z}{T_0} \quad (1.39)$$

as well as a normalized amplitude $U$ such that

$$A(z, \tau) = U(z, \tau) \sqrt{P_0} e^{-\alpha z / 2} \quad (1.40)$$

where $P_0$ is the peak power of the incident pulse. Using these parameters and ignoring the third order dispersion term, Eq. 1.18 takes the form

$$\frac{\partial U}{\partial z} + i \frac{\beta_2}{2 T_0^2} \frac{\partial^2 U}{\partial \tau^2} - i \gamma P_0 |U|^2 e^{-\alpha z} = 0 \quad (1.41)$$

or

$$\frac{\partial U}{\partial z} + i \frac{\text{sign}(\beta_2)}{2 L_D} \frac{\partial^2 U}{\partial \tau^2} - i \frac{|U|^2}{L_{NL}} e^{-\alpha z} = 0 \quad (1.42)$$

where $\text{sign}(\beta_2) = \pm 1$ is the sign of the second order derivative. The parameter $L_D$ is known as the dispersion length and is provided by the relation

$$L_D = \frac{T_0^2}{|\beta_2|} \quad (1.43)$$

The dispersive length and the nonlinear length (Eq. 1.43 and Eq. 1.38 respectively) express the length scales over which the effects of GVD and nonlinearity respectively start to become significant. Therefore, for example, an analysis considering solely the effect of SPM applies to the case where the fibre length is of the order of the nonlinear length but much lower than the dispersive length, while if both the nonlinear length and the dispersive length are of the order of the fibre length, both the effects of SPM and GVD have to be considered. It is common to introduce a parameter $N$, defined as

$$N = \sqrt{\frac{L_D}{L_{NL}}} \quad (1.44)$$

It becomes apparent that the parameter $N$ dictates the relative importance of the SPM and GVD effects on pulse evolution.

To examine the combined effect of SPM and GVD on pulse evolution, the case of an initially unchirped Gaussian pulse for $N=1$ is considered. Numerical simulations based on solving the NLSE (1.18) were performed for different fibre lengths, while the fibre
loss and the third-order dispersion term were ignored. Fig. 1.2 corresponds to pulse propagation in the normal dispersion regime ($\beta_2 > 0$) of a fibre. It can be seen that the pulse broadens very rapidly in the normal dispersion regime. This pulse broadening leads to a reduced spectral broadening compared to the case when the effect of GVD is ignored.

The pulse evolution is completely different for propagation in the anomalous dispersion regime ($\beta_2 < 0$), as shown in Fig. 1.3. In this case, an initial broadening is observed in the temporal domain, while a steady state is reached after a distance of $\sim 5L_D$. This behaviour is due to the fact that when $L_D = L_{NL}$ the GVD-induced frequency chirp almost cancels the SPM-induced frequency chirp in the central part of the pulse. The pulse actually adjusts itself during propagation so that a chirp-free pulse state is reached. In the case that the input pulse has a hyperbolic secant profile rather than a
Gaussian, both the temporal and the spectral characteristics of the pulse remain unchanged during propagation, if a lossless propagation is assumed. Pulses with a hyperbolic secant profile are normally referred to as soliton pulses and have attracted significant attention for use in optical communication systems.

![Numerical simulations of the pulse shape](image1)

![Numerical simulations of the pulse spectra](image2)

**Figure 1.3**: Numerical simulations of the pulse shape (a) and spectra (b) of an initially unchirped Gaussian pulse propagating in the anomalous dispersion regime of a fibre when $N=1$.

### 1.1.1.2 Cross-phase modulation

When two or more light beams of different frequency or polarization state are simultaneously launched on a nonlinear medium, each beam induces an intensity dependent phase modulation to itself according to the SPM effect. Apart from SPM, a nonlinearity-induced interaction of the propagating beams inside the nonlinear
medium is also observed, with each beam inducing an optical phase change to every other beam. This effect is known as XPM.

The simplest form of the XPM effect concerns the simultaneous launching of two co-propagating fields on the same polarization axis of a fibre. It is assumed that both waves propagate in the fundamental fibre mode and that they have the same modal distribution, i.e. the dependence of the modal distribution on the frequency of the propagating wave is disregarded. Following an analysis similar to the one described in 1.1.1, and applying the same assumptions, the following set of two coupled NLSEs is reached [1]

\[
\frac{\partial A_1}{\partial z} + i \frac{\beta_{31}}{2} \frac{\partial^2 A_1}{\partial T^2} - \frac{\beta_{31}}{6} \frac{\partial^3 A_1}{\partial T^3} + \frac{\alpha_1}{2} A_1 - i \gamma_1 A_1 \left( |A_1|^2 + 2 |A_2|^2 \right) = 0
\] (1.45)

\[
\frac{\partial A_2}{\partial z} + d \frac{\partial A_2}{\partial T} + i \frac{\beta_{32}}{2} \frac{\partial^2 A_2}{\partial T^2} - \frac{\beta_{32}}{6} \frac{\partial^3 A_2}{\partial T^3} + \frac{\alpha_2}{2} A_2 - i \gamma_2 A_2 \left( |A_2|^2 + 2 |A_1|^2 \right) = 0
\] (1.46)

where \( A_j \) is the slowly varying field, \( \alpha_j \) is the propagation loss, \( \gamma_j \) is the nonlinear parameter \( \gamma \), \( \beta_{1j}, \beta_{2j} \) and \( \beta_{3j} \) are the first, second and third order derivatives of the propagation constant \( \beta_{0j} \) and the index \( j=1,2 \) denotes the \( j \)-th field. In Eq. 1.45 and 1.46, time is expressed by the parameter \( T \), which is measured relative to a time frame moving at the group-velocity of the first pulse, as defined in Eq. 1.17. The parameter \( d \) is equal to

\[
d = \frac{v_{g1} - v_{g2}}{v_{g1} v_{g2}}
\] (1.47)

where

\[
v_{g1} = \frac{1}{\beta_{11}}, \quad v_{g2} = \frac{1}{\beta_{12}}
\] (1.48)

are the group-velocities of the two pulses. The parameter \( d \) expresses the group-velocity mismatch between the two co-propagating pulses. This parameter greatly affects the XPM interaction, since pulses having very different group-velocities tend to walk off from each other, leading to a reduced XPM interaction.

Studying the last term of Eq. 1.45 and 1.46 and taking into account the analysis in section 1.1.1.1, it can be concluded that when the two interacting beams have the same polarization, the phase change induced by XPM is twice as effective as the phase change induced by SPM for the same intensity. This is a consequence of the number of
terms contributing to the nonlinear polarization (Eq. 1.5), which doubles when the two interacting beams have distinct optical frequencies compared to the case when the frequencies are degenerate [1]. It should be noted that an XPM interaction can also take place between cross-polarized beams, regardless of whether the two beams have the same or different frequencies. However, due to the tensorial nature of the third-order susceptibility, the relevant magnitude of the XPM phase change is different in this case. It can be shown that for cross-polarized beams and considering a linearly birefringent fibre, the XPM phase change drops down to $\frac{2}{3}$ of the SPM induced phase change [1].

### 1.1.1.3 Four-Wave mixing

FWM is another process stemming from the third-order nonlinear susceptibility. Quantum-mechanically it is described by the annihilation of two photons belonging to the same, or different, waves and the generation of two photons at different frequencies, so that energy conservation and momentum are conserved. FWM is a parametric process that requires energy conservation and phase-matching between the interacting waves. FWM is efficient only under strict phase-matching conditions. The energy conservation requirement for the FWM process yields the equation [1, 5]

$$\omega_3 + \omega_4 = \omega_1 + \omega_2$$  \hspace{1cm} (1.49)

where $\omega_j$ is the frequency of the $j$-th field. The phase-matching condition requires that the net phase mismatch is equal to zero, and is expressed mathematically by the relation

$$[\beta(\omega_3) + \beta(\omega_4) - \beta(\omega_2) - \beta(\omega_1)] + \Delta\beta_{NL} = \Delta\beta_L + \Delta\beta_{NL} = 0$$  \hspace{1cm} (1.50)

where $\Delta\beta_L$ is the wavevector or linear phase mismatch (the parameter $\beta(\omega_j)$ denotes the propagation constant of the $j$-th field) and $\Delta\beta_{NL}$ is the nonlinear, power-dependent phase mismatch [1, 5]. A more rigorous analysis of the phase-matching condition for efficient FWM will be provided in Chapter 4.

When solely a strong pump is incident on a fibre, FWM causes the generation of two new waves at different frequencies to build up from noise. This process is known as spontaneous FWM. On the other hand, if three waves are incident on an optical fibre
and considering all the degenerate and partially degenerate processes, nine new frequencies can be generated [5]. In general all weaker frequencies are normally neglected apart from the stronger frequency component $\omega_4$. The most common configuration for FWM-based applications concerns the simultaneous launching of a strong pump at a frequency $\omega_p$ together with a weak signal at $\omega_s$. FWM results in the generation of a new wave at a frequency $\omega_f$, as well as the simultaneous amplification of the weak signal. Therefore, the FWM process can be simultaneously used for wavelength conversion and parametric amplification applications. A thorough analysis of the FWM process will be provided in Chapter 4.

1.1.2 Inelastic nonlinear processes

1.1.2.1 Raman scattering

Raman scattering describes the inelastic scattering of a photon by a molecule, which results in the formation of a photon of lower frequency and an optical phonon corresponding to a transition of the molecule to a higher vibrational state. The frequency difference between the incident photon and the scattered photon is dictated by the vibrational energy modes of the molecule. Materials having a crystalline nature have well defined vibrational energy states. On the contrary, for amorphous materials such as glasses, the vibrational modes spread into bands that overlap, forming a continuum. Hence, the frequency range over which a scattered downshifted photon can appear, which will be herein referred to as the Raman gain bandwidth, is broad and multi-peaked in optical fibres. It should be noted that a high-energy photon can also be created through the Raman scattering process, provided that a phonon of a suitable momentum and energy is available.

When a pump beam of low intensity is incident on an optical fibre, photons falling inside the entire bandwidth of the Raman-gain spectrum of the fibre are generated. This process is known as spontaneous Raman scattering and is relatively weak. Certain vibrational modes, which are solely dependent on the fibre material, are most likely to appear and therefore the corresponding frequency components build up most rapidly. For the case of silica glass, the dominant vibrational mode gives rise to a
photon at a frequency downshifted by ~13.2 THz from the pump frequency [1, 6]. This is shown in Fig.1.4, where the Raman gain spectrum of silica glass is presented and the peak of the Raman gain is evident. The Raman scattered longer wavelength radiation is known as the Stokes wave.

![Raman gain spectrum of silica glass at a pump wavelength of 1 µm [6].](image)

**Figure 1.4:** Raman gain spectrum of silica glass at a pump wavelength of 1 µm [6].

For an intense pump beam incident on an optical fibre, the dominant frequency component of the Raman gain builds up almost exponentially, with most of the pump power transferred to it at high gains. This case corresponds to the nonlinear phenomenon of stimulated Raman scattering (SRS), which requires a certain intensity threshold to be reached. The phenomenon of SRS is commonly employed in Raman amplifiers, in which case a strong pump is launched on an optical fibre together with a weak signal that falls inside the Raman gain bandwidth of the fibre. For optimum amplification performance, the frequency difference between the pump and the signal is chosen so that it corresponds to the peak of the Raman gain of the fibre.

If only a CW pump is considered to be incident on an optical fibre and defining the Raman threshold as the input pump power at which the generated Stokes power becomes equal to the pump power at the fibre output, then the threshold condition approximately becomes [1, 6]

\[ P_{thr} = 16 \frac{A_{eff}}{g_{eff} L_{eff}} \]  

(1.51)
where $P_{th}$ is the threshold pump power and $g_r$ is the Raman gain coefficient, which is related to the spontaneous Raman scattering cross-section. Eq. 1.51 assumes that the main contribution to the Stokes power is generated from a narrow region around the peak of the Raman gain and that the Raman-gain spectrum has a Lorentzian shape.

When, instead of a CW pump, optical pulses are launched into a fibre, each pump pulse generates a Stokes pulse when the threshold for SRS is reached. The mutual interaction between the pump pulses and the generated Raman pulses is governed by a set of two coupled equations, which are similar to Eqs. 1.45, 1.46 and include both the nonlinear Kerr effect and the Raman effect. The general form of these equations is [1]

$$\frac{\partial A_p}{\partial z} + \beta_{1p} \frac{\partial A_p}{\partial t} + i \frac{\beta_{2p}}{2} \frac{\partial^2 A_p}{\partial t^2} - \frac{\beta_{3p}}{6} \frac{\partial^3 A_p}{\partial t^3} + \alpha_p A_p = i \gamma_p A_p \left( |A_p|^2 + (2 - f_R) |A_s|^2 \right) - \frac{g_p}{2} |A_p|^2 A_p$$

$$\frac{\partial A_s}{\partial z} + \beta_{1s} \frac{\partial A_s}{\partial t} + i \frac{\beta_{2s}}{2} \frac{\partial^2 A_s}{\partial t^2} - \frac{\beta_{3s}}{6} \frac{\partial^3 A_s}{\partial t^3} + \alpha_s A_s = i \gamma_s A_s \left( |A_s|^2 + (2 - f_R) |A_p|^2 \right) + \frac{g_s}{2} |A_p|^2 A_s$$

where $A_j$ is the slowly varying field, $\alpha_j$ is the propagation loss, $\gamma_j$ is the nonlinear parameter, $\beta_{ij}, \beta_{2j}$ and $\beta_{3j}$ are the first, second and third order derivatives of the propagation constant $\beta_0$ and the index $j=p,s$ denotes the pump and the Raman signal respectively. The parameter $f_R$ represents the fractional contribution of the vibrational Raman response to the induced nonlinear polarization and has a value of 0.18 [1, 6, 7], while the gain coefficients $g_p$ and $g_s$ are connected to the Fourier transform $\tilde{h}_R$ of the Raman response $h_R(t)$ [1, 7] through the relations

$$g_s = 2 \gamma_s f_R \left| \tilde{h}_R(\Omega_R) \right|, \quad g_p = 2 \gamma_p f_R \left| \tilde{h}_R(\Omega_R) \right|$$

In the anomalous dispersion region of an optical fibre, short pulses having a hyperbolic-secant nature can give rise to a phenomenon commonly referred to as the soliton self-frequency shift (SSFS) [1]. SSFS is usually observed by launching higher order soliton pump pulses, as these pulses narrow in the time domain and broaden in the spectral domain at the initial stages of pulse propagation [1]. The spectral broadening can lead to seeding of the SRS effect, since the blue components of the pulse can pump the red components. As a result, the main spectral peak seems to shift.
in frequency. In the time domain, the red-shifted components appear as a Raman pulse that follows the input pump pulse. In the case that the Raman pulse is formed at a distance that coincides with the distance at which the higher-order pump soliton has its minimum width in the time domain, the Raman pulse receives almost the entire pump power and propagates as a fundamental soliton. Due to its nature, the formed soliton is known as a Raman soliton.

1.1.2.2 Brillouin scattering

Brillouin scattering is similar to Raman scattering in the sense that it involves the interaction of a photon with the material it is propagating through, resulting in the generation of a new photon that is downshifted in frequency. However, the major difference between the two processes is that acoustic phonons are participating in Brillouin scattering instead of optical phonons that participate in Raman scattering. Brillouin scattering has its origins in the effect of electrostriction, i.e. the increase in the material density in response to the intensity of an applied electromagnetic field. This material density change has its time response determined by the velocity of a sound wave propagating through the material and causes a proportional change of the linear refractive index of the material. The pump-induced modulation of the refractive index forms a kind of refractive index grating, that moves through the material at the acoustic velocity [1, 6]. As a result, an incident photon can be scattered from the formed index grating, resulting in the formation of a new photon that is downshifted in frequency due to the Doppler shift associated with the interaction of the photon with a moving index grating. This scattering process describes the SBS effect and the frequency shift of the scattered photon, compared to the incident photon, is known as the Brillouin shift. In the quantum-mechanical description of SBS, the process involves the annihilation of a photon and the generation of a Stokes photon and an acoustic phonon. Both energy and momentum are conserved during the Brillouin scattering process. Conservation of energy states that

\[ \omega_B = \omega_p - \omega_s \]  

(1.55)

where \( \omega_p \), \( \omega_s \) and \( \omega_B \) are the frequencies of the pump, Stokes and Brillouin waves respectively. The conservation of momentum dictates that

\[ \vec{k}_B = \vec{k}_p - \vec{k}_s \]  

(1.56)
where $\vec{k}_p$, $\vec{k}_s$ and $\vec{k}_B$ are the wave-vectors of the pump, Stokes and Brillouin waves respectively. Since the Brillouin wave, generated by electrostriction, is an acoustic wave,

$$\omega_B = v_A |\vec{k}_B| = v_A |\vec{k}_p - \vec{k}_s|$$  \hspace{1cm} (1.57)

where $v_A$ is the acoustic velocity. Due to its acoustic nature, the Brillouin wave has a frequency $\omega_B$ much lower than the optical frequencies $\omega_p$ and $\omega_s$, therefore

$$|\vec{k}_p| \approx |\vec{k}_s|$$  \hspace{1cm} (1.58)

and

$$\omega_B = v_A |\vec{k}_B| = 2v_A |\vec{k}_p| \sin \frac{\theta}{2}$$  \hspace{1cm} (1.59)

where $\theta$ is the angle between the pump and the Stokes wave. It becomes apparent that $\omega_B$ is maximum in the backward direction, while it is equal to zero in the forward direction. Therefore, since the only relevant directions in a SMF are the forward and backward direction, SBS occurs only in the backward direction (Fig. 1.5). Using Eq. 1.59, the Brillouin frequency shift $\nu_B$ is

$$\nu_B = \frac{\omega_B}{2\pi} = \frac{2v_A |\vec{k}_p|}{2\pi} = \frac{2v_A}{2\pi} \frac{2\pi n}{\lambda_p} = \frac{2n v_A}{\lambda_p}$$  \hspace{1cm} (1.60)

where $n$ and $\lambda_p$ are the refractive index of the medium and the wavelength of the pump respectively.

![Figure 1.5: Graphical representation of the Brillouin effect.](#)

The SBS process in a material is characterized by the Brillouin gain spectrum, which expresses the cross-section of SBS in the frequency domain. It turns out that the gain spectrum has a spectral line (or more than one spectral lines, in the case of inhomogeneous materials) which peaks at $\omega = \omega_B$ and has a very small spectral width of the order of a few MHz, which is related to the damping time of the acoustic waves (phonon lifetime). In bulk silica, the Brillouin shift can be calculated from Eq. 1.60.
Using $v_A = 5.96 \text{ km/s}$ and $n = 1.45$, it turns out that for bulk silica, the Brillouin shift is expected to be $v_B \approx 11.1 \text{ GHz}$ at $\lambda p = 1.55 \mu m$. The Brillouin gain spectrum of silica optical fibres though can differ significantly from that of bulk silica. This is due to the guided nature of the acoustic waves in the core of a fibre and the inhomogeneities in the fibre core cross-section across the fibre length, mainly due to fabrication imperfections. Therefore, fibres with a high germanium concentration in their core tend to have a reduced Brillouin shift, with the reduction of the Brillouin shift being almost inversely dependent on the germanium concentration [8]. Fibres with a strong inhomogeneous distribution in their core normally exhibit a multi-peaked Brillouin gain spectrum behaviour and reduced Brillouin gain.

With regard to the spectral width $\Delta v_B$ of the Brillouin-gain peak, it turns out that it depends on the Brillouin shift and varies almost quadratically with it. On the other hand, the peak value of the Brillouin gain is almost wavelength independent, having a value of $g_B \approx 5 \times 10^{-11} \text{ m/W}$ [1]. However, it has to be noted that the Brillouin gain strongly depends on whether the incident light has a CW or a pulsed nature. In particular, the Brillouin gain is significantly reduced for pulses having a spectral width exceeding $\Delta v_B$. Therefore, for pump pulses of a time width smaller than the acoustic phonon lifetime, which is around 10 ns for fused silica at room temperature and at 1.55 $\mu m$, Raman scattering dominates [1]. In practice, it is found that SBS dominates for pulse durations down to around 4 ns (assuming transform-limited pulses).

If only a single frequency CW pump is considered to be incident on an optical fibre and by defining the Brillouin threshold similarly to the Raman threshold (i.e. as the input pump power for which the generated Stokes power is equal to the pump power at the fibre output), the threshold condition approximately becomes [1, 6]

$$P_{thr} = 21 \frac{A_{eff}}{g_B L_{eff}}$$  \hspace{1cm} (1.61)

where $P_{thr}$ is the threshold pump power and $g_B$ is the Brillouin gain coefficient, related to the Brillouin scattering cross-section. Although fairly accurate, Eq. 1.61 fails to predict $P_{thr}$ with precision, mainly due to the fact that the Brillouin gain is affected by fibre core inhomogeneities in terms of doping levels and core dimension variations across the fibre length. However, in general SBS dominates over SRS in the case of a
narrow linewidth pump. For example, considering a typical fibre-based optical communication system operating at 1.55 µm, for $A_{\text{eff}} = 80 \, \mu\text{m}^2$, $L_{\text{eff}} = 20$ km and $g_B \approx 5 \times 10^{-11} \, \text{m/W}$, the use of Eq. 1.61 predicts a $P_{\text{thr}}$ of $\sim 1.6$ mW. Therefore, it becomes apparent that, under CW or quasi-CW conditions, Brillouin scattering is the dominant limiting nonlinear effect in optical fibre-based systems. On the other hand, for short pump pulses with a spectral width $\Delta \nu_p$ much smaller than $\Delta \nu_B$, the Brillouin gain is reduced below the Raman gain and SRS dominates over SBS, giving rise to a forward-propagating Raman pulse [1].

1.2 Holey fibre technology

1.2.1 Photonic bandgap fibres and holey fibres

Microstructured optical fibres (MOFs) represent a new class of fibre that has only recently emerged [9, 10, 11]. MOFs are characterized by the presence of an arrangement of air holes that run down the fibre length. The holes act as a cladding region, therefore MOFs can be fabricated from a single material as opposed to conventional fibres. MOFs can guide light through two different physical mechanisms: the photonic bandgap effect and the modified total internal reflection effect.

The photonic bandgap effect in optical fibres [9, 10, 11, 12] requires the existence of a periodic, 2-dimensional pattern of holes that invariantly runs along the fibre length perpendicularly to the fibre axis. Similar to planar photonic crystal structures, the existence of a periodic structure in the fibre cross-section results in the formation of photonic bandgaps, with frequencies lying inside the bandgap unable to propagate within the cladding. Breaking this periodicity by forming a structural defect in the photonic crystal, it is possible to confine and propagate light of any frequency lying inside the bandgap through the defect. In other words, light lying inside the bandgap is allowed to propagate in the close vicinity of the defect, while far from the defect it experiences the periodicity of the photonic crystal, which cancels the wave propagation through it. Fibres utilizing this light propagating mechanism are called photonic bandgap fibres (PBGFs). Since the defect is normally formed by increasing the dimensions of a hole in the 2D-hole pattern (Fig. 1.6a), PBGFs allow waveguiding
in air, and are therefore appealing for sensor applications, since the holes can be filled with gases. They are also interesting for telecommunication applications, in which case limitations due to nonlinear phenomena and fibre loss can be minimized. On the other hand, it is possible to create solid-core PBGFs, by replacing the holes with rods of a material with higher index compared to the index of the solid core (Fig. 1.6b). Such fibres could be in general easier to fabricate and splice, while they will also offer the potential of doping the core region, so as to realize fibre amplifiers/lasers or Bragg gratings.

![Figure 1.6: Examples of (a) an air-guiding silica-based PBGF (fabricated at the ORC) and (b) a solid core silica-based PBGF [13]. In (b), the bright cylinders correspond to germanium-doped regions.](image)

The modified internal reflection or index guiding effect in MOFs is similar to the total internal reflection in step-index fibres. Although the operation of the index-guiding fibres does not depend on the presence of a periodic arrangement of holes, typically such fibres are fabricated by realising a hexagonal lattice of holes with the central hole of the pattern replaced by a solid glass rod, so as to form the high-index core, as shown in Fig. 1.7 [14, 15]. The modified internal reflection guiding mechanism in this kind of fibres is related to the fact that the presence of holes lowers the effective refractive index of the surrounding region of the solid core that forms the cladding [9, 10, 11, 14, 15]. Hence, light is confined in the higher-index solid core, which has a diameter of $\sim 2d - d$, where $A$ is the hole-to-hole spacing and $d$ is the diameter of the holes (Fig. 1.8), and does not propagate in the cladding that is filled with air holes. Therefore, such fibres are normally referred to as photonic crystal fibres. Within this thesis, the term ‘holey fibres’ (HFs) will be used for fibres utilizing the index-guiding effect.
Chapter 1: Small-core, HNLFs

Figure 1.7: Examples of HFs fabricated at ORC. (a) Large mode area silica HF, (b) small-core and high NA silica HF, (c) cladding pumped Yb$^{3+}$-doped silica HF, (d) extruded highly nonlinear bismuth HF.

Figure 1.8: HF cross-section sketch. The parameters $\Lambda$ and $d$ correspond to the hole-to-hole spacing and the hole diameter respectively.

The optical properties of HFs stem from the way that the guided mode experiences the cladding region. In HFs, the presence of small air holes with dimensions of the same order of magnitude as the wavelength of optical radiation makes the effective cladding index a strong function of wavelength. At long wavelengths, the holes are too small to be properly imaged by the incident light since the field extends further into the holey cladding region. Therefore, the light experiences an average cladding index, corresponding to the root-mean-square volume-weighted average of the indices of the air and the glass material [16]. On the other hand, at short wavelengths, the field impinges on the glass-air interface, while it is strongly rejected from the air holes. For
this reason, the field distribution tends to peak at the higher-index glass regions, resulting in an effective cladding index that is greater than the average cladding index [16].

The dependence of the refractive index of the cladding on the wavelength of the incident light is responsible for the unique property of HFs with a low $d/\Lambda$ ratio to exhibit single-mode operation, regardless of operating wavelength [15]. Furthermore, since the properties of index-guiding MOFs depend on both the arrangement and the dimensions of the holes in the cladding region, a multitude of important properties in terms of dispersion profile and nonlinear behaviour can be achieved using suitable fibre designs and geometries. Therefore, as opposed to fibres of conventional design, HFs offer the unique properties of broadband single-mode guidance even for large core diameters, anomalous dispersion at wavelengths way below 1.3 µm and even down to ~600 nm, a large normal dispersion at the 1.55 µm telecommunications window, very large values of nonlinearity and very high values of birefringence [17]. By scaling the dimensions of the fibre profile, HFs can have mode areas ranging three orders of magnitude. Large mode area HFs are envisaged as great candidates for the delivery of very high powers. On the other hand, HFs with a small mode area exhibit a very high nonlinearity, hence they can be used for the realization of compact, nonlinear, fibre-based devices. In this thesis, emphasis is going to be given on the properties of small-core HFs, and their potential in nonlinear applications is going to be examined.

1.2.2 Holey fibre fabrication

Several approaches have been followed for the fabrication of HFs. For silica HFs, the capillary stacking technique, shown in Fig. 1.9, has become the most common fabrication method, mainly due to the design flexibility it offers [9, 17, 18].
In the capillary stacking approach, capillaries and rods of a typical diameter around 1-2mm are stacked together and inserted into a larger diameter tube (typically around 20-25mm) in a close-packed space arrangement reproducing the arrangement of holes that is to be obtained in the final fibre. A rod, placed in the middle of the tube, acts as the solid core of the HF. Suitable choice of the dimensions of the capillaries and the solid rods is essential, in order to ensure a good fit inside the tube. The resulting HF preform is then drawn into a cane of a diameter of a few mm and inserted into an external solid jacket tube. Applying a second drawing stage to this final preform, the HF is produced. The capillary stacking technique allows for novel designs to be realized, leading to the fabrication of fibres with very attractive optical characteristics, as it will be shown in the rest of this Chapter. Despite its widespread acceptance, capillary stacking is generally acknowledged to be both a time consuming and labour intensive fabrication method, especially since it requires the separate fabrication of the capillaries and rods employed. Moreover, due to the difficulties in suitably arranging

**Figure 1.9**: Capillary stacking method. (a) HF preform fabrication by insertion of capillaries and rods inside a larger hollow tube. (b) Insertion of the cane into the jacket tube.
the rods and capillaries inside the tube, it is very difficult to fabricate HFs with an arbitrary hole lattice using this technique.

Extrusion has recently emerged as an alternative to the capillary stacking HF fabrication technique [19, 20, 21, 22]. It is especially suitable for compound-glass HFs and polymer materials, since these materials normally exhibit a transition temperature much lower compared to silica glass. Extrusion is performed by bringing a billet of glass under high temperature and pressure conditions (determined by the specific properties of the glass used) and forcing it through a structured die of suitable design (Fig. 1.10). At the output of the die, a fibre preform, with a design determined by the die used, is obtained.

![Stainless-steel die](image)

**Figure 1.10:** Simplified schematic of the extrusion apparatus. A picture of a stainless-steel die used for HF fabrication is also shown.

As in the case of capillary stacking, two drawing stages are applied: the first one involves the fabrication of the cane, while the second concerns the fabrication of the HF after insertion of the cane into a jacket tube. The difference between the two approaches lies solely in the fabrication of the cane, since extrusion is used in place of stacking for the fabrication of the fibre preform (Fig. 1.11). Using the extrusion process, robust and reproducible fibre designs have been realised. The major advantage of the extrusion process lies in its simplicity, since the fibre preform is created in one easy extrusion step, without the need for labour intensive stacking. Furthermore, exotic designs, which cannot be realised by application of stacking,
might be possible using the extrusion process, provided that a suitable die can be designed and fabricated. On the other hand, extrusion can lead to increased fibre loss, due to contamination of the glass by the surface of the die and the devitrification products introduced at the cooling stage of the glass.

![Figure 1.11: Steps involved in HF fabrication by application of the extrusion process](image)

The structured element stacking (SEST) approach has been recently applied for the fabrication of HFs [23], since it combines the simplicity of extrusion with the design flexibility of the stacking method. This technique has been developed by our group at the ORC during the course of my studies, with the objective of enabling the fabrication of the complex fibre structures required to achieve good dispersion control in soft-glass HFs. In particular, dispersion control is an issue of critical importance for nonlinear device applications and fibre designs that allow a trade-off in nonlinearity for improved dispersion properties (whilst at the same time maintaining single-mode operation) are of great interest. Such designs generally require a complex arrangement of air holes. At present, it is difficult to realise complex holey cladding structures by extrusion alone, especially due to the complexity of the die-design required. The SEST approach relies on analysing a complex fibre structure into a number of distinct structured elements that are easier to fabricate. By application of extrusion, the
structured elements are fabricated, and by subsequent stacking of these elements, the fibre perform is formed. Therefore, the SEST method simplifies the stacking process and allows the fabrication of complex preform structures. In Fig. 1.12, the basic steps of the SEST approach are demonstrated. Extrusion is first applied to produce the macroscopic jacket tube and the core (6-hole structure) and cladding (7-hole structure) elements. The fabricated structured elements are then reduced in size (caning) down to a few mm and are stacked inside the jacket tube. The resulting preform can then be drawn into the final fibre. In this thesis, a SEST HF fabricated by our group has been used extensively employed in various applications and will be described in detail in the following Chapters.

![Figure 1.12: HF fabrication by application of the SEST approach (the figure is courtesy of Dr. Julie Leong).](image)

HFs have also been fabricated by the application of precision ultra-sonic assisted mechanical drilling on glass rods [24]. Using this technique, preforms consisting of holes of an arbitrary size, shape and arrangement can be fabricated. When combined with a computer-controlled micrometer for precise alignment, the position of the drilled holes can be determined with extreme accuracy [25]. Although it is a relatively
straightforward and simple technique, it is extremely time consuming, especially when complex designs consisting of a large number of holes are realised. Moreover, ultrasonic assisted drilling is usually associated with a large contamination of the preform material and an increased impact of surface roughness on the propagation loss of the HF.

1.3 Achieving high nonlinearity per unit length in optical fibres

The parameter that is used to assess and quantify the nonlinear behaviour of optical fibres is the effective nonlinear coefficient $\gamma$, defined by Eq. 1.13. It becomes apparent from the equality that for the realization of HNLFs, both a small effective area $A_{\text{eff}}$ and a high nonlinear refractive index $n_2$ are desirable. The optimization of these parameters is discussed in this section.

1.3.1 Nonlinear refractive index

The nonlinear refractive index $n_2$ is the coefficient of proportionality between an applied electric field and the induced variation of the refractive index, i.e. [1]

$$n_2(E^2) = n(\omega) + n_2|E|^2$$

(1.62)

where $n(\omega)$ is the linear part of the refractive index, which is dependent on the optical frequency $\omega$ and is generated by the first order susceptibility.

With regard to optical fibres, the parameter $n_2$, which relates to the third order susceptibility through Eq. 1.14, depends exclusively on the material that forms the core. Silica has a relatively low nonlinearity of $n_2 \approx 2.2 \times 10^{-20}$ m$^2$/W [1, 14]. Hence, the utilization of nonlinear effects in silica optical fibres requires relatively high light intensities or long fibre lengths.

In general, according to the empirical Miller rule [26], the third order susceptibility is proportional to the fourth power of the linear susceptibility [27, 28]. Therefore, glasses composed of ions that exhibit a high polarizability are expected to exhibit a high
nonlinear refractive index. Although the Miller rule can only give a rough indication of the $n_2$ values of a material, it turns out that, indeed, a higher linear refractive index generally results in a higher nonlinear refractive index value $n$. This is shown in Fig. 1.13, where the relation between $n_2$ and $n$ is presented for various glasses [29]. It becomes apparent from the figure that by introducing heavy atoms (such as heavy metal compounds) or ions with a large ionic radius (such as Se and Te), in which case the polarizability of the components of the glass matrix is increased, an increase of the nonlinear refractive index $n_2$ is obtained. As a result, several high refractive index compound glasses, such as gallium-lanthanum-sulphide, lead-silicate, bismuth-oxide, telluride and arsenic-sulphide exhibit considerably greater nonlinearity than silica [20, 28, 30, 31, 32, 33]. For example, the nonlinear coefficient $n_2$ is $\sim 4 \times 10^{-19}$ m$^2$/W at 1060 nm for the lead-silicate glass SF57 [14], $\sim 5.9 \times 10^{-19}$ m$^2$/W at 1550 nm for tellurite glass [33] and $\sim 3.2 \times 10^{-19}$ m$^2$/W at 1550 nm for bismuth-oxide glass [34].

**Figure 1.13:** Relation between the refractive index $n$ and nonlinear refractive index $n_2$ for various types of glass (The graph was contributed by Dr. Xian Feng) [29].

Despite the fact that the intrinsic nonlinearity of compound glasses can be more than a hundred times greater than silica, their practical use in fibre fabrication has been limited. This is due to the difficulty in achieving single-mode operation, low loss and tailorable dispersion properties with these kind of glasses using conventional solid cladding technology [14], since it is hard to obtain suitably matched glasses, both optically and thermally for the core and the cladding. However, successful fabrication of compound-glass step-index fibres with relatively low loss has been reported and
important all-optical applications have been demonstrated with such fibres [35, 36, 37, 38, 39].

An important issue concerning compound-glass, step-index fibres is group-velocity dispersion (GVD). Due to the relatively low contribution of the waveguide dispersion to the GVD, material dispersion dominates and compound-glass step-index fibres tend to have a very large dispersion at the 1550 nm region. Pulse broadening and walk-off effects can therefore significantly affect the performance of such fibres in practical all-optical applications [35].

1.3.2 Effective mode area

The effective area $A_{\text{eff}}$ of an optical fibre represents the area that the fundamental mode occupies when propagating through the fibre and is mathematically expressed by Eq. 1.15. The value of $A_{\text{eff}}$ depends both on the core size and the NA of the fibre [40].

With regard to the effect of the NA on the $A_{\text{eff}}$, one should bear in mind that the NA is dependent on the refractive index difference between the core and cladding by the relation

$$NA = \sqrt{n_{\text{co}}^2 - n_{\text{cl}}^2}$$  \hspace{1cm} (1.63)

where $n_{\text{co}}$, $n_{\text{cl}}$ are the refractive indices of the core and the cladding respectively. Hence, a large NA indicates a tight confinement of the light within the core and correspondingly a small $A_{\text{eff}}$.

On the other hand, for a given NA, a reduction in the core size causes a decrease in $A_{\text{eff}}$, up to a limit where the mode cannot be confined in the core. Beyond this limit, $A_{\text{eff}}$ increases as the core diameter is reduced, due to poor confinement of the mode [41, 42]. Therefore, to minimize the value of $A_{\text{eff}}$, it is required to achieve a high NA by choosing suitable cladding and core materials, as well as to reduce the core dimensions up to the point where the fundamental mode can be effectively confined in the core [40, 41].
In standard fibres, the minimum achievable $A_{\text{eff}}$ is limited by the NA values that can be realized by germanium doping of the core region, so as to achieve a large difference between the core and cladding refractive indices. On the other hand, HFs can exhibit a large NA, due to the large index contrast between air and glass, and hence tight mode confinement. In particular, for a large air-filling fraction $d/\Lambda$ (Fig. 1.8), the effective refractive index of the cladding region can be significantly lower than the refractive index of the core region (Eq. 1.63), therefore very large NA values, potentially reaching the ultimate limit of an air suspended rod, can be realized [41]. Furthermore, the core size of HFs can be scaled down to extremely low values of the order of a micron. For small-core, pure silica HFs with a high NA, nonlinearity values up to $\sim 70$ W$^{-1}$km$^{-1}$ have been reported [43].

Theoretical predictions, as obtained from numerical simulations, concerning the effective mode area of a triangular lattice silica HF at 1550 nm are shown in Fig. 1.14. It can be seen that HF technology can offer great flexibility in achieving a small $A_{\text{eff}}$ by adjustment of the air filling fraction, so as to increase the fibre NA, and a reduction in the hole-to-hole spacing $\Lambda$. Furthermore, a limit in the minimum achievable effective area exists for a given NA, due to mode confinement issues.

![Figure 1.14: Numerically calculated dependence of the effective mode area of a silica, triangular lattice HF as a function of the hole-to-hole spacing for different air-filling fractions. The dashed curve corresponds to a silica jacketed air-suspended rod (JASR) of diameter $\Lambda$ [41].](image-url)
1.3.3 High effective nonlinearity in compound-glass holey fibres

Conventional SMFs exhibit a low nonlinearity per unit length, of the order of $\gamma = 1 \text{ W}^{-1}\text{km}^{-1}$. An enhanced nonlinear behaviour can be achieved by combining a reduction in the core diameter with the addition of dopants, such as germanium, in the core. The inclusion of suitable dopants may increase the value of the nonlinear coefficient $n_2$ in the core and at the same time improve the NA of the fibre, since the linear refractive index of the core is also modified. This higher NA corresponds to a tighter mode confinement, which, accompanied by the reduction in the core diameter, leads to a drastically reduced value of $A_{\text{eff}}$ (section 1.3.2). However, it should be noted that larger levels of Ge-doping result in higher Rayleigh scattering. Therefore, the increase in nonlinearity stemming from Ge-doping comes at the expense of higher fibre attenuation. Since an increased fibre loss decreases the fibre nonlinear efficiency through a reduction in the effective length, there is a trade-off between nonlinearity enhancement and increased propagation loss in the case of Ge-doping [2]. A typical value of nonlinearity per unit length for commercial, silica HNLFs, achieved by this combination of core diameter reduction and dopants, is 10 to 20 W$^{-1}\text{km}^{-1}$ [14].

As apparent from sections 1.3.1 and 1.3.2, suitably designed HFs can exhibit a very small $A_{\text{eff}}$, while compound glasses possess a nonlinear refractive index that can be orders of magnitude larger than that of silica. Therefore, if HF technology is combined with compound glasses with high material nonlinearity, unprecedented values of nonlinearity per unit length can be realised. HFs exhibiting a very high nonlinear parameter $\gamma$ have been fabricated from various compound glasses, such as gallium-lanthanum-sulphide [44], lead-silicate [45, 46], bismuth-oxide [47] and tellurite [20], revealing the potential of compound-glass HF technology.

It should be mentioned that, for a fair comparison between silica based and compound glass based HNLFs, both the nonlinearity and the dispersion properties of the fibres have to be considered. As it will be shown in section 1.4.4, HFs can be suitably designed so as to exhibit novel dispersion properties. Therefore, compound-glass HFs can potentially exhibit superior performance compared to silica-based HNLFs, since they can combine the extreme material nonlinearity of compound glasses with the tight mode confinement and the novel dispersion properties that HF technology can offer.
1.4 Properties of small-core, highly nonlinear holey fibres

1.4.1 Single-mode guidance in holey fibres

While conventional step-index fibres are heavily multi-mode in the short wavelength regime, HFs can support a finite number of guided modes even at very high frequencies. An intuitive, simplified approach to explain this behaviour was provided by Russell [9], who pictured the presence of the holes as a “modal sieve” (Fig. 1.15). Since the light is evanescent in the air, the holes act as barriers. The fundamental mode exhibits a single lobe that can fit inside the core region and has a spatial distribution that is large enough to avoid slipping through the gaps between the holes encircling the core. In the case of higher order modes, their spatial distribution is smaller and can fit through these gaps. For suitably designed HFs with small air-filling fraction, i.e. \( d/\Lambda < 0.4 \) [48], it is possible that only the fundamental mode can be guided, while all higher-order modes can slip through the holes. Obviously, as the air holes become larger, successive higher order modes can be guided.

Using an approach known as the effective-index method [15], a normalized frequency parameter \( V_{\text{eff}} \) can be defined for the case of HFs in analogy with the \( V \) parameter in step-index fibres. In particular, the \( V \) parameter for HFs is defined by the relation

\[
V_{\text{eff}} = \frac{2\pi A}{\lambda} \sqrt{n_{\text{ce}}^2(\lambda) - n_{\text{ie}(\text{eff})}^2(\lambda)}
\]  

(1.64)
where \( \lambda \) is the wavelength of the light travelling through the fibre, \( A \) is the core radius, which for the case of a triangular arrangement of holes is equal to the hole-to-hole spacing, \( n_{co}(\lambda) \) is the wavelength dependent refractive index of the core associated with the effective index of the fundamental mode and \( n_{cl(eff)}(\lambda) \) is the wavelength dependent, lowest-order allowable cladding mode, known as the fundamental space-filling mode [49]. As recently shown, single-mode operation in HFs is achieved for \( V_{eff} < \pi \) [49].

It becomes apparent from Eq. 1.64 that single-mode guidance over a very wide wavelength range requires that the inverse dependence of \( V_{eff} \) on wavelength is balanced by a corresponding change in the term \( \sqrt{n_{co}^2(\lambda) - n_{cl(eff)}^2(\lambda)} \), in such a way that the value of \( V_{eff} \) remains below \( \pi \). Indeed, as mentioned in section 1.2.1, HFs can exhibit such a behaviour due to the strong wavelength dependence of their effective cladding index on the wavelength of the light travelling through the fibre. At long wavelengths, the field extends deep into the holey cladding and light experiences a relatively low effective cladding index, corresponding to the average index of the cladding region. At short wavelengths, the field is rejected from the air holes, the field distribution peaks at the higher-index glass regions, and the effective cladding index is raised. As a result, the effective cladding index is significantly lower than the core index at low frequencies, whereas it approaches the value of the core index at high frequencies. This reduction in the index difference between the core and the microstructured cladding, as the wavelength of operation gets shorter, can balance the tendency towards multimode behaviour, leading to a stationary value of \( V_{eff} \) [10, 11, 16, 49].

In Fig. 1.16, the effective indices of the cladding, core and guided modes of a triangular-lattice silica HF with an air-filling fraction of \( d/A = 0.6 \) are shown [11]. It can be seen that the effective indices of the guided modes fall between the core and the effective cladding indices, as expected for an index-guiding fibre. Furthermore, it is obvious that the effective cladding index at low frequencies is much lower than the core index, while it approaches the core index at high frequencies. Due to the vanishing index contrast between the core and the cladding, only a fundamental and a second-order guided mode are supported in this HF, regardless of the wavelength of
operation. It can be shown that for a HF of similar design (with a triangular holey lattice) and an air-filling fraction \( d/A \) below 0.4, the effective index of the second-order mode falls below the effective cladding index for all frequencies, hence endlessly single-mode operation is possible (Fig. 1.17) [48].

![Modal index of a HF with triangular air-hole lattice and an air-filling fraction \( d/A \) of 0.6. The fibre supports both a fundamental mode and a second-order mode with a normalized cut-off frequency of \( A/\lambda \) of around 1.5. The inset demonstrates a cross-section of the HF [11].](image-url)
1.4.2 Propagation loss in small-core holey fibres

HFVs can be fabricated using a single material. Since both Rayleigh scattering and the infrared (IR) absorption losses are lower in pure silica compared to germanium-doped silica, HFVs made from pure silica should potentially have less intrinsic loss than conventional Ge-doped fibres [50, 51]. Moreover, it has been shown that the unmatched viscosity between the core and the cladding results in increased imperfection loss, so HFVs have another potential advantage compared to conventional SMFs [52].

However, HFVs at present exhibit higher loss compared to SMF fibres, the best-reported losses so far ranging between 0.3 to 0.4 dB/km at 1550 nm [50, 53]. The main reason for this inconsistency is the increase in Rayleigh scattering due to roughness of the surface in the boundaries between the core and the holes [50, 54]. This loss mechanism is particularly strong for small-core HFVs, since there is a stronger interaction of the light in the core with the holes of the first rings [14]. Moreover,
imperfections and inhomogeneities that arise during the fibre fabrication process itself contribute to a higher loss [50, 54].

Another loss mechanism that plays a significant role in single material, small-core HFs stems from the intrinsically leaky nature of the propagating modes and is referred to as confinement loss. Confinement loss arises from the fact that in single-material HFs, the core has the same refractive index as the material beyond the finite holey cladding. Therefore, the propagating modes are not completely bound in the core and can leak through the cladding. In the case that the extent of the holey cladding region is not sufficient to isolate the core from the solid jacket, or the thickness of the silica bridges between the holes is of the order of the wavelength of the incident light, confinement loss can be severe. Since small-core HFs are characterized by a small pitch (hole-to-hole spacing) $\lambda$, they are more susceptible to the effects of confinement loss, due to a reduced physical separation between the solid core and the glass material beyond the finite cladding. To avoid the detrimental effect of confinement loss, care should be taken in the fibre design stage [55]. A common approach for its reduction relies on the addition of more rings of holes around the core, albeit at the expense of increased fabrication effort. Extensive numerical studies have predicted that confinement loss can be reduced down to acceptable levels, below 0.2 dB/km, for a fibre design with a large air-filling fraction and a large number of rings [41].

In general, the intrinsic material loss of compound glasses is much higher compared to that of silica glass, ranging typically in the dB/m scale at 1.55 µm [25]. As a result, the corresponding loss of compound glass based fibres is also expected to be much higher than the loss of silica HNLFs. Indeed, with regard to HFs made of compound glasses, the loss levels reported at present are typically of the order of 2-5 dB/m at 1550 nm, i.e. much higher than the loss of silica HNLFs, which is typically less than 0.5 dB/km [20, 45, 47]. However, the fact that the fabrication process of compound glasses is still under development should be taken into account. Impurities and defects associated with the compound-glass HF fabrication processes greatly contribute to the large value of the propagation loss [56]. Recent advances in compound-glass HF fabrication techniques have enabled the realization of a tellurite HF with a loss as low as 0.4 dB/m, revealing the potential for a further drastic reduction of the propagation loss of compound-glass HFs [33]. After all, it should be appreciated that compound-glass HFs
are targeted towards the development of sub-meter, sub-Watt nonlinear devices, hence losses as high as \( \sim 1 \text{ dB/m} \) can be tolerated due to the higher nonlinearity.

### 1.4.3 Birefringence in small-core holey fibres

Even a perfectly circular core SMF actually supports two orthogonal linearly polarized modes with the same spatial distribution. The two modes are degenerate in an ideal fibre that maintains cylindrical symmetry throughout its entire length, since the refractive indices and thus the associated propagation constants of the two modes are the same. However, unavoidable geometry deviations, internal stress, external influences, such as bending and twisting, can break this ideal, perfect symmetry. As a result, the two orthogonal polarization states that the fibre supports are split and propagate with different phase velocities.

With regard to HFs, they are usually designed to have a triangular or hexagonal symmetry, hence they exhibit a considerable amount of birefringence. This birefringent behaviour is more pronounced in the case of small-core HFs with large air-filling fractions, since even slight deviations from the ideal symmetry result in a considerable amount of birefringence.

The parameter that is often used to assess the birefringent behaviour of a fibre is the beat length \( L_B \). It expresses the period of the variation in the resulting state of polarization when both modes are excited simultaneously and is defined by the relation

\[
L_B = \frac{2\pi}{|\beta_x - \beta_y|}
\]

(1.65)

where \( \beta_x, \beta_y \) are the propagation constants of the two non-degenerate polarization states that the fibre supports [2].

In HFs, when a strong birefringent behaviour is required, it is usually achieved by inducing a structural asymmetry in the cladding area. The use of asymmetric hole sizes is a common approach [57]. Beat lengths of the order of 0.3 mm have been reported for HFs using such designs [58].
1.4.4 Dispersion properties of small-core holey fibres

The overall GVD is determined by the contribution of two terms, the material and the waveguide dispersion. The material dispersion originates from the fact that different wavelengths travel with different velocities in a material, because of the dependence of its refractive index on the wavelength. On the other hand, the waveguide dispersion (WD) is caused by the explicit dependence of the mode propagation constant on the wavelength and is determined by the waveguide structure of the fibre.

While in standard optical fibres the waveguide contribution is relatively small, the great design flexibility of the refractive index distribution in HFs can result in strong waveguide dispersion and thus novel dispersion properties. By adjusting the core dimensions, the air-filling fraction and the geometry of the holey cladding, HFs that exhibit dispersion properties suitable for a large number of applications can be realised.

A unique property of HFs, which is impossible to achieve by employing conventional fibre structures, is that they can be properly designed so as to exhibit zero dispersion at a wavelength well below 1.3 µm, while remaining single-mode. In order to shift the zero-dispersion wavelength towards shorter wavelengths, a large contribution of waveguide dispersion is required. This can be achieved for a small pitch and relatively large air-filling fraction [59]. Extreme examples of such a strong waveguide dispersion contribution are presented in Fig. 1.18, where it can seen that the fabrication of HFs with a small pitch, $\Lambda$, of between 1 to 2 µm and a $d/\Lambda$ above 0.5 enables anomalous dispersion at wavelengths extending down to 850 or even 550 nm [59].
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Figure 1.18: (a) Dispersion profile of the high-NA silica HF shown in the inset. The fibre has a diameter of \( \sim 1 \mu m \) (defined as the shortest dimension of the silica solid region) and silica bridges of width \( \sim 120 \) nm, connecting the core to the cladding. The two measurements correspond to the two polarization states of the fundamental guided mode. (b) Dispersion profile of the silica HF with a regular triangular air-hole array shown in the inset. The HF exhibits a hole-to-hole spacing of 1 \( \mu m \) and an air-filling fraction \( d/\Lambda \) of 0.62 (solid line). The dispersion of a silica strand with a similar core size (\( \sim 1.45 \mu m \)) is also shown (dashed line) [59].

Fibres exhibiting zero dispersion at such a short wavelength [59, 60] are extremely attractive, since they permit soliton propagation in the near-IR and the visible part of the spectrum. Furthermore, the realization of a shift in the ZDW can be extremely useful for SC generation, which in general requires the combination of near-zero dispersion and high power at the pump wavelength [61]. By employing suitable HF designs, it is possible to realize fibres with a ZDW lying close to the convenient, in terms of high power laser availability, wavelength regions of either 0.8 \( \mu m \) or 1.06 \( \mu m \). Such fibres will allow the development of efficient broadband sources, which can be attractive for a range of applications, as it will be shown in Chapter 5.
HFs can also be designed so as to exhibit a very high normal dispersion and a negative dispersion slope at 1.55 μm. Such fibres could be employed in dispersion compensation applications, replacing the conventional DCFs [2]. In Fig. 1.19, the predicted dispersion profile of a HF with a regular triangular air-hole array, a pitch of 0.932 μm and a very high air-filling fraction of 0.893 is shown. This HF exhibits a normal dispersion of −474.5 ps/nm/km at 1550 nm, and could compensate conventional SMF within 0.05 ps/nm/km over a 236-nm wavelength range [62].

In many nonlinear applications, such as flat and wideband SC generation, ultra-short soliton pulse transmission, FWM-based parametric amplification and XPM-based wavelength conversion, control of the fibre dispersion slope is crucial, since an ultra-flattened dispersion is desirable [63]. By careful control of the pitch and the air-filling fraction, HFs with such behaviour can be fabricated [63, 64, 65]. For HFs with a regular triangular air-hole array, ultra-flattened dispersion is obtained for fibres with a pitch of ~2.5 μm and an air-filling fraction of ~0.2 [65]. However, such fibres suffer from a large confinement loss, unless a large number of rings of holes is used. Improved designs for ultra-flattened dispersion that address the issue of confinement loss involve the use of rings of increasing hole size, as shown in Fig. 1.20a [66]. The corresponding fibre dispersion profile is presented in Fig. 1.20b. An ultra-flat dispersion over ~600 nm is predicted for this fibre.

The waveguide dispersion in HFs is particularly profound in the case of small-core, compound-glass HFs. High refractive index glasses exhibit zero GVD at very long wavelengths, hence they have a normal dispersion at 1550 nm. However, designs of HFs that combine a small-core with a large air-filling fraction can effectively reduce the overall dispersion to such an extent that anomalous dispersion can be achieved at 1550 nm [22]. It will be shown later in the thesis that by employing suitable HF designs, it is possible to realize compound-glass HFs with a ZDW lying inside the C-band or even HFs with a low dispersion slope.
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Figure 1.19: Dispersion profile of a silica HF with a regular triangular air-hole array with $A = 0.932 \ \mu m$ and $d/A = 0.893 \ \mu m$. The dispersion of the fibre is $\sim - 474 \ \text{ps/nm/km}$ at 1550 nm [62].

Figure 1.20: Ultra-flattened dispersion profile of a silica HF with 5 air-hole rings of varying hole-diameter. The fibre cross-section is shown in (a) and has a hole-to-hole spacing of $A = 1.58 \ \mu m$ and $d_1/A = 0.31$, $d_2/A = 0.45$, $d_3/A = 0.55$, $d_4/A = 0.63$, $d_5/A = 0.95$ ($d_n$ corresponds to the n-th ring). (b) The corresponding fibre dispersion profile [66].

1.5 Demonstrated applications of small-core, highly nonlinear holey fibres

Nonlinear effects are attractive for various telecommunication applications, ranging from signal regeneration and pulse compression to wavelength conversion and optical demultiplexing. Several demonstrations that exploit the strong nonlinear behaviour of pure silica, small-core HFs have already been reported. An overview of the
telecommunication device applications reported for highly nonlinear HFs is provided in this section. All the applications that are presented have used pure silica HFs unless otherwise stated.

### 1.5.1 Soliton propagation and pulse compression

The generation and propagation of solitons through HFs has been studied extensively. Using a small-core HF with a high polarization extinction ratio and a ZDW at around 800 nm, soliton formation from positively chirped Gaussian pulses produced from a diode pumped ytterbium fibre source operating at 1.06 µm was demonstrated [67]. In the linear regime, pulse compression by a factor of 14 was observed after just 1.2 m of fibre. Operating at higher powers, i.e. in the non-linear regime, solitons were formed and non-linear pulse compression was observed.

By shifting the ZDW of small-core HFs even lower, down to 740 nm, soliton effects have been clearly observed at wavelengths as low as 850 nm [68]. Nonlinear pulse compression, due to SPM, was also demonstrated.

A very interesting phenomenon regarding soliton propagation is intra-pulse SRS [1]. When SPM generates a spectral width comparable with the frequency shift related to Raman interaction, Raman self-pumping causes energy transfer to longer wavelengths provided that the dispersion is anomalous [69, 70]. Hence, a red-shift of the pulse is observed, giving rise to the phenomenon of SSFS [1]. The formation of Raman solitons has been demonstrated in small-core HFs, since their high nonlinearity allows for red shifted solitons to be formed at low peak powers.

The dependence of the frequency shift of Raman solitons on the input peak power allows for some degree of tunability. Exploiting the SSFS effect induced by a highly nonlinear HF (\(\gamma=70 \text{ W}^{-1}\text{km}^{-1}\)), Raman solitons were produced over the wavelength range from 850 to 1050 nm by varying the peak power of pulses generated from a Ti:sapphire laser that operated at 806 nm [69]. Hence, it becomes apparent that intra-pulse Raman scattering can extend the operational window of Ti:sapphire lasers, making the formation of very short pulses possible at larger wavelengths. Tunable
SSFS over the range from 1560 to ~1680 nm has also been reported for soliton pulses at a high repetition rate of 10 GHz launched in 12.6 m of a highly nonlinear HF with $\gamma = 62 \text{ W}^{-1}\text{km}^{-1}$ [71].

An active device based on the SSFS effect has also been demonstrated [72]. Pulses at 1060 nm were launched together with a 966 nm pump beam into approximately 5 m of a highly nonlinear Yb-doped HF. Amplification of the signal at 1060 nm took place and, depending on the pulse peak power, Raman solitons could be tuned in the region from 1060-1330 nm. The shift of the solitons was controlled by varying the gain in the amplifier, thus leading to the demonstration of a tunable femtosecond soliton source.

With regard to HFs made from compound glasses, Raman soliton generation has been demonstrated in the C-band for lead-silicate based fibres [22]. Using 0.37 m of a ~2.0 µm core HF made from the commercially available SF57 glass, a wavelength shift of 45 nm was observed for approximately 45 pJ input pulses. The autocorrelation measurement revealed a pulse width of 190 fs, with the input pulse width being 1.5 ps.

### 1.5.2 Optical thresholding

A 2R regenerative switch operating at 1550 nm has been reported using 3.3 m of a polarization maintaining HF with $\gamma = 35 \text{ W}^{-1}\text{km}^{-1}$ [73]. The device operated on the basis of SPM in combination with narrowband, offset spectral filtering. The data signal was amplified and allowed to propagate in the nonlinear HF, where SPM was generated. A low-intensity input signal was rejected by the filter, since it could not generate enough SPM, while a high intensity signal generated enough SPM to enable significant light to be transmitted through the offset filter. By appropriate choice of the filter’s wavelength offset and its spectral characteristics, reshaping operation was demonstrated for relatively low peak power $x$ length product requirements.

The same concept was used as a thresholder in an optical code-division multiplexing scheme operating in the C-band to improve the performance of the system by removing the low-level pedestal that accompanies matched filtering. Using a ~9 m-
long HF with $\gamma = 31 \text{ W}^{-1}\text{km}^{-1}$, SPM together with offset filtering resulted in an approximate 3-dB improvement in receiver sensitivity [74].

1.5.3 Optical switching and demultiplexing

All-optical switching has been reported at wavelengths close to 1550 nm using just 5.8 m of a small-core, polarization maintaining, HF in a Sagnac loop mirror configuration [75]. Strong XPM between synchronous pump and signal pulses input to the HF resulted in a successful switching operation. However, limitations imposed by the power of the pump did not allow a $\pi$ phase shift to be reached, hence complete switching was not achieved.

The switching capability of a nonlinear optical loop mirror (NOLM) is particularly useful for achieving high-speed demultiplexing. A 50 m-long HF with ZDW at 1552 nm and $\gamma = 18 \text{ W}^{-1}\text{km}^{-1}$ was used to form a NOLM and this device enabled the demultiplexing of optical time-division multiplexing (OTDM) signals up to 160 Gb/s [76]. The operation of the device was demonstrated in the C-band and was based on the phase shift introduced to the multiplexed signal from a 10 Gb/s, strong, control signal due to severe XPM inside the HF NOLM. A bit-error rate (BER) test showed a 5.12 dB penalty of the demultiplexed 80/10 Gb/s compared to the back-to-back system case.

1.5.4 Wavelength conversion

Efficient, high-speed wavelength conversion is an essential operation for all-optical wavelength-division multiplexing (WDM) schemes. Wavelength conversion has been demonstrated for pure silica HFs by utilizing strong FWM or XPM.

Efficient FWM requires a low dispersion with a low dispersion slope at the spectral region of operation, together with a high nonlinearity and a short fibre length in order for the phase-matching condition to be satisfied [77]. Another key issue is the reduction of SBS, so as to avoid loss of the pump power [78]. Using just 15 m of a polarization maintaining, silica HF with a nonlinearity $\gamma = 70 \text{ W}^{-1}\text{km}^{-1}$, wavelength
conversion of 10 Gb/s nonreturn-to-zero (NRZ) pulses was demonstrated in the C-band with an efficiency of –16 dB over a ~10 nm bandwidth [78].

Wavelength conversion using high nonlinearity HFs has also been achieved by utilization of strong XPM effects. The high nonlinearity of HFs allows for the use of very small lengths of fibre, thus reducing pulse walk-off effects [1]. Using just 5.8 m of a HF with $\gamma = 60 \text{ W}^{-1}\text{km}^{-1}$, an almost penalty-free wavelength conversion of 10 Gb/s RZ pulses was demonstrated in the C-band over a 15 nm bandwidth [79]. The importance of using HFs with normal dispersion over the bandwidth where wavelength conversion is desired becomes apparent from a direct comparison with a previous approach, where the HF that was used had anomalous dispersion in the C-band [80]. In the latter case, coherence degradation [81] resulted in an approximately 4 dB power penalty of the converted pulses compared to the input pulses [80].

1.5.5 Supercontinuum generation

The generation of SC in HFs is the result of the contribution from several nonlinear phenomena. This spectacular spectral broadening can arise from different combinations of pulse energies and wavelength regions. In particular, SC using HFs has been demonstrated using pulses with durations in the femtosecond, picosecond and even nanosecond regime [60, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91].

With regard to applications concerning telecommunications, the operation of a wavelength-tunable optical pulse source incorporating a 12.5 m-long HF was reported [89]. In this experiment, a HF with $\gamma = 24 \text{ W}^{-1}\text{km}^{-1}$ was placed inside a fibre loop that was pumped from a fibre ring laser. The laser operated at 1537 nm with a repetition rate of 10 GHz and produced 6 ps pulses. The HF generated a SC over 120 nm, due to the combined effect of Raman and FWM processes. Using a bandpass filter (BPF), only a small part of the resulting spectrum (1 nm bandwidth) was selected and allowed to propagate back through the fibre loop containing the HF. By adjusting the cavity length of the loop, synchronous operation with the pump was achieved, hence leading to the demonstration of a HF based optical parametric oscillator with high tunability.
In a different application, a SC over 30 nm was generated at the region between 1536-1565 nm from 20 meters of a polarization maintaining HF with $\gamma = 70 \text{ W}^{-1}\text{km}^{-1}$. The spectrum was sliced by an arrayed waveguide to produce 36 channels with 100 GHz spacing. BER measurements showed that the pulse quality was high across the different channels [90].

A flat SC generation in the 1550 nm telecommunications window was also reported using 200 meters of a polarization maintaining HF with a $\gamma$ of $19 \text{ W}^{-1}\text{km}^{-1}$ and ultra-flat zero dispersion at the 1550 nm region. The SC spanned over 40 nm [91].

SC generation has also been reported for compound-glass HFs. Using 75 cm of a 2.6 µm core fibre made from the commercially available SF6 glass, a broad SC was generated by pumping with pulses having less than 1 kW of peak power and with a duration of 100 fs at a centre wavelength of 1550 nm [19]. In another experiment, a broad SC spanning from 400 nm to beyond 1750 nm was achieved by pumping 60 fs pulses into a 30 cm long, 2.6 µm core SF6 fibre at a centre wavelength of 1560 nm [92].

1.5.6 Amplification and lasing

Fibre amplifiers based on the Raman effect can potentially extend the optical transmission bands over the gain bandwidth window of EDFAs. High Raman efficiency in conventional fibres can be obtained by reducing the fibre effective area or increasing the germanium concentration in the core. HF technology has been proposed to further increase this figure, since it enables a drastic reduction in the effective mode area. A Raman amplifier using 75 m of a HF with an effective area of ~2.85 µm has been reported [93]. A strong pump pulse at 1536 nm was multiplexed with a weak signal at the L wavelength band (1600-1640 nm) and launched in the fibre. Raman amplification was observed, which had higher gain and a lower noise figure achieved when the signal wavelength was close to the peak of the Raman gain curve, 13.2 THz from the pump wavelength.
Moreover, optical parametric amplification utilizing FWM has been reported using a 12.5 m-long highly nonlinear HF with a ZDW at 1544 nm [94]. A large value of gain slope was reported, with parametric gains above 20 dB extending over a bandwidth of ~30 nm.

The combination of the tight mode confinement in small-core HFs and rare-earth doping of their core region can potentially lead to the implementation of fibre amplifiers with high gain efficiencies and low thresholds of operation. Such active devices based on HFs have been demonstrated. A fibre-laser incorporating 3.4 m of a small-core, erbium-doped, HF has been reported [95]. Pumped by a laser diode at 980 nm, the fibre-laser exhibited a low pump power threshold of 0.55 mW at 1535 nm and a slope efficiency of 57.3%. Mode-locked operation of a 1-m long ytterbium-doped small-core HF laser has also been demonstrated [58]. The laser was pumped at 966 nm and had a laser threshold of 5 mW. Tunable mode-locked operation was achieved over the region from 1030-1050 nm.

1.6 Conclusions

In this Chapter, the main properties of small-core HFs were described. It became apparent that HF technology allows the fabrication of small-core fibres that can simultaneously exhibit single-mode guidance, novel dispersion properties, birefringent behaviour and very high nonlinearity per unit length. All these properties are ideal for a number of telecommunication applications that exploit strong nonlinear effects, such as wavelength conversion, optical thresholding, optical switching, demultiplexing, soliton transmission and SC generation useful for DWDM systems. Amplification and lasing have also been demonstrated in HFs.

Most of the nonlinear applications that have been demonstrated so far for HFs concern pure silica HFs. However, the combination of HF technology with compound glasses that exhibit high intrinsic nonlinearity can lead to astonishingly high values of effective nonlinearity per unit length, thus allowing the realization of compact, nonlinear devices with low power requirements. The potential offered by this direction will be investigated in the remainder of this thesis.
Chapter 1: Small-core, HNLFs

References


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Chapter 1: Small-core, HNLFs


Chapter 2

Characterization of small-core, compound-glass holey fibres

The results from the characterization of highly nonlinear compound-glass HFs are presented in this Chapter. HFs with different core diameters and designs are characterized for two different compound glasses: the commercially available lead-silicate Schott glass SF57 and a bismuth-oxide based glass provided by the Asahi Glass Company. The nonlinear refractive index of the bismuth-oxide based glass used was \( n_2 \approx 3.2 \times 10^{-19} \text{ m}^2 / \text{W} \) at 1550 nm, while the lead-silicate SF57 glass exhibits an \( n_2 \approx 4 \times 10^{-19} \text{ m}^2 / \text{W} \) at 1060 nm\(^*\) [1]. Two types of bismuth-oxide based glasses were employed for fibre fabrication. They differed in their content of hydroxyl (OH) groups, which contributes significantly to the propagation loss at 1550 nm. One type is denoted as normal glass herein, since it was melted in ambient atmosphere and contained a certain amount of OH groups. The other type was dehydrated glass that was melted in a glove box under a dry atmosphere, thus exhibiting a very low content of OH. The experimental results are presented for two fibre designs: a design resembling the strand-on-air case, leading to a maximization of the fibre nonlinearity, and a design with a hexagonal arrangement of holes, fabricated with the SEST approach (section 1.2.2) suitable for dispersion tailoring. The relative advantages of each design are discussed and the potential of these fibres in practical nonlinear applications is examined.

2.1 Structural features of the characterized holey fibres

It was mentioned in section 1.3.3 that, in order for a high fibre nonlinearity to be achieved, apart from the use of a glass with a high intrinsic nonlinearity, a small-core, a high air-filling fraction and a low value of confinement loss are essential. In order to take full advantage of the high nonlinearity of compound glasses, the design presented

\( ^* \) The \( n_2 \) values were provided by the corresponding glass manufacturers.
in Fig. 2.1 was realised. In this particular design, the core has a triangular shape and is supported by three fine struts at relative angles of 120°. The whole design resembles the strand-on-air approach, which represents the best case in terms of air-filling fraction and mode confinement. For strut lengths of between 6-8 µm, a low value of confinement loss can simultaneously be achieved, leading to very high fibre nonlinearities. Extrusion has proven to be a well suited preform fabrication technique for the realization of this design, hence it was preferred to other methods due to its simplicity, as explained in section 1.2.2.

Figure 2.1: Typical cross-section (a) optical microscope and (b) SEM images of the characterized triangular-core fibres. The photos correspond to a bismuth-oxide fibre with an internal core diameter of 1.7 µm. (c) Definition of enclosed and effective core diameter.

In order to classify the different fibres produced using this design, the diameter of the circle that fits exactly inside the triangular-core region was used as the nominal core diameter. This diameter is referred to as the enclosed core diameter. However, a figure for the core diameter that is more representative of the optical properties of the HFs with the structure shown in Figs. 2.1a and 2.1b can be derived. The enclosed circle is related to a triangle that circumscribes it. The diameter of the circle that occupies the same area as this triangle is referred to as the effective core diameter (Fig. 2.1c). The use of this definition for the core diameter instead of the enclosed core diameter yields a better approximation of the fibre’s behaviour when compared to numerical simulations, as will be presented in a subsequent section in this Chapter. The validity of using the effective core diameter is also supported by IR images of the near field pattern of the propagating fundamental mode in these fibres, which clearly has a triangular shape. The relation between the effective core diameter $D_{\text{eff}}$ and the corresponding enclosed core diameter $D_e$ is
\[ D_{\text{eff}} = \frac{3}{\pi \sqrt[3]{3}} \cdot D_e \]  \hspace{1cm} (2.1)

In practical nonlinear applications, a parameter of equal importance to a high fibre nonlinearity per unit length is the fibre dispersion profile. Especially for RZ modulation employing short pulses, a high dispersion leads to substantial pulse broadening and nonlinear performance degradation. In the case of the HF design, presented in Fig. 2.1, the only adjustable parameter that determines the fibre dispersion profile for a given compound-glass material is the fibre core diameter. However, the core diameter also determines the fibre nonlinearity, hence the dispersion characteristics and the nonlinearity cannot be simultaneously optimized using such a design. A different approach relies on the realization of more complex fibre designs, such as the one shown in Fig. 2.2.

**Figure 2.2:** Typical cross-section SEM image of the characterized SEST fibres with a hexagonal arrangement of holes. The photo corresponds to a lead-silicate fibre with a 3.2 µm core diameter.

This design has a hexagonal arrangement of effectively 4 rings of holes (48 holes in total). A combination of extrusion and stacking is required for the fabrication of this design, as explained in section 1.2.2. Unlike purely extruded HFs, which only allow scaling of the microstructured region, while the relative hole size or air-filling fraction is limited by the strut length and thickness required to ensure low confinement loss, the fibre design presented in Fig. 2.2 has two independent adjustable parameters: the hole-to-hole-pitch \( \Lambda \), which can be adjusted by the scale of the microstructured region and the hole diameter \( d \) (or relative hole size \( d/\Lambda \)). Separate optimization of these parameters can lead to fibre designs that combine a high nonlinearity with novel dispersion properties. Hence, fibres with hexagonal arrangement of holes are
considered extremely promising for practical nonlinear applications. Fibres with such a design and for various core diameters have been realized using the SEST approach (section 1.2.2) and the results from the characterization of their properties are presented in this Chapter.

All the HFs presented in this section have been fabricated at the ORC. The efforts of the fibre-fabrication group were aimed at reducing fibre loss, achieving maximum nonlinearity $\gamma$ and, for the case of SEST designs, identifying suitable designs that combined a high nonlinearity with novel dispersion properties. The results stemming from the characterization process I performed have been invaluable to the fibre fabrication group, since they revealed the dependency of the HF properties on parameters such as the holey cladding structure, the core dimensions and the fabrication conditions, for instance the drawing temperature, the applied pressure and the design of the die. Moreover, the experimental measurements were compared to the predictions of the numerical models that the fibre-modelling group have developed. The generally good agreement between theoretical predictions and experimental measurements ensured the validity of the inverse designs employed for the identifications of suitable fibre designs and led to gradual improvement in the HF fabrication process. Furthermore, the characterisation results were used as input in the numerical simulations I performed to assess the behaviour of the HFs in nonlinear applications and validate the experimental performance of the HF-based devices I implemented, as presented in Chapters 3, 4 and 5.

### 2.2 Measurement techniques

For the assessment of the optical properties of the fabricated fibres, it was necessary to implement suitable measurement setups, since the use of standard measurement techniques, employed in the case of conventional fibres, became difficult or impractical for small-core HFs.

In general, free-space coupling was preferred to butt-coupling for launching light into the small-core HFs, since it provided a better coupling efficiency. The fibres under test
were mounted on a three-axis, piezoelectrically-controlled, nano-positioning stage with a resolution of 20 nm. The input light was coupled into a mechanically cleaved input facet of the fibre using either a high-magnification microscope objective (either a x40, 0.65 NA objective with a focal length of 4.6 mm or a x60, 0.85 NA objective with a focal length of 2.9 mm) or a small focal length (3.1 mm) and high-NA (~0.63) aspherical lens, chosen on the basis of experimentally optimizing the coupling efficiency. Typical values of the achieved coupling efficiency were in the range 15-30%, with lower values corresponding to fibres of smaller core diameters.

In order to optimize the coupling efficiency, it was very important to ensure that the input and output fibre facets were clean and accurately cleaved. A bad cleave can result in significant loss enhancement due to increased scattering loss at the rough output surface of the fibre, while an improperly cleaned cleave can lead to increased absorption losses from particles accumulating on the fibre facet. It is important to note that in the case of HFs, conventional polishing methods cannot be applied, since lapping films can destroy the HF structure while liquid adhesives can enter through the holes that form the cladding. In order to minimise the effects of bad end-facet cleaves, manual (hand) cleaving was avoided, since it normally led to bad quality cleaves, and a conventional mechanical cleaver was employed. The settings of the mechanical cleaver had to be optimized for each fibre. The quality of the cleaves was assessed by illumination with a white light source and observation under a microscope or by observation of the radiation pattern on a monitor using an IR camera. A circularly symmetric and uniform pattern essentially implies a good cut. Although commercially available cleavers are currently optimized solely for silica fibres, optical microscope images confirmed that good cleaves could be achieved.

It should be noted that the fabricated fibres were not jacketed, hence a fraction of the launched light could also propagate along the outer solid glass region (Fig. 1.8), as it could be totally internally reflected at the air-glass or holey cladding-glass interface. The detection of this light at the output of the fibre would have been misleading with regard to the estimation of the power launched into the fibre, hence its elimination was imperative. Due to the high refractive index of compound-glass HFs, the application of a normal index matching liquid along the fibre length would have been ineffective. For this reason, a solution of a high-index graphite adhesive, which acted as a highly
absorbing material, was applied to the outer surface of the fibre under test, so as to strip off the propagating cladding modes and remove the cladding light when needed.

In this section, the measurement techniques I applied and the corresponding setups that I implemented for the reliable characterization of small-core, compound-glass HFs are presented. All the setups were based on free-space, lens coupling, apart from the set up involving the estimation of the Brillouin shift, which was based on butt-coupling and was developed with the help of Mr. Ono.

### 2.2.1 Determination of the propagation loss

Before determining the propagation loss of the compound-glass HFs, their mode profile was examined. CW light from a laser diode was propagated through an EDFA and free-space coupled into the fibres. Effectively single-mode guidance could be observed for all the fibres presented in this report, as it was indicated by the images of the near-field pattern at the output-end of the fibres under test.

In order to assess the propagation loss of the fabricated HFs in the telecommunications window around 1550 nm, incoherent light from a high power, EDFA operating as an ASE source, was free-space coupled into the cleaved input facet of the fibres. The measurement of the propagation loss was based on a method widely known as the cutback technique [2], which relies on recording the output power from the fibre under test for various lengths of fibre. For a given input light power, if $P_1$ is the power coming out of $L_1$ meters of the fibre while $P_2$ is the output power when the fibre length is reduced (cut) down to $L_2$ meters, the attenuation of the fibre is provided by the relation

$$\alpha = \frac{10}{L} \cdot \log_{10} \left( \frac{P_1}{P_2} \right) \text{ dB/m}$$

(2.2)

where $L$ is equal to $L_1 - L_2$ and is measured in meters. Starting with ~2-2.5 meters of HF for the propagation loss measurement and cutting back pieces of the order of 30-40 cm, approximately six to seven measurements were taken for each one of the HFs under test. The propagation loss was then expressed by the mean value and the
standard deviation of the set of these measured values. Care was taken so as to keep the launching conditions into the fibre under test as stable as possible.

It should be noted that the measurement of the propagation loss in HFs tends to yield a relatively high uncertainty. This uncertainty can be attributed to the importance of a clean and accurately cleaved output fibre facet for the precise determination of the output power in every power measurement performed. A bad cleave can lead to increased absorption losses and hence to an overestimation of the fibre propagation loss. In order to minimise the effect of bad end-facet cleaves in the measurement of the output power, and therefore in the estimation of the propagation loss, manual (hand) cleaving was avoided, since it normally led to an overestimation of the propagation loss and inconsistency in the quality of cleaves, and a conventional mechanical cleaver was employed. Furthermore, in order to decrease the effects of bad cleaving on the propagation loss estimation, several mechanical cleaves were applied after each cutback. The value for the output power, which corresponded to the best achieved cleave, was kept and considered for the estimation of the propagation loss through Eq. 2.2. Care was also taken so as to ensure that no light was propagating in the fibre cladding, either by optimising the launching conditions or by applying the high-index graphite adhesive, so as to strip off the propagating cladding modes and remove the cladding light when needed. Finally, it was crucial to ensure that the coupling efficiency into the fibre did not change during the measurement, otherwise large variations in the measured propagation loss were observed.

### 2.2.2 Measurement of the nonlinear coefficient

The measurement of the nonlinear coefficient of the small-core HFs is based on the measurement of the SPM induced phase shift on a dual frequency, optical beat signal propagating through the fibre [3, 4]. The beat signal is formed by two CW optical signals. Assuming that the wavelength separation of the two CW pumps is sufficiently small and a relatively short piece of fibre is employed, the effect of dispersion can be neglected. In this case, the nonlinear phase shift of the beat signal is given by the relation [3, 4]

\[
\Phi_{SPM} = \frac{2 \cdot \omega_0}{c} \cdot \frac{n_2}{A_{eff}} \cdot L_{eff} \cdot P_{avg}
\]  

(2.3)
where $\omega_0$ is the central frequency of operation, $c$ is the speed of light, $n_2$ is the nonlinear refractive index of the fibre, $P_{\text{avg}}$ is the average power of the beat signal and $L_{\text{eff}}$ is the effective length of the fibre (Eq. 1.36). It should be mentioned that the loss coefficient for the estimation of $L_{\text{eff}}$ is expressed in m$^{-1}$ and is related to the loss coefficient expressed in dB/m by the relation

$$a(\text{m}^{-1}) = \ln (10^{[a(\text{dB/m})/10]})$$

Since the nonlinear coefficient is proportional to the ratio $n_2/A_{\text{eff}}$, it becomes apparent from Eq. 2.3 that the nonlinear coefficient $\gamma$ can be calculated if the phase shift due to SPM is measured for different average power levels.

The SPM induced phase shift can be determined in the spectral domain, since the electrical field that represents the beat signal is a periodic function in time and hence it has a discrete spectrum, consisting of harmonics of the beat frequency. A typical SPM spectrum, generated by the propagation of a beat signal in a fibre, is shown in Fig. 2.3.

**Figure 2.3:** Typical spectrum of a beat signal that has suffered SPM, obtained from a spectrum analyser. The zero and the first order harmonics of the signal are shown.

It can be shown that, by taking the Fourier transform of the relation that provides the evolution of the electric field of the beat signal, the following analytical solution is found

$$\frac{I_0}{I_1} = \frac{J_0^2(\varphi_{\text{SPM}}/2) + J_1^2(\varphi_{\text{SPM}}/2)}{J_1^2(\varphi_{\text{SPM}}/2) + J_2^2(\varphi_{\text{SPM}}/2)}$$

(2.5)
where $I_0$, $I_1$ are the intensities of the zero and first order harmonics respectively and $J_n$ stands for the Bessel function of the $n$-th order \[3\]. Hence, the phase shift for an average launched signal power $P_{\text{avg}}$ can be readily determined from a measurement of the relative intensity of the harmonics in the spectral domain.

It should be noted that Eq. 2.3-2.5 are valid under the assumption that the effect of fibre dispersion can be ignored. In conventional silica-based fibres, long lengths of fibres are generally required in order for a sufficient nonlinear phase shift, and therefore an adequate dynamic measurement range, to be realized. Therefore, dispersion can become an important issue and lead to inaccurate results, especially in the case of fibres exhibiting a large dispersion at the frequency of operation \[5\]. Moreover, long lengths of fibre cause a reduction in the threshold of SBS, therefore limiting the usable power range in the measurements. To reduce the effects of dispersion while ensuring that SBS is suppressed, fibre lengths around a few hundred meters are employed in measurements involving conventional silica-based fibres, while the wavelength separation between the two CW forming the beat signal is kept below $\sim 0.4$ nm. In the case of small-core, compound-glass HFIs, the large fibre nonlinearity ensures that fibre pieces as low as a few meters can induce a substantial phase shift for the acquisition of a reliable measurement. Therefore, by combining a short fibre piece with a small wavelength separation between the two CW input signals, the effects of dispersion can be neglected in the measurements of the nonlinear coefficient.

In the case of birefringent fibres, Eqs. 2.2-2.5 are valid when the beat signal is aligned on a principal fibre polarization axis. Since all of the small-core HFIs which were tested exhibited some birefringent behaviour (section 1.4.3), the input beat signal had to be aligned on one of the primary polarization axis of the HF under test. To find the principal axes, the experimental setup shown in Fig. 2.4a was implemented. Unpolarized ASE light from an EDFA passed through a free-space, rotating polarizer and was launched into the fibre under test. By rotating the input and output polarizers respectively, the position of the input polarizer was found for which the extinction ratio between the recorded maximum and minimum power levels at the photodiode, obtained with suitable rotation of the output polarizer, was maximised. This position
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The input polarizer was then aligned to one of the fibre’s principal polarization axes.

After the principal polarization axes of the HF under test were identified, the output polarizer was removed and the experimental setup shown in Fig. 2.4b was implemented for the measurement of the nonlinear coefficient $\gamma$. For the measurements, two CW, tunable distributed-feedback lasers were used to provide the beat signal. The beat signal was amplified using a high power EDFA. The operating wavelength of the lasers was chosen to be $\sim 1563$ nm, since the EDFA that was used provided a better noise figure and higher gain at this wavelength. The wavelength separation between the two signals was chosen to be around $\sim 0.2$ nm, so as to minimise the effect of dispersion. The optical power from the two signals was adjusted so that the EDFA was driven into saturation. This yielded an optimum SNR of around 45 dB with the noise originating from the ASE of the EDFA.

![Experimental setup for (a) identifying the principal polarization axes and (b) measuring the nonlinear coefficient of compound-glass HFs. PC: Polarization controller.](image)

By proper adjustment of the polarization controllers, identical polarizations were achieved for the two frequencies. The amplified beat-frequency signal was then free-space coupled into a short piece of the HF under test, typically around 1-3 meters depending on the fibre loss, after passing through a variable attenuator. The attenuator
was formed by a combination of a $\lambda/2$ waveplate and a polarizer: rotation of the waveplate resulted in control over the input power to the fibre.

By monitoring the launched power and the output spectrum, the ratio between the first and zero order harmonics for different input powers was recorded. From this ratio, the corresponding phase shift was calculated using Eq. 2.5. It should be noted that a small nonlinear phase shift was induced by the amplifier itself, prior to propagation through the fibre. This small nonlinear phase shift ($\sim 0.08$ rad) was subtracted from the measured phase shift after propagation through the fibre. Plotting the phase shift against the input power, the nonlinear coefficient was determined by the slope of the curve and Eq. 2.3. It should be noted that in Eq. 2.3, $P_{\text{avg}}$ refers to the power launched into the fibre under test. Therefore, the performed power measurements were calibrated using the coupling efficiency data collected from the propagation loss measurement. Throughout the measurement, it was important to make sure that the coupling efficiency into the fibre did not change i.e. that a proper optical alignment was ensured. Moreover, it was crucial to monitor the spectrum of the launched light at the HF input, so as to make certain that both CW signals forming the optical beat had identical polarizations during the measurement. By taking care of these issues, reliable and reproducible measurements of the nonlinear coefficient of the fabricated small core, compound-glass HFs were obtained. Finally, it should be mentioned that, for the input powers and fibre lengths employed for the measurement of the nonlinear coefficient of the compound-glass HFs, no evidence of SBS was observed.

2.2.3 Measurement of the dispersion

With regard to dispersion characterization of HFs, the pulse delay technique [6], the phase shift method [7] and the interferometric technique [8, 9, 10] have already been applied successfully in pure silica HFs.

In the pulse delay technique, a fast photodetector together with a fast oscilloscope are used to measure the difference in the arrival times of pulses that are generated by a tunable source and propagate through the fibre under test [2, 11]. A long length of fibre is crucial in order for a sufficient time delay to be generated and fall inside the sensitivity of the instruments used. In a different approach [6], femtosecond pulses are
used in combination with a two-photon diode (diode with a large bandgap, so that a photocurrent is produced only via two-photon absorption), in order to allow for the measurement of small group-delays and hence relatively short lengths of fibre to be used. The need for very short pulses and the requirement for the use of very sophisticated instruments, such as a two-photon detector, are the main limitations of this technique.

With regard to the phase shift method, it is based on intensity modulation of the optical signal carried by a high-frequency sine wave RF signal, ranging typically between 10 MHz and a few GHz. An RF network analyzer is employed to measure the phase difference (shift) between the modulated signal, received after propagation through the fibre under test, and the applied modulation signal. By measuring the phase shift for different carrier wavelengths, the group-delay can be obtained as a function of wavelength and hence the dispersion characteristics can be retrieved. However, in order to achieve reliable phase differences, a large dispersion x length product is normally required.

Both the pulse delay and the phase shift techniques generally require long lengths of fibre, as a high dispersion x length product is essential. The pulse delay method, proposed in [6], has been applied in very short lengths, in the order of a few centimetres. However, extremely short pulses in combination with a sophisticated two-photon detector are required, hence this method is considered impractical. On the contrary, interferometric techniques can effectively be used for the estimation of the dispersion in very short lengths of SMFs and are able to provide accurate results over a wide wavelength span, without the need for test equipment with high temporal resolution [12, 13, 14, 15, 16]. Due to the relative simplicity, accuracy and short length requirements of the interferometric techniques, and since the high coupling and propagation loss of the compound-glass HFIs severely limits the fibre length that can be employed for dispersion measurements, it was considered advantageous to implement an interferometric set-up for the measurement of the dispersion of compound-glass HFIs.

The implemented set-up is presented in Fig. 2.5. The incoherent ASE light from an Er/Yb fibre amplifier, covering the region from 1525 up to 1570 nm, was employed in
the measurements as a broadband source. The light beam was collimated and guided through a free-space linear polarizer. Using a pellicle beamsplitter, the beam was divided into two paths: a reference air path, the length of which could be varied by a delay line, and a test path, which contained the fibre under test. In the air path, the variable delay line was formed by two prisms mounted on moving bases. In the test path, a $\lambda/2$ waveplate was employed to align the state of polarization of the launched light into the fibre to one of the principal axes of the fibre under test. A high-NA lens (~0.6) was used to couple light into the fibre. After transmission through the two paths, a second beam splitter recombined the two beams and the resulting beam was fed into an optical spectrum analyzer (OSA).

![Figure 2.5: Arrangement for the measurement of the dispersion of compound-glass HFs based on interferometric fringes observed in the frequency domain. PBS: Polarization beam splitter.](image)

By proper coarse modification of the reference air path length through the adjustment of the position of prism #1, the time delay difference between the test and the reference beam became smaller than the coherence time of the employed broadband source. The interferometer was then balanced and, since chromatic dispersion caused different wavelength components of the broadband light beam to experience different group-delays, $\tau_g$, as they propagated through the fibre, interference fringes were formed in the spectrum of the combined beam at the output of the system [17]. The spectral intensity of the interference fringes formed in the balanced interferometer followed a sinusoidal modulation, according to the well-known equation describing the interference of two beams.
where $\Phi(\omega)$ is the frequency-dependent phase difference between the reference and test beams, while $I_{\text{ref}}(\omega)$, $I_{\text{test}}(\omega)$, $I(\omega)$ are the intensity of the reference path, the test path and the combined intensity at the output of the system respectively. A typical received spectrum for a balanced state of the implemented interferometer is shown in Fig. 2.6 and spectral fringes are evident. The peaks in the spectrum correspond to wavelengths where the phase difference between the reference and test beams was such that constructive interference took place. Hence, a phase difference of $2\pi$ existed between two consecutive peaks and the group-delay as a function of frequency was obtained by the equation

$$
\tau_g(\omega) = \frac{2\pi}{\omega_i - \omega_{i+1}}
$$

(2.7)

where $\omega_i$, $\omega_{i+1}$ are the positions of two successive maxima in the modulation spectrum and $\omega = (\omega_i + \omega_{i+1}) / 2$ [17]. From a simple differentiation of the group-delay, the dispersion characteristics of the fibre under test was obtained from the relation

$$
D = \frac{1}{L} \frac{d\tau_g}{d\lambda}
$$

(2.8)

with $L$ being the length of the fibre used in the measurement.

A different approach for the estimation of the dispersion characteristics of the compound-glass HFs relied on bringing the interferometer to a balanced state by modifying the position of prism #1. Then the position of prism #2 was accurately adjusted, so as to precisely match the time delay $T_0$ induced by the reference path to the group-delay of a wavelength falling inside the wavelength region covered by the employed broadband source. The centre of the formed fringes corresponded to a group-delay $\tau_g$ exactly equal to $T_0$. This situation is depicted in Fig. 2.7. By monitoring the centre of the formed fringes in the frequency domain for different time delays $T_0$, the chromatic dispersion of the fibre under test could be retrieved, for the wavelength span defined by the operational wavelength of the broadband source, directly through application of Eq. 2.8 [13]. It should be noted that the rate of change of the interference pattern in the frequency domain depends on the actual value of the dispersion [16]. A high dispersion results in dense wavelength spacing in the received fringes in the frequency domain, while widely spaced fringes are observed for low
dispersion values. Hence, measurement of the dispersion close to the ZDW region requires the use of a source with a wider spectral width, or the use of a longer fibre.

In order to test the accuracy of the implemented interferometer, the dispersion of a DCF was measured. Using a fully-automated, all-fiberised phase-shift set-up, the dispersion profile of the dispersion-compensating fibre (DCF) was retrieved for a ~28.5m-long fibre piece. Then, using just a ~1.44m-long piece of the same DCF, the two interferometric-based dispersion methods, i.e. the estimation of the dispersion from a single interferogram (Eq. 2.7) and through the determination of the central fringes for different air path delays (Eq. 2.8), were applied. The results are compared in Fig. 2.8 and a good agreement is evident.

![Figure 2.6: Typical interference fringes obtained in the case of a balanced interferometer.](image)
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Figure 2.7: Typical interference fringes obtained in the case of a balanced interferometer, adjusted so that the reference path time delay $T_0$ is equal to the group-delay $\tau_g$ of a wavelength falling inside the spectral region of operation of the broadband source employed, i.e. in the C-band.

Figure 2.8: Comparison of the retrieved dispersion profile by application of the phase delay method, the single interferogram method and the central fringes methods for a commercial DCF.


2.2.4 Measurement of the Brillouin Gain

In a typical Brillouin gain measurement set-up, a probe signal of power $P_{pr\_in}$ at a frequency $v_0 + \Delta v$ is launched into a fibre of length $L$ that exhibits a propagation loss $\alpha$ together with a counter-propagating pump of power $P_p$ at a frequency $v_o$. The probe signal at the output of the fibre $P_{pr\_out}$ experiences an exponential growth with $P_p$ due to the induced by SBS frequency-offset dependent gain $g_B(\Delta v)$. The probe power at the fibre output is

$$P_{pr\_out} = P_{pr\_in} \cdot \exp(g_B(\Delta v)P_pL_{eff} / A_{eff} - aL)$$  \hspace{1cm} (2.9)

where $L_{eff}, A_{eff}$ are the effective length and the effective area of the fibre respectively \cite{18}. In the absence of the pump, the power of the probe signal at the output of the fibre experiences a loss according to the relation

$$P_{pr\_out}(P_p = 0) = P_{pr\_in} \cdot \exp(-aL)$$  \hspace{1cm} (2.10)

Defining $G_{dB}(\Delta v)$ as the frequency offset-dependent ratio of the output probe signal in the two cases, i.e. with and without the pump, expressed in dB, it follows that

$$G_{dB}(\Delta v) = 10 \cdot \log_{10} \left( \frac{P_{pr\_out}(P_p = 0)}{P_{pr\_out}(P_p = 0)} \right) = 10P_pL_{eff} g_B(\Delta v) / \ln(10)A_{eff}$$  \hspace{1cm} (2.11)

and

$$g_B(\Delta v) = G_{dB}(\Delta v) \cdot \frac{\ln(10)A_{eff}}{10P_pL_{eff}}$$  \hspace{1cm} (2.12)

Therefore, by comparing the power of the probe at the output of the fibre, with and without the presence of the pump, for various pump-probe frequency offsets $\Delta v$, the fibre Brillouin gain profile $g_B(\Delta v)$ can be obtained from Eq. 2.12.

In Fig. 2.9, a schematic diagram of the set-up employed for the estimation of the Brillouin gain profile is shown. Light from an external cavity laser, tunable in the C-band and operating at a wavelength $\lambda_{ls}$ corresponding to a frequency $v_{ls}$, passed through a 3 dB splitter and was divided into the pump and probe port (Fig. 2.9, inset 1). In the pump port, the light from the laser was amplified through the use of a high-power Er/Yb fibre amplifier up to ~27 dBm and launched into the fibre through facet B. The amplified light at frequency $v_{ls}$, (Fig. 2.9, inset 2) coming from this port was
used as the pump. In the probe port, the light generated from the laser was modulated by a Mach-Zehnder modulator (MZM), driven by a microwave generator at a frequency $f_m$, and sidebands were generated symmetrically around the pump. By proper adjustment of the DC bias voltage of the MZM, the intensity at $v_0$ could be minimized in the absence of a modulation signal. When the MZM was operating under this pump-suppressed condition, only the odd-order sidebands of the modulated signal at frequencies $v_o \pm N \cdot f_m$, $N=1,3,5\ldots$, were present in the output spectrum after the MZM, with only the first-order sidebands being of significant power (Fig. 2.9, inset 3). The ratio of the first odd-order sidebands to pump, at the output of the modulator, was $\sim 20$ dB. The resulting signal was then further modulated at a frequency of $1.5$ kHz using an acousto-optic modulator and, after amplification up to $\sim 3$ dBm using an EDFA and randomization of its polarization by a polarization scrambler, it was launched into the fibre through facet B.

The loop configuration employed here ensured a counter-propagating pump at frequency $f_0$ with a direction from A to B and first order sidebands at frequencies $v_o \pm f_m$ with a direction from B to A. In order to obtain the Brillouin gain profile of the fibre under test, the modulation frequency $f_m$ was swept around the region of the predicted Brillouin frequency shift with a step of $\sim 5$ MHz. When the modulation frequency was around the Brillouin gain shift, the low frequency first-order sideband exiting facet 2 of the fibre under test was amplified due to the SBS effect, while the intensity of the high frequency first-order sideband was reduced [19], since under SBS it seeded gain to the pump (Fig. 2.9, inset 4). At the experimental operating conditions, the pump remained undepleted through this process. Using a combination of two circulators in the pump port, the resulting probe waveform (containing the first-order sidebands affected by SBS) was guided through a tunable fibre Bragg grating (FBG) with a 3 dB bandwidth of $\sim 6$ GHz. By proper adjustment of the FBG, the high frequency first-order sideband was eliminated and only the low frequency first-order sideband remained (Fig. 2.9, inset 5). The low-frequency first-order sideband reflected from the FBG was detected by a photodiode. By comparing the detected light intensity in the photodiode with and without the presence of the pump in the pump port (Er/Yb fibre amplifier on and off respectively), the Brillouin gain profile could be obtained. With regard to the pump light reflected at the interface between the silica fibre and the compound-glass fibre under test, it did not affect the detected probe light.
measurement, since the lock-in amplifier was employed to distinguish between the modulated signal in the direction from B to A (probe port) and the unmodulated pump in the direction from A to B (pump port). It should be noted that the results were calibrated by the coupling efficiency of the pump power into the fibre, and the approximately 35 MHz frequency shift that the acousto-optic modulator induced in the optical frequency. Furthermore, Eq. 2.12 is valid for parallel linear probe and pump polarizations aligned to one of the principal birefringence axes of the fibre. As it originates from the coherent mixing of two waves, the efficiency of the SBS effect is polarization dependent. Since a polarization scrambled probe was used in the measurements and the observed Brillouin gain for all the compound-glass fibres under test was low (1-1.5 dB), the measured Brillouin coefficient was estimated by the relation [20, 21]

$$g_B(\Delta v) = G_{dd}(\Delta v) \cdot \frac{\ln(10) A_{eff}}{10 P_p L_{eff}} \cdot \frac{1}{n}$$

(2.13)

with $n$ being the coherence mixing efficiency and considered to be equal to $\frac{1}{2}$.

**Figure 2.9**: Experimental setup for the measurement of the Brillouin gain profile of compound-glass HF's.
2.2.5 Measurement of the beat-length

The birefringence of optical fibres is usually quantified from beat-length measurements. In the case of conventional fibre designs, the beat-length can be directly measured using helium-neon lasers. When visible light is launched into the fibre at 45° relative to one of the fibre’s principal axes, polarization beating takes place [2]. The combination of this polarization beating with Rayleigh scattering from the fibre core causes the formation of alternating bright and dark regions at the side of the fibre. The separation distance of the dark regions directly provides the beat-length. With regard to HFs, this method cannot provide accurate results, since normally the Rayleigh scattered light from the fibre core is further scattered by the holey cladding. Instead of this direct beat-length measurement, an indirect way based on observation of the polarization beating induced fringes, which are formed in the spectral domain, is followed [22].

The experimental set up, implemented for the measurement of the beat-length of the compound-glass HFs in the C-band, is presented in Fig. 2.10. The ASE light from an Er/Yb fibre amplifier, covering the wavelength span from 1525 up to 1570 nm, was employed as a broadband source. Using a combination of a polarization beam splitter and a \( \lambda/2 \) waveplate, the ASE light was linearly polarized at 45° relative to one of the fibre’s principal polarization axes. Similarly, a polarizer acting as a polarization analyser was placed at the output of the fibre, with its transmission axis at 45° relative to the principal polarization axis. Due to polarization beating, fringes appear in the output spectrum. If \( L \) is the fibre length, then the acquired wavelength-dependent phase difference at the output of the fibre is

\[
\phi(\lambda) = \left[ \beta_x(\lambda) - \beta_y(\lambda) \right] L = \frac{2\pi L}{L_B} 
\]

(2.14)

where \( \beta_x(\lambda), \beta_y(\lambda) \) are the wavelength dependent propagation constants of the two degenerate modes and \( L_B \) is the beat-length. Differentiating Eq. 2.14 with respect to the wavelength, it follows that

\[
\frac{\Delta \phi}{\Delta \lambda} = -\frac{2\pi L}{L_B^2} \frac{dL_B}{d\lambda} 
\]

(2.15)

hence
\[ L_B^2 = (\Delta \lambda)L \left| \frac{dL_B}{d\lambda} \right| \]  

(2.16)

A common approximation is that the beat-length is inversely proportional on the wavelength, i.e.

\[ L_B \propto \lambda^{-1} \]  

(2.17)

Using Eqs. 2.16 and 2.17, the beat-length can be approximated by

\[ L_B = \frac{\Delta \lambda}{\lambda} \cdot L \]  

(2.18)

Hence, \( L_B \) can be estimated from the observed periodicity \( \Delta \lambda \) of the obtained fringes in the wavelength domain [22].

![Figure 2.10: Experimental setup for the measurement of the beat-length of compound-glass HFs. PBS: Polarization beam splitter.](image)

2.3 Characterisation results for the various fabricated fibres

In this section, the results from the characterization of highly nonlinear HFs made of either bismuth-oxide or lead-silicate based glass are presented. Two fibre designs are examined: a triangular-core design, resembling the strand-on-air case and aiming at exploiting the maximum nonlinearity offered by the employed glasses, and a design with a hexagonal arrangement of holes, suitable for the fabrication of fibres with novel dispersion properties. The triangular-core fibres were fabricated by a pure extrusion process, while the fibres with a hexagonal arrangement of holes were fabricated using the SEST approach (section 1.2.2).

For each compound glass, preforms were prepared by applying the extrusion or the SEST process (section 1.2.2), depending on the desired fibre design. From each
preform, a fibre with a length up to a few hundred meters was drawn in a fibre
drawing tower and was wound on a fibre-winding drum. The conditions during the
fibre drawing process, such as the temperature of the furnace, the pressure applied
within the preform, the preform speed and the drawing speed, determined the size of
the features in the final fibre [23]. Hence, by suitably changing the drawing conditions,
it was possible to adjust the fibre parameters during fabrication. In this way, different
fibre bands, corresponding to different fibre parameters, were formed on a single fibre-
winding drum using a single fibre preform. This approach provided the opportunity to
study the effects of the microstructured characteristics on the fibre properties.

2.3.1 Triangular-core, bismuth-oxide based holey fibres

Two different fibres were characterized in terms of propagation loss: A fibre made
from ‘normal’ bismuth-oxide glass melted in ambient atmosphere and a fibre made
from dehydrated bismuth-oxide glass. Both fibres were fabricated using the extrusion
technique. For the ‘normal’ fibre, three different bands were drawn from the same
preform by appropriate choice of the external fibre diameter. The bands had a different
enclosed core diameter, ranging from 1.4 µm for band #3 to 1.7 µm for band #1. With
regard to the dehydrated glass, two bands were produced from a single dehydrated
preform. Although they had the same core diameter, they were fabricated under
different tension. It should be noted that simulations demonstrated that the bismuth-
oxide HFs, with a triangular design as presented are not strictly single-mode. Indeed,
the V-number of an air-suspended rod of bismuth-oxide glass with a core diameter of
1.4 µm would be equal to ~5. In fact, core sizes <1 µm would be required for this fibre
type to be strictly single-mode. However, effectively single-mode guidance can be
observed when a fibre is multimode but the higher order modes exhibit very high
values of confinement loss. Fibres can therefore exhibit effectively single-mode
guidance over a broad wavelength range, since the confinement losses associated with
higher order modes are usually much more severe than that of the fundamental mode.
Observation of the near field pattern IR image of the fabricated bismuth-oxide based,
triangular-core fibres revealed an effectively single-mode guidance for core diameters
below 2 µm (Fig. 2.11).
2.3.1.1 Propagation loss

The results from the propagation loss measurements of the bismuth-oxide based HFs are shown in Tab. 2.1, both for the normal and the dehydrated glass. The HFs made from normal glass (#1-#3) exhibited a relatively consistent propagation loss. Useful conclusions regarding the impact of the holey structure on the propagation loss can be drawn by a direct comparison of the loss of the HFs with the corresponding propagation loss of the bulk glass. A bulk, unstructured fibre produced from the same glass batch, with a similar fabrication process, exhibited a loss of ~1.6 dB/m [24]. Thus, it becomes apparent that the holey structure leads to an increase in the propagation loss. This tendency can be attributed to the fact that the interaction of the light with the air/glass boundaries near the core in HFs enhances the impact of surface roughness [25]. Since the modal field overlaps with the air holes of the triangular-core fibre, structured fibres will have a higher loss due to surface imperfections at the air/glass interface around the core. The overlap of the modal field with the air holes is shown in Fig. 2.12, where the predicted fundamental mode at 1550 nm for a core size of ~1.8 µm is presented. Moreover, it should be noted that, despite almost similar core sizes, band #1 and band #2 exhibit quite a different loss. As SEM images showed, band #1 had shorter struts and smaller holes than band #2, so this behaviour can be attributed to a relatively increased confinement loss in band #1.
Figure 2.12: Predicted by numerical simulations fundamental mode profile at 1550 nm for a bismuth-oxide, triangular-core fibre with core size of 1.8 µm (Simulations performed by Dr. Ebendorff-Heidepriem).

### Propagation loss of the triangular-core, bismuth-oxide based HF\s

<table>
<thead>
<tr>
<th>Band</th>
<th>Type of Bulk Glass</th>
<th>Outer diameter (µm)</th>
<th>Enclosed core diameter (µm)</th>
<th>Propagation Loss (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>‘Normal’</td>
<td>170</td>
<td>1.7</td>
<td>3.4 ± 0.3</td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td>155</td>
<td>1.6</td>
<td>2.6 ± 0.3</td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td>140</td>
<td>1.4</td>
<td>3.3 ± 0.3</td>
</tr>
<tr>
<td>#4</td>
<td>Dehydrated</td>
<td>170</td>
<td>2.0*</td>
<td>8.2-10.6</td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td>170</td>
<td>2.0</td>
<td>7.6 ± 0.3</td>
</tr>
</tbody>
</table>

* drawn at higher tension compared to fibre #5

Table 2.1: The results from the measurement of the propagation loss of the triangular-core, bismuth-oxide HF\s in the C-band.

With respect to the HF\s made from the dehydrated bismuth-oxide based glass, a much better performance in terms of loss was expected compared to the HF\s made from normal glass, since a bulk, unstructured fibre made from the dehydrated glass batch exhibited a loss of 0.45 dB/m. However, the HF\s fabricated from dehydrated glass exhibited a very high loss. The large range of loss values for the part of the fibre that was drawn at higher tension suggests the presence of localized losses, possibly due to surface imperfections and microcrystal formation. It should also be noted that the use of graphite adhesive applied to the outer surface of the fibre was necessary when using this fibre band in order to eliminate the significant amount of light that was guided in the cladding. The fibre drawn at lower tension exhibited a more consistent behaviour.
in terms of loss. However, the loss was still very high, possibly due to surface crystallization induced during the fabrication process, since, according to the information provided by colleagues in the fabrication group, the drawing temperature of the HFs made from dehydrated glass was high enough to allow surface feature formation.

2.3.1.2 Nonlinear coefficient

Using the method described in section 2.2.2, the nonlinear coefficient $\gamma$ was measured for each of the three bands of the HF made from normal bismuth-oxide glass. In Fig. 2.13, a plot of the induced nonlinear phase shift against the launched power, for each of these bands, is shown. To facilitate a direct comparison, the nonlinear phase shift is expressed per unit of effective length. The plots were interpolated by a linear fit and the slope of the fit determines the nonlinear coefficient. It can be seen directly from the graph that the slope of the fit increases for smaller core dimensions. The results from the various measurements are shown in Tab. 2.2. It should be noted that for the determination of the uncertainty in the estimation of the value of $\gamma$, the uncertainty in the measured propagation loss of the fibres, which affected both the estimation of the launched power into the fibre and the effective fibre length, had to be taken into account.

### Nonlinear coefficient of the bismuth-oxide (normal glass) HFs

<table>
<thead>
<tr>
<th>Band</th>
<th>Type of Bulk Glass</th>
<th>Enclosed core diameter ($\mu$m)</th>
<th>Effective Nonlinearity $\gamma$ ($W^{-1}km^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>‘Normal’</td>
<td>1.7</td>
<td>$630 \pm 42$</td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td>1.6</td>
<td>$742 \pm 87$</td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td>1.4</td>
<td>$1125 \pm 71$</td>
</tr>
</tbody>
</table>

Table 2.2: The results from the measurement of the effective nonlinear coefficient $\gamma$ of the normal glass, triangular-core bismuth-oxide HFs at 1563 nm.

All of the three bands exhibit a very high nonlinearity, with band#3 having a nonlinear coefficient that is 3 orders of magnitude greater than the nonlinearity of standard SMF. Therefore, the potential of using such fibres in telecommunications applications becomes apparent, since they can effectively lower the power and length demands of nonlinear devices.
Figure 2.13: Nonlinear Phase Shift per unit of effective length plotted against the launched power for the normal glass, triangular-core bismuth-oxide HFs at 1563 nm (a) band #1, 1.7 µm enclosed core diameter (b) band #2, 1.6 µm enclosed core diameter and (c) band #3, 1.4 µm enclosed core diameter.
In order to compare the experimental results with the theoretical predictions, the theoretical case of an air suspended rod (ASR) [26] of bismuth-oxide is considered, as shown in Fig. 2.14. Although it is only a simplified theoretical model, the ASR represents the ideal case with regard to the maximum possible effective nonlinearity.

![Figure 2.14: The theoretical case of an air-suspended rod, where $\alpha$ is the core radius.](image)

The effective nonlinearity, $\gamma$, for the ASR is plotted against the core diameter, $2\alpha$, of the rod in Fig. 2.15. It can be seen that a decrease in the core diameter leads to a higher nonlinearity, up to a minimum point where the core can no longer confine the mode tightly. After this critical core diameter, a further decrease in the core dimensions degrades the nonlinear behaviour. Since the structure of the characterized bismuth-oxide based HFs resembles the case of the air suspended rod, a close agreement is expected between this theoretically derived curve and the experimental results.

![Figure 2.15: The effective nonlinearity at 1550 nm plotted against the core diameter for the bismuth-oxide based, air suspended, rod case. The measured values of the nonlinearity for the bands #1-#3 of the triangular-core HF's made from normal bismuth-oxide glass are interpolated on the graph (the ASR modelling is courtesy of Dr. V. Finazzi).](image)
Indeed, by interpolating the measured values on the graph, a fairly good agreement is apparent, as shown in Fig. 2.15. It should be noted that the effective core diameters of the HFs were considered for comparison with the ASR model, for the reasons that have been explained in section 2.1.

2.3.1.3 Dispersion characteristics

Although the bulk bismuth-oxide glass exhibits a strong normal dispersion of approximately -107 ps/nm/km at 1550 nm, numerical simulations have shown that the extreme waveguide properties of the fabricated fibres have considerably altered their overall dispersion characteristics, hence anomalous dispersion is expected in the 1550 nm telecommunications window.

In order to verify the numerical predictions, an experimental study of the SPM spectra of soliton pulses after propagating through the 1.4 µm enclosed core diameter fibre, was performed. The set-up is shown in Fig. 2.16. An actively mode-locked erbium fibre ring laser (EFRL) was used for the experiment. The wavelength of operation was set at 1555.6 nm and the repetition rate was chosen to be 9.95 GHz. The laser produced soliton pulses that were amplified using a high-power EDFA and free-space coupled to 0.53 m of the fibre. The duration of the pulses at the input of the fibre was ~ 2.0 ps full-width at half-maximum (FWHM). Care was taken to ensure that the polarization of the signal was aligned on the primary polarization axis of the fibre.

Fig. 2.17 shows optical spectra obtained at the output of the fibre for varying input optical power levels. The main feature observed is a wavelength shift of the original signal, which is strongly dependent on the energy of the incoming pulses.
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Figure 2.17: The Raman soliton spectra at the output of 53 cm of the 1.4 µm enclosed core diameter, bismuth-oxide HF for different levels of input pulse energy.

The shift increases as the energy of the input pulses is increased, becoming as high as ~ 40 nm for a moderate input pulse energy of ~ 18pJ. The shapes of these SPM-broadened spectra suggest the presence of higher order soliton effects in the form of SSFS, the manifestation of which requires anomalously dispersive media [27]. Therefore, it can safely be concluded that the dispersion of the fibre is indeed anomalous at these wavelengths.

To confirm the anomalous dispersion of the bismuth-oxide HFs, the implemented interferometric setup for dispersion measurement was used. The dispersion of the 1.4 µm fibre was estimated to be ~ 140±1.5 ps/nm/km at 1550 nm, hence it was verified that the fibre exhibited a strong anomalous dispersion in the C-band.

2.3.1.4 Brillouin properties

An attempt to measure the Brillouin properties of the bismuth-oxide, triangular-core fibres was performed. However, large fluctuations in the received probe power were observed, leading to a Brillouin gain spectrum that was difficult to interpret. These fluctuations were attributed to the very large NA of the triangular-core fibres, due to their strand-on-air like design. A large portion of the launched probe light was therefore reflected at the input facet of the fibre, resulting in significant power fluctuations. An estimation of the Brillouin shift and Brillouin gain bandwidth for
fibre band #1 (1.7 µm core) was, however, attempted and the values of 8.93 GHz and 50-80 MHz were obtained (Fig. 2.18).

![Figure 2.18: Brillouin gain spectra of band #1 of the fabricated bismuth-oxide based triangular-core HFs; two different attempts to measure the same fibre are plotted in the figure [21].](image)

### 2.3.1.5 Splicing to standard single-mode fibres

The prospect of successfully splicing compound-glass HFs with conventional silica fibres was studied using the 1.6 µm enclosed core diameter bismuth-oxide fibre. The quality of the cleaves that a conventional mechanical cleaver (YORK FK11) could produce was initially assessed using an optical microscope to observe the cut faces. Changing the tension applied to the fibre over a range enabled the optimum parameters of the cleaver to be configured.

Splicing was performed by means of a single fibre fusion splicer (ERICSSON FSU 975). To reduce the mode-mismatch loss between the silica fibre and the bismuth-oxide HF, an intermediate buffer stage was introduced. A germanium-doped silica-based fibre with a NA of ~0.3 and an $A_{\text{eff}}$ of ~ 15 µm$^2$ was used as a buffer stage. The splice loss between the SMF and the buffer fibre was ~ 0.3 dB.

The bismuth-oxide glass has a greatly lower melting temperature than silica. Hence, parameters such as the fusion time and the fusion current had to be set to very low values, in order to avoid melting of the bismuth-oxide glass. Many different combinations of splicing parameters were tested and data from numerous splices were
collected. The best splicing losses that were achieved ranged between 8.0-8.5 dB, with either a slight (~0.5 dB) or no reduction of the coupling loss compared to butt-coupling. The high excess loss of the splices should be predominantly caused by mode-mismatch at the interface between the bismuth-oxide fibre and the buffer fibre. In other words, the very dissimilar mode field diameters of the spliced fibres cause significant power loss around the unmatched core edges.

In a simplified approach to calculate the lowest limit of the splice loss between the high NA fibre and the bismuth fibre under test, the triangular modal shape of the fundamental mode field distribution of the bismuth fibre is ignored and a perfectly Gaussian distribution is assumed. Under these assumptions and using the measured value of the effective nonlinear coefficient $\gamma$ of the bismuth fibre used for splicing, the effective mode area of its fundamental mode is estimated to be $\sim 1.7 \mu m^2$, corresponding to a spot size of $\sim 0.7 \mu m$. For a perfectly aligned splice formed between two fibres with spot sizes $w_1$ and $w_2$, the loss due to mode-mismatch is provided by the expression [2]

$$a = 20\log_{10}\left(\frac{2 \cdot w_1 \cdot w_2}{w_1^2 + w_2^2}\right)$$

(2.19)

Applying Eq. 2.19, the loss due to mode field diameter mismatch is estimated to be $\sim 4.4 \text{ dB}$. However, this estimated loss does not take into account the difference in the shape of the fundamental mode of the two fibres, since it approximates the triangular modal shape of the HF with a perfectly Gaussian one. This modal shape mismatch is expected to degrade the quality of the splice significantly. Hence, modal shape mismatch and mode field diameter mismatch should form the major sources of the observed splicing loss. In general, for a rigorous analysis of the contribution of modal mismatch related losses, numerical modelling of the guided modes of the spliced fibres is required [28]. Excess loss could be introduced by parameters such as Fresnel reflections ($\sim 4\%$ at the Bismuth-silica interface), longitudinal, transverse and angular misalignment of the spliced fibres and even imperfect cleaves or dirt present on the fibre edges.
The results have shown that bismuth-oxide glass HFs can be spliced to silica fibres. However, extremely fine control of the splicing parameters is required and high splicing losses are observed. Approaches that could potentially reduce splicing losses are the use of a different buffer fibre, with a mode field diameter closer to that of small-core HFs, or the addition of more buffer stages, which would make the transition between the small core of highly nonlinear HFs and the relatively large core of standard silica fibres more gradual. The use of a tapered intermediate HF or the controlled collapse of the air holes of the HF structure by application of repeated arc discharges during splicing [29] might also become promising methods for achieving low-loss splicing in the future.

2.3.2 Triangular-core, lead-silicate based holey fibres

The commercially available SF57 lead-silicate based glass was also employed for the fabrication of small-core HFs. From a single microstructured preform made by extrusion through an eroded, stainless steel die, three different bands of fibre were drawn. The bands each had a different core diameter, ranging from 1.8 µm for band #1 to 1.2 µm for band #3. Targeting to even smaller core diameters, a second preform from the same glass was used for the drawing of ~100m of fibre, which consisted of bands of uniform core diameter in the range of 0.8-1.0 µm. In this attempt, a machined stainless steel die instead of an eroded stainless steel die was used in the extrusion apparatus. From this fibre, only the band with 0.9 µm internal core diameter was fully characterised, since fibre breakage during the pulling resulted in high loss for the rest of the bands. This 0.9 µm core diameter band will be hereinafter denoted as band #4.

Using a commercially available beam profiler, in combination with a neodymium-doped yttrium lithium fluoride (Nd:YLF) laser source, the spatial mode guidance characteristics of the four fibre bands at 1.047 µm were investigated. The mode profile obtained for all fibres had a near triangular shape, similar to the shape of the core, and was in good agreement with that predicted by numerical simulations of the fundamental mode profile (Fig. 2.19). Single-mode, or effectively single-mode, guidance was observed for all fibres at ~1 µm.
### Table

<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Core diameter (µm)</th>
<th>SEM image (µm)</th>
<th>Near Field Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.8</td>
<td><img src="image1.png" alt="SEM Image" /></td>
<td><img src="image2.png" alt="Near Field Pattern" /></td>
</tr>
<tr>
<td>#2</td>
<td>1.4</td>
<td><img src="image3.png" alt="SEM Image" /></td>
<td><img src="image4.png" alt="Near Field Pattern" /></td>
</tr>
<tr>
<td>#3</td>
<td>1.2</td>
<td><img src="image5.png" alt="SEM Image" /></td>
<td><img src="image6.png" alt="Near Field Pattern" /></td>
</tr>
<tr>
<td>#4</td>
<td>0.9</td>
<td><img src="image7.png" alt="SEM Image" /></td>
<td><img src="image8.png" alt="Near Field Pattern" /></td>
</tr>
</tbody>
</table>

**Figure 2.19:** SEM images and corresponding near field patterns for the various lead-silicate triangular-core HFs.

#### 2.3.2.1 Propagation loss

The results from the propagation loss measurement are presented in Tab. 2.3. Compared to previous fabrication attempts of SF57 lead-silicate HFs with a small core diameter and a similar fibre structure, the HFs characterised in this Chapter exhibit a much lower propagation loss. This lower loss is attributed to improvements in the cleaning process of the fibre preform prior to caning and the improved machined
stainless steel die used in the extrusion process. Ultrasonic cleaning prior to the caning process is believed to have contributed to a reduced degree of surface contamination by eliminating unwanted particles on the preform. Moreover, the preform of the fabricated fibres was extruded through a dry lubricant coated die which offers a smoother and better extruded preform surface quality as it decreases the friction between the glass and die [23]. Lower temperatures are required during extrusion through coated die at a fixed speed, thus the preforms have less tendency in crystallisation. It is anticipated that further improvements in the fabrication process will result in an even lower loss, making the possibility of building compact nonlinear devices from compound-glass HFs even more realistic.

**Propagation loss of the triangular-core, lead-silicate HFs**

<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Outer diameter (µm)</th>
<th>Enclosed core diameter (µm)</th>
<th>Propagation Loss (dB/m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous fabrication attempts</td>
<td>-----</td>
<td>1.3</td>
<td>9 [27, 23]</td>
<td>No ultrasonic cleaning Machined die</td>
</tr>
<tr>
<td>#1</td>
<td>120</td>
<td>1.8</td>
<td>2.0 ± 0.1</td>
<td>Ultrasonic cleaning Machined die</td>
</tr>
<tr>
<td>#2</td>
<td>100</td>
<td>1.4</td>
<td>2.5 ± 0.3</td>
<td>Eroded and coated die</td>
</tr>
<tr>
<td>#3</td>
<td>80</td>
<td>1.2</td>
<td>2.6 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>100</td>
<td>0.9</td>
<td>2.3 ± 0.2</td>
<td>Ultrasonic cleaning Machined die</td>
</tr>
</tbody>
</table>

*Table 2.3:* The results from the measurement of the propagation loss of the triangular-core, lead-silicate HFs in the C-band.

Comparing the loss values of fibre bands #1-3, it should be noted that the propagation loss of the HFs increases with a decrease in the core size. This behaviour has been predicted from simulations and originates from the overlap of the modal field with the air holes in HFs (Fig. 2.20). The magnitude of this overlap increases with a decrease in the core size, hence the effect of surface imperfections becomes more significant, leading to a higher loss [30]. Furthermore, the lower loss that band #4 exhibited revealed the superior performance that the machined stainless steel die and the applied novel cleaning process offered.
2.3.2.2 Nonlinear coefficient

After the determination of the propagation loss, the nonlinear coefficients of the lead-silicate based, triangular-core HFs were measured. The plots of the induced nonlinear phase shift against the launched power for three of the fibre bands (#1, #3, #4) are shown in Fig. 2.21. Again, the nonlinear phase shift was expressed per unit of effective length.
Figure 2.21: Nonlinear Phase Shift per unit of effective length plotted against the launched power for the triangular-core, lead-silicate HFs at 1563 nm (a) band #1, 1.8 µm enclosed core diameter (b) band #3, 1.2 µm enclosed core diameter and (c) band #4, 0.9 µm enclosed core diameter.
The results from the measurements are summarised in Tab. 2.4. One can conclude that extreme values of effective nonlinearity can be achieved by applying small-core, HF technology to lead-silicate SF57 glass.

### Nonlinear coefficient of the triangular-core, lead-silicate HFs

<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Enclosed core diameter (µm)</th>
<th>Effective Nonlinearity γ (W⁻¹km⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.8</td>
<td>409 ± 24</td>
</tr>
<tr>
<td>#3</td>
<td>1.2</td>
<td>605 ± 44</td>
</tr>
<tr>
<td>#4</td>
<td>0.9</td>
<td>1860 ± 140</td>
</tr>
</tbody>
</table>

**Table 2.4:** The results from the measurement of the effective nonlinear γ of the triangular-core, lead-silicate HFs at 1563 nm.

In Fig. 2.22, the measured γ values of the SF57 HFs are compared to those theoretically predicted from ASR modelling.

![Figure 2.22](image-url)  
**Figure 2.22:** The effective nonlinearity at 1550 nm plotted against the core diameter for the lead-silicate, air suspended, rod case. The ASR modelled curves are plotted both for \( n_2 = 35 \times 10^{-20} \text{m}^2/\text{W} \) and \( n_2 = 41 \times 10^{-20} \text{m}^2/\text{W} \) [31]. The measured values of the nonlinearity for the fabricated triangular-core, lead-silicate HFs are interpolated on the graph (the ASR modelling is courtesy of Dr. V. Finazzi).
It can be seen that the obtained nonlinear coefficients of bands #1 and #3 were significantly lower than those anticipated by numerical simulations. A possible explanation for this behaviour might be a poor mode confinement due to short and/or thick struts. A poor mode confinement may lead to a drastic increase in the effective mode area, therefore the fibre performance can deviate from that predicted from the ASR modelling and a much lower effective nonlinearity value might be obtained. In Tab. 2.5, the data concerning the length and width of the struts of the fabricated HFs, as calculated from SEM images acquired from the fibre fabrication group, is presented. It can be seen that band #4, which exhibited the ultra-high nonlinearity and was fabricated from the machined die extruded preform, had struts with a length-to-width ratio of ~37, while the corresponding figure for fibres made from the dry lubricant coated die extruded preform was below 20. This poor strut length-to-width ratio might lead to poor isolation of the core from the outer solid glass region, resulting in an increased effective mode area and therefore a decreased $\gamma$ value.

<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Enclosed core diameter (µm)</th>
<th>Strut length (µm)</th>
<th>Strut width (µm)</th>
<th>Strut Length-to-width ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.8</td>
<td>5.3</td>
<td>0.32</td>
<td>16.6</td>
</tr>
<tr>
<td>#3</td>
<td>1.2</td>
<td>3.77</td>
<td>0.25</td>
<td>15.1</td>
</tr>
<tr>
<td>#4</td>
<td>0.9</td>
<td>4.1</td>
<td>0.11</td>
<td>37.3</td>
</tr>
</tbody>
</table>

Table 2.5: Length and width of the struts of the fabricated triangular-core, lead-silicate HFs. The values were determined from SEM images.

On the contrary, the use of the machined stainless steel die seemed to have yielded excellent results in terms of achieved nonlinearity per unit length. The $\gamma$ value of 1860 W$^{-1}$km$^{-1}$, obtained for the fibre with a core diameter of 0.9µm, represents the highest value yet reported for a fibre and is within the 10-20% of the maximum value possible in this glass in the C-band ( ~ 2000 W$^{-1}$km$^{-1}$).

### 2.3.2.3 Brillouin properties

An attempt to measure the Brillouin properties of the lead-silicate, triangular-core fibres was also performed. However, as in the case of the bismuth-oxide, triangular core fibres, very large fluctuations in the received probe power were observed, hence a reliable measurement could not be performed. The power fluctuations were again
attributed to reflections of the probe light at the input facet of the fibre, resulting in significant power fluctuations.

2.3.3 Lead-silicate based holey fibres with a hexagonal arrangement of holes

From a single preform fabricated by application of the SEST technique, HFs with a hexagonal arrangement of effectively 4 rings of holes (48 holes in total) were produced. The core sizes of the fabricated HFs ranged between 2.4-4.5 µm, with a \( d/A \) ratio of 0.48 in the outer cladding region and 0.55 in the region surrounding the core. Using SEM images, three fibre bands of a stable core diameter of 4.3 µm (band #1), 3.4 µm (band #2) and 2.4 µm (band #3) were identified and characterized.

Using a commercially available beam profiler, in combination with a Nd:YLF laser source, the spatial mode guidance characteristics of the three bands, at 1.047 µm, were investigated. The obtained mode profile for all fibres had a near hexagonal symmetry similar to the profile of the fibre, in good agreement with that predicted by numerical simulations of the fundamental mode profile (Fig. 2.23). Single-mode, or effectively single-mode, guidance was observed for all fibres at 1 µm, therefore single-mode operation was expected for operation at wavelengths lying inside the C-band.


<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Core diameter (µm)</th>
<th>SEM image (µm)</th>
<th>Near Field Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>4.3</td>
<td><img src="image1.png" alt="SEM image" /></td>
<td><img src="image2.png" alt="Near Field Pattern" /></td>
</tr>
<tr>
<td>#2</td>
<td>3.4</td>
<td><img src="image3.png" alt="SEM image" /></td>
<td><img src="image4.png" alt="Near Field Pattern" /></td>
</tr>
<tr>
<td>#3</td>
<td>2.4</td>
<td><img src="image5.png" alt="SEM image" /></td>
<td><img src="image6.png" alt="Near Field Pattern" /></td>
</tr>
</tbody>
</table>

**Figure 2.23**: SEM images and corresponding near-field profiles of the lead-silicate SEST HFs with a hexagonal hole arrangement.

### 2.3.3.1 Propagation loss

The results from the performed propagation loss measurements are presented in Tab. 2.6. It is evident that, although the core diameters of the three bands examined here are larger than those of the triangular-core, lead-silicate fibres examined in the previous section (Tab. 2.3), the propagation loss of the SEST fibres with a hexagonal arrangement of holes is much higher. This excess propagation loss might be attributed to a greater scattering loss, due to increased surface imperfections (surface roughness, contamination) at the air/glass interface. Moreover, confinement loss might be an issue, since the air-filling fraction (and hence the NA) of these fibres is much lower than in the case of the triangular-core HFs. It is therefore expected that some light
might be coupled to the cladding, leading to increased propagation loss. Further improvement in the preform surface quality and optimization of the SEST technique, so as to enable the addition of more than one ring of structured elements might potentially decrease the propagation losses of the fabricated HFs to values close to the bare fibre losses.

**Table 2.6:** The results from the measurement of the propagation loss of the lead-silicate SEST HFs with a hexagonal hole arrangement in the C-band.

<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Enclosed core diameter (µm)</th>
<th>Propagation Loss (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>4.3</td>
<td>3.2 ± 0.3</td>
</tr>
<tr>
<td>#2</td>
<td>3.4</td>
<td>3.5 ± 0.3</td>
</tr>
<tr>
<td>#3</td>
<td>2.4</td>
<td>4.0 ± 0.4</td>
</tr>
</tbody>
</table>

### 2.3.3.2 Nonlinear coefficient

The nonlinear coefficients of the lead-silicate based SEST HFs were then measured. Diagrams of the received nonlinear phase shift (per unit of effective length) against launched power, for the three fibre bands, are presented in Fig. 2.24. The results are summarized in Tab 2.7.
Figure 2.24: Nonlinear Phase Shift per unit of effective length plotted against the launched power for the lead-silicate SEST HFs with a hexagonal hole arrangement at 1563 nm (a) band #1, 4.3 µm enclosed core diameter (b) band #2, 3.4 µm enclosed core diameter and (c) band #3, 2.4 µm enclosed core diameter.
Chapter 2: Characterization of small-core, compound glass HFs

### Nonlinear coefficient of the SEST lead-silicate HFs

<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Enclosed core diameter (µm)</th>
<th>Measured Effective Nonlinearity $\gamma$ (W$^{-1}$km$^{-1}$)</th>
<th>Predicted Effective Nonlinearity $\gamma$ (W$^{-1}$km$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>4.3</td>
<td>$164 \pm 14$</td>
<td>170</td>
</tr>
<tr>
<td>#2</td>
<td>3.4</td>
<td>$243 \pm 21$</td>
<td>250</td>
</tr>
<tr>
<td>#3</td>
<td>2.4</td>
<td>$396 \pm 42$</td>
<td>414</td>
</tr>
</tbody>
</table>

Table 2.7: The results from the measurement of the effective nonlinear $\gamma$ of the lead-silicate SEST HFs with a hexagonal hole arrangement at 1563 nm.

The results of Tab. 2.7 are in agreement with the expectation that the nonlinearity per unit length increases with a reduction in the core diameter. Numerical simulations based on the SEM images of the fabricated fibres revealed a good agreement between the measured values of the nonlinear parameter $\gamma$ and the theoretically anticipated values (the simulations concerning the numerical modelling were performed by Dr. Francesco Poletti). Compared to the case of the triangular-core, lead-silicate HFs, the nonlinear performance of the SEST HFs with a hexagonal arrangement of holes presented here is inferior, owing to the larger fibre core diameters.

#### 2.3.3.3 Dispersion characteristics

In SEST HFs, a portion of the effective nonlinearity is sacrificed in favour of achieving superior dispersion characteristics. The GVD of the three fibre bands was experimentally determined using the interferometric dispersion measurement set-up. In Tab. 2.8, the results from the dispersion measurements at 1.55 µm are presented for the different fibre core sizes. Bands #2 and #3 exhibit anomalous GVD throughout the C-band, highlighting the enhanced effect of waveguide dispersion. With regard to band#3, the interferometric set-up was inadequate to provide accurate results, since the combination of low dispersion and low dispersion slope made the measurement very prone to mechanical and environmental instabilities. However, it was confirmed that the dispersion of the fibre at 1.55 µm was normal, with a value ranging between -1 to -9 ps/nm/km. Hence, it was expected that the ZDW lay at a wavelength slightly longer than the C-band wavelength regime. In Chapter 4, the FWM response of fibre band#3 will be used to estimate the fibre’s ZDW.
In Fig. 2.25, the measured dispersion values are interpolated on the predicted by numerical simulations GVD profiles. The numerical simulations were performed by applying a full vector model, which used refractive index profiles based on SEM images of the real fibre structure (the simulations were performed by Dr. Poletti). A good agreement between the theoretical expectations and the measured dispersion values is evident, confirming the validity of the applied numerical modelling.

<table>
<thead>
<tr>
<th>Fibre Band</th>
<th>Enclosed core diameter (µm)</th>
<th>Measured dispersion (ps nm(^{-1})km(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>4.3</td>
<td>In the range from -1 to -9</td>
</tr>
<tr>
<td>#2</td>
<td>3.4</td>
<td>22 ± 4</td>
</tr>
<tr>
<td>#3</td>
<td>2.4</td>
<td>55 ± 3</td>
</tr>
</tbody>
</table>

**Table 2.8:** The results from the measurement of the dispersion of the lead-silicate SEST HFs with a hexagonal hole arrangement at 1550 nm.

**Figure 2.25:** Predicted dispersion profiles of the fabricated lead-silicate SEST HFs with a hexagonal hole arrangement (The numerical simulations were performed by Dr. Poletti). The measured dispersion values at 1550 nm (squares) are interpolated on the graph.

It can be seen from Tab. 2.8 that, as the core dimension decreases, the ZDW is pushed towards shorter wavelengths, leading to an anomalous dispersion in the C-band, while at the same time the nonlinear parameter \(\gamma\) increases. This behaviour clearly reveals the above-mentioned trade-off between dispersion performance and nonlinearity per...
unit length for fibres with ZDWs around the C-band. By slightly compromising the magnitude of the nonlinearity, fibres with a ZDW located inside the C-band can be fabricated. On the other hand, by modifications in the fibre design, i.e. by selecting a different air-filling fraction, designs offering a much higher nonlinearity and optimized dispersion performance are possible. Improvements in the fabrication process of SEST fibres will ultimately enable the realization of such designs, making the use compound-glass HFs in practical applications a reality.

2.3.3.4 Beat-Length measurements

The ability of the SEST fibres, with a hexagonal hole arrangement, to maintain linear polarization was also tested. By launching light on one of the principal polarization axes of the lead-silicate HF fibre band #3, an extinction ratio of 22 dB between the signals received on the two orthogonal polarization axes at the output of the fibre was measured. For the same fibre, a beat-length measurement was performed.

Furthermore, a measurement of the beat-length of the SEST HF fibre band #3 was performed. In Fig. 2.26a, the received spectrum at the output of a 2.1m-long piece of band #3 for the case when ASE light is launched parallel to one of the principal birefringence axes of the fibre is presented. In Fig. 2.26b, the case when the ASE light is aligned at 45° relative to the principal birefringence axes is shown. Polarization beating is evidently causing the appearance of fringes in the obtained output spectra. The periodicity of the fringes is ~ 4.92 nm, yielding a beat-length $L_B \sim 6$ mm and a $\Delta n \sim 2.58 \times 10^{-4}$ between the refractive indices of the two principal axes.
2.3.3.5 Brillouin properties

A measurement of the Brillouin gain spectra of the SEST lead-silicate fibres, with a hexagonal hole arrangement, was performed. Due to the poor coupling efficiency provided by butt-coupling of SMF into the lead-silicate fibre, the observed Brillouin gain was small. However, the relatively good stability of the system and the small fluctuations of the probe power allowed for a successful measurement to be performed. In Fig. 2.27, the Brillouin gain spectra of fibre bands #1 and #2 are presented. The measured Brillouin frequency shift and the Brillouin gain bandwidth for band #1 were 7.66 GHz and 74 MHz respectively, while for band #2 the corresponding values were 7.58 GHz and 114 MHz respectively. For the bulk lead-silicate glass, the acoustic velocity $v_A$ is approximately 3.13 km sec$^{-1}$, hence the Brillouin frequency shift of the bulk glass is
\[ v_b = \frac{2\nu \lambda}{n} = 7.27 \text{ GHz} \] (2.20)

where \( n \) is the refractive index of the glass and \( \lambda \) is the wavelength of operation. In the case of an optical fibre, instead of \( n \), the effective index of the fibre \( n_{\text{eff}} \) has to be taken into consideration in Eq. 2.20. Therefore, the Brillouin frequency shift of a fibre is normally smaller than the corresponding Brillouin frequency shift of the bulk glass. However, in the performed measurements for the SEST fibres, the acquired Brillouin frequency shift of the two fibre bands was determined to be slightly higher than the Brillouin frequency shift of the bulk glass. This can be attributed to the fabrication process of the SEST fibres. Since an extrusion step has to be applied during fabrication, the physical properties of the glass (for example its density) might slightly be altered, leading to a modification of the acoustic velocity.

**Figure 2.27:** Brillouin gain spectra of (a) band #1 and (b) band #2 of the fabricated lead-silicate SEST HFs [21].

The Brillouin gain coefficient could also be determined from the measurements, yielding a value of \( 2.6 \times 10^{-11} \text{ m / W} \) and \( 2.1 \times 10^{-11} \text{ m / W} \) for fibre bands #1 and #2 respectively. However, it has to be appreciated, that, due to the small gain of the probe, the results concerning the Brillouin gain coefficient should be considered indicative rather than accurate.
2.4 **Assessment of the nonlinear performance of the fabricated holey fibres**

For the assessment of the nonlinear performance of the characterized HFs in terms of their potential use in compact, nonlinear devices operating at low input powers, a suitable figure-of-merit (FOM) has to be used [26]. According to Eq. 2.3, the phase shift induced from nonlinear effects in optical fibres is proportional to the average power input into the fibre, the nonlinear coefficient $\gamma$ and the effective length of the fibre [3]. Therefore, if a certain nonlinear phase shift is to be achieved for a specific input power, a large $\gamma \times L_{\text{eff}}$ product is required. According to Eq. 1.36, the maximum effective fibre length is $L_{\text{eff, max}} = 1/\alpha$. Hence, the term $\gamma/\alpha$ is often used as a FOM. However, the requirement for practical, compact nonlinear devices imposes limitations on the length of the fibre that should be used. It is therefore reasonable to fix the fibre length to 1m, since ideally the length of compact nonlinear devices should be of this order. Hence, the term $\gamma \times L_{\text{eff, @1m}}$, where $L_{\text{eff, @1m}}$ is the effective length of the fibre for 1m of real fibre length, can be used to assess the performance of optical fibres in compact nonlinear devices. In Tab. 2.9, the $\gamma \times L_{\text{eff, @1m}}$ FOM of the characterized fibres are presented. For comparison, the $\gamma \times L_{\text{eff, @1m}}$ FOM of a silica highly nonlinear DSF and a state-of-the-art silica HF are also provided [26]. It can be seen that compound-glass HFs have clearly a very good performance, since their high nonlinearity compensates for their loss. However, it should be noted that, due to the small effective areas required, severe splicing and coupling losses are expected to degrade the nonlinear performance of small-core, compound-glass HFs. Thus, efforts should be made to find methods to optimize the coupling efficiency and decrease the coupling loss when using such fibres. Furthermore, it is important to take into account that in practical nonlinear applications, dispersion is a major limiting factor. Therefore, efforts have to be made so as to simultaneously optimize the nonlinear characteristics as well as the dispersion profile of compound-glass HFs. As mentioned in section 2.1, the SEST fabrication approach is considered very promising towards this direction, since by properly adjusting the hole-to-hole-pitch and the hole diameter in the cladding, fibre designs that combine a high nonlinearity with novel dispersion properties can be realized.
## 2.5 Conclusions

Small-core HFs made of both bismuth-oxide and lead-silicate glasses have been characterised in terms of their loss, nonlinearity and dispersion characteristics. The best fabrication attempts for both materials exhibited consistent losses of 2-4 dB/m, with the loss increasing for smaller cores due to the more profound effect of surface roughness. It is anticipated that improvements in the fabrication of compound-glass HFs will lead to a further reduction in the propagation loss, ideally down to the loss-limit imposed by the bulk glass itself. Although attempts with dehydrated glass have
not been successful so far, it is believed that such an approach will lead to a significantly better propagation loss performance.

The potential of compound-glass HFs in achieving a very high nonlinearity was clearly demonstrated. In particular, a 0.9 µm core HF made from lead-silicate based glass exhibited a nonlinearity of about 1860 W⁻¹km⁻¹, three orders of magnitude greater than the nonlinearity of standard optical fibres. For even smaller core dimensions and thus higher nonlinearities combined with lower propagation loss levels, compound-glass HFs promise a route towards sub-metre, sub-Watt nonlinear devices.

In order to exploit the full potential of compound-glass HFs, their behaviour in terms of dispersion has to be assessed. Due to the limitations imposed by the relatively high loss in such fibres, techniques such as the pulse propagation method fail to provide reliable results, since they require long lengths of fibre to be used. Interferometric techniques provide a convenient alternative approach, since they require short lengths and eliminate the need for test equipment with high temporal resolution. Using an interferometric approach, the dispersion characteristics of the fabricated fibres were identified.

It was shown that, although HFs with a triangular-core design can provide very tight mode confinement, leading to unprecedented values of the nonlinear coefficient per unit length, they are relatively inflexible in terms of tailoring their characteristics, since the fibre core is the only design parameter. The highly nonlinear, triangular-core HFs were predicted to be anomalously dispersive at 1550 nm, due to the strong waveguide dispersion. A study of the SPM effect in such a bismuth-oxide based fibre confirmed the numerical predictions, since the formation of Raman solitons was clearly observed in the signal spectrum. Dispersion measurements based on the interferometric technique revealed a strongly anomalous dispersion at 1550 nm.

On the contrary, fibres fabricated with the SEST approach having a hexagonal arrangement of holes offer the opportunity for realization of designs that enable separate optimization of the hole-to-hole pitch and the hole diameter, so as to combine a high value of nonlinearity with novel dispersion properties. Indeed, the
characterization measurements of such a fibre design made from the commercially available SF57 lead-silicate glass revealed a very low dispersion value in the C-band, a ZDW lying near the C-band region and a relatively high value of the nonlinear coefficient (164 W⁻¹ km⁻¹). The good polarization maintaining properties of this fibre favours its use in nonlinear applications requiring polarization stability, such as switching and wavelength conversion based on a KS configuration.
References


Chapter 3

Cross-phase modulation based wavelength conversion in a lead-silicate holey fibre

Efficient, fast and tunable wavelength conversion is an essential signal processing function for the realization of robust, high speed and high capacity WDM networks, since it enables the implementation of ultrafast wavelength routing and wavelength reuse applications [1]. Fibre-based wavelength converting devices have been considered particularly advantageous due to their excellent noise performance, their ability to be easily integrated in optical systems and their ultrafast response.

An ideal all-optical wavelength converter in a WDM system should have the capability of converting any unknown input wavelength to any desired output wavelength without performance limitations. FWM-based wavelength conversion techniques offer the great advantage of bit-rate and modulation format transparency [2]. Nevertheless, being extremely sensitive to phase-matching conditions, they are likely to suffer from stability issues, especially when long lengths of fibre are employed [3], and lead to a wavelength dependent conversion efficiency performance unless a flat dispersion profile over a wide wavelength span is realised, as it will be shown in Chapter 4 (Fig. 4.9a). On the other hand, XPM-based wavelength converters represent an efficient, robust and relatively simple technique of achieving high-performance all-optical wavelength conversion, providing a good conversion efficiency at relatively low pump powers. However, the limitation of XPM-based techniques is that they apply to intensity-modulated signals only.

Various wavelength conversion schemes utilizing XPM in optical fibres have been successfully demonstrated. In this Chapter, the dispersion tailored lead-silicate SEST HF presented in section 2.3.3 (denoted as fibre band #1) is employed in two particularly attractive wavelength conversion XPM-based configurations at 10 Gb/s. The first approach relies on the use of optical filtering for the transformation of XPM-induced phase modulation to intensity modulation. The simplicity and stability of this
scheme makes it a good candidate for realistic all-optical wavelength conversion applications. The second approach is based on the nonlinear birefringence induced by XPM. A Kerr-shutter (KS) configuration is used, which has the advantage of enabling the realization of very small timing windows.

It should be noted that the experiments presented in this Chapter constitute the first all-optical telecommunication applications of compound-glass HFs ever demonstrated. In the demonstrated wavelength conversion schemes, the use of the highly nonlinear lead-silicate SEST HF with a low dispersion and a relatively low dispersion slope in the C-band facilitates the implementation of compact wavelength converters, with a performance largely insensitive to the actual wavelength of operation within the C-band. The results clearly demonstrate the merits of compound-glass HF technology and its great potential in fibre-based, all-optical, nonlinear applications.

3.1 Wavelength conversion based on a co-polarized pump-signal configuration and optical filtering

3.1.1 Principle of operation

The principle of this scheme is presented in Fig. 3.1. A pulsed pump beam is propagated through a highly nonlinear optical fibre together with a weak CW signal. Assuming that the fibre is birefringent, it is important to have both the pump and the signal linearly polarized and launched into one of the principal polarization axes of the fibre, so as to maximize the efficiency of the induced XPM. Due to XPM, the CW signal develops optical sidebands. The sideband lying in the longer wavelength side is generated from the derivative of the leading edge of the pump pulse, while the sideband in the shorter wavelength side originates from the trailing edge of the input pulse [4, 5]. If one of the sidebands is selected using an optical filter offset to the wavelength position of the CW, the phase modulation can be transformed to intensity modulation and a high-quality wavelength-converted output can be obtained. A parameter of critical importance in this configuration is the efficient suppression of both the CW and the pump signal, so as to ensure that only the spectral components present in one of the sidebands are kept. The approaches most commonly followed
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rely on the use of a narrow filter with a sharp extinction profile, or the use of a combination of a BPF and a notch filter able to sufficiently suppress the CW [5]. It should be mentioned that, ideally, due to the derivative origin of the sideband generation, if the spectral width of the employed BPF matches the spectral width of one of the generated sidebands, it is possible for the wavelength-converted pulse to be even shorter than the input pulse. However, issues such as the dispersive walk-off between the pump and signal waves and the filter bandwidth required for efficient suppression of the CW component normally lead to a longer converted pulse than the pump pulse [5].

![Figure 3.1: Wavelength conversion based on induced XPM and offset filtering](image)

The first demonstrations of wavelength conversion using this scheme employed DSFs. Due to the relatively small nonlinear coefficient of these fibres, several kilometres of fibre were required [5, 6, 7], so stability and practicality were an issue. The use of silica-based HF s has enabled a significant reduction in length requirements [8, 9], while the employment of HNLFs of conventional step-index design based on compound glasses has allowed for the realization of a meter-long nonlinear devices operating at relatively low powers [10]. However, since it is difficult to tailor the dispersion properties of compound-glass HNLFs, dispersion and walk-off effects can significantly affect the bandwidth of the XPM sidebands, leading to performance degradation for signal wavelengths placed far from the pump [10].
In this section, the use of the dispersion tailored SF57 SEST HF presented in section 2.3.3 and denoted as fibre band #1 is reported. Using just 2.1 m of this fibre, which exhibits a low normal dispersion in the C-band, error free performance with a relatively low power penalty is achieved.

### 3.1.2 Experimental setup and parameters affecting the performance of the system

In Fig. 3.2, the experimental set-up of the implemented wavelength converter is shown.

![Figure 3.2: Experimental setup of the implemented wavelength converter based on XPM and offset filtering. PC: polarization controller.](image)

A 10 GHz, actively mode-locked, EFRL producing ~2.2 ps FWHM hyperbolic-secant pulses, at a central wavelength that could be tuned in the range 1530-1560 nm, was used as a transmitter in the pump port. In the experiment, the central wavelength of the pulses was set to 1544.6 nm. The pulses were modulated with a $2^{31}$ pseudo-random bit sequence (PRBS) at 10 Gb/s, using a lithium-niobate MZM, and were combined through a 3 dB coupler with a CW probe beam generated from a laser source tunable inside the C-band. The resulting beam was amplified by a high power Er/Yb amplifier and free-space launched into a 2.1 m-long SF57 SEST HF (section 2.3.3, fibre band #1) with a coupling efficiency of ~25%. The polarizer was aligned to one of the principal polarization axes of the fibre (as described in section 2.2.2) and the two polarization controllers at the pump and probe ports were adjusted so that the power
exiting the polarizer was maximized. In this way, optimized formation of XPM-induced sidebands was obtained at the output of the fibre.

At the output of the fibre clear XPM-induced sidebands were developed at the probe wavelength. The CW probe, together with the generated sidebands, were initially selected by a 3 nm BPF and amplified through an EDFA. A narrow 0.5 nm grating was employed to filter a portion of one of the generated sidebands. The signal selected by the grating filter was further amplified through an EDFA and the induced out-of-band ASE was reduced using a 1 nm BPF. At the output of the system a notch filter was employed to further suppress the CW probe. The optical notch filter was realized using a 5m long polarization maintaining fibre in a loop configuration.

For optimization of the performance of the wavelength converter, several issues had to be addressed. First of all, since both the pulsed pump and the CW probe were amplified in the same high power amplifier for simplicity, the ratio of their average power at the input of the amplifier (point A, Fig. 3.2) was of critical importance in terms of both performance and reproducibility. It was required that the combined average power of the two signals sufficed to drive the high power EDFA in its saturation regime, so that the available output power from the amplifier would be maximized and remain relatively insensitive to input power fluctuations, while the ASE would be suppressed. When the ratio of the average powers was adjusted in favour of the pulsed pump, the power carried by the amplified CW component was low and the first amplifier at the output port (point B, Fig. 3.2) could not be brought to saturation, due to the decreased power carried by the CW and the generated sidebands. This led to a poor optical signal to noise ratio, and a heavily degraded eye at the output of the wavelength converter was obtained. On the other hand, if the ratio of the average probe to pump power at the input of the high power amplifier was adjusted greatly in favour of the probe, then the effects of XPM in the HF were not strong enough, and the XPM-induced sidebands carried too low a power compared to the CW probe. In this case, it was difficult to effectively suppress the CW probe at the output of the system and a large power penalty was observed when BER measurements were performed. It was hence essential to suitably adjust the ratio of the average pump power to the average probe power, prior to the high power amplifier at the input of the set-up, so as to ensure optimum performance in terms of wavelength-converted eye
diagram and BER results of the wavelength-converted signal. Moreover, the performance of the wavelength converter greatly depended on the position of the grating filter used for the selection of the wavelength-converted signal. Placing the grating filter too close to the CW probe resulted in insufficient suppression of the CW probe. On the other hand, if the grating filter was placed close to the edge of one of the XPM-induced sidebands, a heavily degraded eye diagram was obtained due to the poor optical signal to noise ratio at the edges of the sidebands and the inability to drive the second amplifier at the output of the system into saturation (point C, Fig. 3.2). A suitable filter position, representing a trade off between sufficient suppression of the CW probe component and adequate performance in terms of induced noise, was therefore essential to be experimentally selected.

3.1.3 Experimental results

Due to the common input high power amplifier configuration and the substantial length of Er-doped fibre inside the amplifier, XPM was induced onto the CW probe within the amplifier as well as due to the propagation through the SF57 HF. In order to study the relative significance of the induced XPM, the received spectra at the output of the high power amplifier were compared with the spectra received at the output of the 2.1 m-long SF57 HF for various CW probe positions. For this experiment, the pump was set at a central wavelength of 1544.6 nm and the probe was tuned inside the gain region of the high power amplifier. The ratio of the average probe to pump power was set to 7.2 dB prior to the input high power amplifier, since such a ratio was found to ensure optimal performance in terms of eye diagrams and BER measurements. The average output power from the high power amplifier was ~380 mW (note that the coupling efficiency into the SF57 HF was ~25%). In Fig. 3.3a, the acquired spectra for three different probe wavelengths are presented. It can be seen that, in all cases, the observed sidebands at the output of the highly nonlinear HF were predominantly induced by the propagation through the SF57 HF rather than the high power amplifier. Clear peaks, arising from a degenerate FWM process between the pump and the probe inside the SF57 HF, were also observed in the received spectra. In Fig. 3.3b a close-up view of the sidebands, developed due to XPM after propagation through the SF57 HF,
is provided for three different probe wavelengths. It can be seen that the bandwidth of the XPM-induced sidebands is virtually unaffected by the probe wavelength.

![Figure 3.3](image)

**Figure 3.3:** (a) Received spectra before the high power amplifier (light colours) and corresponding spectra after propagation through the SF57 HF (dark colours) for three different probe wavelength positions. (b) Close-up view of the sidebands induced by XPM for three different probe wavelength positions. A similar bandwidth is observed in all cases.

Since the bandwidth of the XPM-induced sidebands depends on the relative GVD between the pump and the probe wavelengths, it is expected to change dramatically in long fibres and/or fibres with a large dispersion slope [10]. Therefore, the similar
bandwidth of the acquired sidebands is a strong indication of the walk-off insensitive operation of the implemented wavelength converter, due to the tailored dispersion characteristics of the employed SF57 HF.

To demonstrate the detrimental effect of walk-off on the bandwidth of the XPM-induced sidebands, numerical simulations were carried out. Unchirped, sech-profile pulses with a FWHM of 2.2 ps and a peak power of ~4.6 W at a central wavelength of 1530 nm were considered as pump pulses. The probe was a weak CW beam lying at 1560 nm, which was chosen far away from the pump in order to allow the effects of dispersion become more easily obvious. Using the values of ZDW, dispersion slope, nonlinear parameter and loss corresponding to the SF57 HF, the simultaneous propagation of the probe and pump beams through a 2.2 m-long SF57 HF was simulated. For this choice of wavelength separation between the probe and pump beams, the walk-off length was ~5.5 m, while the dispersion length for the pulse width chosen in the simulations was ~119 m, hence both pulse walk-off and dispersion effects were expected to be negligible. In Fig. 3.4, the blue line demonstrates the formation of XPM sidebands around the CW probe. To study the effect of walk-off, the dispersion slope of the fibre was set to 1.5 ps/nm²/km, while the ZDW was left unchanged. In this case, the walk-off length was just ~0.73 m, while the dispersion length was ~16 m at the wavelength of the pump, hence walk-off effects were significant. The red line in Fig. 3.4 demonstrates the generated XPM sidebands in this case. The reduction in the bandwidth of the sidebands due to walk-off effects is evident. A slight asymmetry observed in the generated sidebands is also attributed to the significant walk-off effect between the probe and the pump beams in this case.
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Figure 3.4: Simulations demonstrating the effect of walk-off on the XPM sidebands. The blue line corresponds to the fabricated SF57 HF with a dispersion slope of 0.2 ps/nm²/km, while the red line to a similar fibre in terms of ZDW, nonlinear parameter and propagation loss but with a dispersion slope of 1.5 ps/nm²/km. Parameters used: Pump wavelength=1530 nm, Pump peak power=4.6 W, Pump pulses FWHM=2.2 ps, Probe wavelength=1560 nm.

Fig. 3.5 presents optical spectra at various positions in the experimental set-up for the case of a CW probe placed at 1559.1 nm, which was the largest wavelength detuning of the probe relative to the pump that the operational region of the high power amplifier allowed. As shown in Fig. 3.5a, although the FWM component was successfully suppressed after the 3 nm filter, some residual power at the pump wavelength was still present. By placing the central wavelength of the grating filter at an offset of ~0.7 nm from the CW probe (Fig. 3.5b), the pump power was eliminated. The resulting signal was then amplified and the out of band ASE noise was removed (Fig. 3.5c). Due to the limited extinction ratio of the grating filter, a significant CW probe component was present together with the desired wavelength-converted signal. After the notch filter and with appropriate adjustment of the polarization controller in the loop, the CW probe was effectively suppressed by as much as ~22 dB (Fig. 3.5d). By experimenting with various probe wavelength positions, it was verified that the behaviour of the wavelength converter was similar throughout the flat gain range of the high power amplifier. Wavelength conversion at shorter wavelengths compared to the pump position was also studied. The average power launched into the fibre was 380 mW in this case. In Fig. 3.6a-d, the optical spectra at various positions of the
experimental set-up are shown for the case of a CW probe placed at 1535.1 nm. The grating filter in this case was placed at an offset of \( \sim 0.75 \) nm from the CW probe (Fig. 3.6b), and, due to the relatively small wavelength separation between the CW probe and the pump, some residual pump power was evident. However, subsequent filtering effectively eliminated this pump power and a clear wavelength-converted signal was obtained (Fig. 3.6d).

**Figure 3.5:** (a-d) Received spectra at various points of the experimental set-up for a CW probe positioned at 1559.1 nm.
The performance of the wavelength converter was assessed in terms of eye diagrams and BER tests. In Fig. 3.7a the received eye diagrams for a wavelength-converted signal at 1535.8 nm and 1559.8 nm are compared to the eye diagram of the input pump pulses. Clear wavelength-converted eye diagrams, albeit with some intensity noise in the ‘ones’ level were received in both cases. The observed intensity noise was attributed to the accumulation of ASE through the two amplification stages at the output of the system, since operation in the normal dispersion regime of the fibre eliminates signal degradation due to the effect of modulation instability. It should be noted that even for the back-to-back signal, a slight intensity noise was observed in the obtained eye diagrams. This noise was attributed to a non-ideal mode locking, hence it was expected that the received eye diagrams were not representative of the pulse quality that should be achievable. The corresponding BER tests are presented in Fig.
3.7b. Error free transmission with a power penalty in the receiver sensitivity of ~0.9 dB at a BER of $10^{-9}$ was achieved for both wavelength-converted signals.

Since the effect of walk-off on the implemented wavelength converter was negligible, due to the relatively low dispersion slope of the fibre and the small piece of fibre employed, the bandwidth of the generated XPM sidebands was unaffected by the probe position (Fig. 3.3b). Furthermore, as it can be seen in Fig. 3.5b and Fig 3.6b, the bandwidth of the grating filter was much narrower than the bandwidth of the
sidebands generated by XPM. Therefore, it was expected that the pulsewidth of the wavelength-converted signal would be effectively determined by the grating filter bandwidth and would be independent of the probe wavelength position. Indeed, SHG-based intensity autocorrelation measurements revealed that the wavelength-converted signals had a pulsewidth of 8.8 ps, assuming a Gaussian pulse profile (Fig. 3.7c). The time-bandwidth product of the converted pulses was \( \sim 0.52 \) (as obtained through a combination of spectral and autocorrelation measurements), which, although somewhat larger than the time-bandwidth product of an ideal transform limited Gaussian pulse (0.44), still indicates high-quality pulses. It should be mentioned, however, that in practical all-optical wavelength conversion applications, it is desirable to obtain an output wavelength-converted pulsewidth similar to the pulsewidth of the input pulses. Although a separate pulse compression stage can be employed at the output of the wavelength converter, it is generally preferred to ensure similar input and output pulsewidths by suitably selecting the bandwidth of the employed as decision gate BPF. In the performed experiment, the bandwidth of the XPM-generated sidebands, as dictated by the output power of the available high power amplifier, the minimum available input pulsewidth and the maximum coupling efficiency into the HF, was not wide enough to allow for the use of a wider BPF, since the CW probe could not be effectively suppressed in this case.

The proposed wavelength converter could potentially be used at even higher bit rates, for example at 160 Gb/s [6], as the response of Kerr-nonlinearity is almost instantaneous. The most important parameters affecting the performance of this scheme at very high rates are the spectral broadening of the pump due to SPM, which might cause cross-talk on the converted signal, and the need for a wider BPF bandwidth when moving to higher rates, in order to avoid the detrimental effects of intersymbol interference in terms of BER performance. At such high rates, care should also be taken, so as to ensure that the filter’s central wavelength position and bandwidth would efficiently suppress the CW signal component.

In conclusion, improvements in the fabrication process of compound-glass HFs, enabling the realisation of fibres with a flatter dispersion profile, a higher nonlinearity per unit length, and a lower propagation loss, would enable the use of such fibres in
practical wavelength-conversion applications at speeds exceeding 40 Gb/s, with moderate power requirements and walk-off insensitive operation.

### 3.2 Wavelength conversion based on a Kerr-shutter configuration

#### 3.2.1 Principle of operation

The operation of a fibre-based KS is based on the nonlinear, intensity dependent birefringence induced in optical fibres by the propagation of high intensity beams [11]. The principle of a KS is schematically shown in Fig. 3.8. A pulsed, high intensity, linearly polarized pump beam at a wavelength $\lambda_p$ is launched on one of the principal polarization axes of a birefringent fibre, while a CW, linearly polarized, low intensity probe beam at a wavelength $\lambda_{pr}$ is launched at an angle $\theta$ of 45° relative to the pump.

At the input of the fibre, the electric field $\tilde{E}_{pr}$ of the probe wave can be described as

$$\tilde{E}_{pr}(0,t) = E_0 \cos \theta \cos(-\omega_{pr} t)\hat{x} + E_0 \sin \theta \cos(-\omega_{pr} t)\hat{y}$$

and since $\theta = 45°$,

$$\tilde{E}_{pr}(0,t) = \frac{E_0}{\sqrt{2}} \cos(-\omega_{pr} t)\hat{x} + \frac{E_0}{\sqrt{2}} \cos(-\omega_{pr} t)\hat{y}$$

where $E_0$ is the amplitude of the input probe electric field and $\omega_{pr}$ its angular frequency. During propagation through the fibre, the two orthogonal polarization components $x, y$ of the probe acquire a phase shift $\Delta \Phi_x$ and $\Delta \Phi_y$ respectively. These phase shifts can be separated into a linear term $\Delta \Phi_{L(i)}$ and a nonlinear, power-dependent term $\Delta \Phi_{NL(i)}$, where $i = x,y$. Therefore, assuming for simplicity lossless propagation, the electric field of the probe at the output of the fibre is

$$\tilde{E}_{pr}(L,t) = \frac{E_0}{\sqrt{2}} \cos\left(\Delta \Phi_{NL(x)} + \Delta \Phi_{L(x)} - \omega_{pr} t\right)\hat{x}$$

$$+ \frac{E_0}{\sqrt{2}} \cos\left(\Delta \Phi_{NL(y)} + \Delta \Phi_{L(y)} - \omega_{pr} t\right)\hat{y}$$
If $\beta_x$, $\beta_y$ are the propagation constants of the polarization components $x$ and $y$ respectively, then

$$\Delta \Phi_{L(x)} = \beta_x L \quad \Delta \Phi_{L(y)} = \beta_y L$$

(3.4)

In a birefringent fibre, the propagation constants are different for the two principal polarization axes, i.e. $\beta_x \neq \beta_y$. By defining $\Delta \Phi_L$ as the phase difference developed between the two polarization components due to modal birefringence, then

$$\Delta \Phi_L = \Delta \Phi_{L(x)} - \Delta \Phi_{L(y)} = \beta_x L - \beta_y L = \frac{2\pi}{\lambda_{pr}}(n_x - n_y)L = \frac{2\pi}{\lambda_{pr}} BL \quad (3.5)$$

where $n_x, n_y$ are the refractive indices of the two polarization components and $B$ is the fibre birefringence. Therefore, combining Eq. 3.3 and Eq. 3.5, the probe electric field can be written as

$$\bar{E}_{pr}(L, t) = \frac{E_o}{\sqrt{2}} \cos(\beta_x L - \omega_{pr} t + \Delta \Phi_{NL(x)} + (\Delta \Phi_{NL} + \Delta \Phi_L)) \hat{x}$$

$$+ \frac{E_o}{\sqrt{2}} \cos(\beta_y L - \omega_{pr} t + \Delta \Phi_{NL(y)})) \hat{y}$$

(3.6)

where

$$\Delta \Phi_{NL} = \Delta \Phi_{NL(x)} - \Delta \Phi_{NL(y)} \quad (3.7)$$

It is obvious from Eq. 3.6 that the two polarization components acquire a relative phase difference while propagating through the fibre. This phase difference at the output of the fibre is expressed as

$$\Delta \Phi = \Delta \Phi_{NL} + \Delta \Phi_L = \Delta \Phi_{NL} + \frac{2\pi}{\lambda_{pr}} BL \quad (3.8)$$

and causes a change in the state of polarization of the probe. With regard to the nonlinear term of the phase shift, this arises from the fact that nonlinear effects in optical fibres are polarization dependent. Particularly for the case of a KS, the nonlinear refractive index change induced by the pump through the XPM effect is different for the two polarization axes of the fibre. This unequal, pump-induced nonlinear refractive index change in the two polarization axes introduces a nonlinear phase difference between the two polarization components of the probe, therefore an intensity dependent change in the probe state of polarization is observed at the output of the fibre.
To transform the pump-induced phase shift into intensity modulation, a polarizer is employed at the output of the fibre. In the absence of pump pulses, the phase shift between the two polarization components of the probe stems only from the linear phase shift term $\Delta \Phi_L$ as shown in Fig. 3.8a. Due to this phase shift, the state of polarization of the probe changes, and is generally elliptical at the fibre output. In the free-space version of the Kerr-shutter, a $\lambda/4$ waveplate is normally employed to convert the elliptical output probe polarization state back to linear. In a fiberised version of the Kerr-shutter, a fibre polarization controller is used in the place of a $\lambda/4$ waveplate. By suitable rotation of the fibre polarization controller, any input polarization state can be transformed to any other output polarization state [12]. Therefore, the fibre-based polarization controller can be used in the place of a $\lambda/4$ waveplate, so as to ensure that the output polarization is linear. If $\theta_2$ is the angle of the resulting output probe linear polarization relative to one of the fibre principal polarization axis, then the axis of the polarizer is aligned to an angle of $\theta_2 + \pi/2$. In this way, the probe transmission is blocked in the absence of pump pulses. When the pump pulses are present, then apart from $\Delta \Phi_L$, a nonlinear phase shift $\Delta \Phi_{NL}$ is induced between the two probe polarization components. This nonlinear phase shift induces an additional change to the state of polarization of the probe, hence some power can now be transmitted through the polarizer. The probe transmissivity depends on the pump intensity and can be controlled by adjusting it. In fact, if the pump power is strong enough to induce a $\pi$ phase shift between the two orthogonal polarization components, the output probe linear polarization becomes aligned to the axis of the polarizer (Fig. 3.8b). The transmission through the polarizer is therefore maximized every time pump pulses are present. In this way, a wavelength-converted signal, which follows accurately the modulation of the pump, can be obtained at the output of the set-up.
Figure 3.8: Principle of operation of a KS as a wavelength converter from wavelength $\lambda_p$ to a wavelength $\lambda_{pr}$, with (a) corresponding to the case when the pump is off and (b) to the case when the pump is on. The relative polarizations of the pump and probe beams are also shown.

Assuming that the dispersion of the fibre is low, the group-velocity of the pump can be considered approximately equal to the group-velocity of the parallel component of the probe. In a simplified approach, if the polarization mode dispersion (PMD) of the fibre is ignored, the group-velocity of the parallel component of the probe can be regarded as equal to the group-velocity of the vertical component. Under these assumptions, the relative phase difference of the two components of the probe can be written as [13]

$$\Delta \Phi_{NL} = 2 \cdot \gamma \cdot P_{pump} \cdot L_{eff} \cdot b$$

(3.9)
where $\gamma$ is the nonlinear coefficient of the fibre, $P_{\text{pump}}$ is the pump power, $L_{\text{eff}}$ is the effective length of the fibre (Eq. 1.36), and $b$ is a parameter that expresses the relative difference between the intensity of the induced Kerr effect in a direction parallel and perpendicular to the pump. For a linearly birefringent fibre, i.e. a fibre that has two principal polarization axes, along which a linearly polarized light remains linearly polarized in the absence of nonlinear effects, the $b$ parameter takes a value of 2/3 [4].

An ideal fibre designed for KS applications should simultaneously exhibit a good polarization stability, a low dispersion and a low walk-off between the pump and the probe pulses [11]. It is straightforward that shorter lengths are less sensitive to environmental variations causing polarization instabilities and also lead to decreased net dispersion and walk-off. Furthermore, to achieve substantial nonlinear phase-shift using short fibres, a high nonlinear coefficient $\gamma$ is essential (Eq. 3.9). Hence, some of the most promising demonstrations of KS operation have relied on the use of HNLFs. Highly nonlinear DSFs represent the most mature technology, and impressive results have been achieved especially in terms of dispersion profile, leading to the demonstration of fast KSs with short timing windows [14]. However, due to the moderate values of $\gamma$ that can be achieved in highly nonlinear DSFs, several tens or hundreds of meters are normally required for a significant phase shift to be introduced and hence compactness is an issue. Furthermore, it is difficult to implement stable and robust KSs using highly nonlinear DSFs, since longer lengths of fibre are more likely to induce instability in the output probe polarization state, due to increased sensitivity in temperature fluctuations and mechanical vibrations. The emergence of HF technology has enabled a significant reduction in the fibre lengths [15], while the ultra high nonlinearity of compound-glass HNLFs has allowed the realization of compact and stable devices employing just a few meters of fibre [16, 17, 18, 19]. Nevertheless, the conventional step-index design of compound-glass HNLFs does not allow for flexible dispersion tailoring, hence these fibres are normally characterized by a high dispersion and a steep dispersion slope in the 1.55 µm window. As a result, pulse broadening and pump-probe walk-off hinder the realization of short timing windows [18].

An ideal candidate for KS applications, offering the ability to simultaneously tackle the effects of dispersion and polarization instability, is compound-glass HF
technology, since fibres with a high value of $\gamma$, a low dispersion and a low dispersion slope can be fabricated. In this section, a KS based on the SEST SF57-HF that exhibits a low dispersion in the C-band is demonstrated. Using just 2.1 m of this fibre, wavelength conversion of 2.2 ps pulses modulated at 10 Gb/s is realized, with a received probe pulsewidth similar to the input pump pulsewidth due to negligible dispersion and walk-off.

### 3.2.2 Experimental setup

The experimental setup for the implementation of a KS wavelength converter using the SF57 HF is shown in Fig. 3.9.

![Experimental Setup](image)

**Figure 3.9:** Experimental setup for the implementation of a KS using 2.1 m of a SF57 HF. PC: polarization controller.

The transmitter at the pump port was based on a 10 GHz actively mode-locked EFRL which generated $\sim$2.2 ps FWHM sech pulses at a central wavelength of 1557.7 nm. The pulses were modulated with a $2^{31}$-1 PRBS from a lithium-niobate MZM and were amplified by a high power Er/Yb amplifier. In the probe port, a tunable, CW laser, operating at 1539.7 nm was used as a source. The probe beam was amplified by a separate EDFA. A bandpass filter (BPF) was employed to remove the out of band ASE noise induced by the amplification stage. The resulting probe was combined with the pump through a 3 dB coupler. At the output of the coupler, the average pump and
probe powers were 23.3 dBm and 18.7 dBm respectively. The combined beam was free-space launched into the 2.1 m long SF-57 HF with a coupling efficiency of ~27%.

In this experiment, the SEST SF57 HF described in section 2.3.3 and denoted as fibre band #1 was used. Due to the relatively small value of the dispersion slope and the short length of fibre used, it was expected that the relative net group-delay between the pump and the probe would not affect the performance of the implemented KS. Furthermore, the ability of the fibre to maintain linear polarization, as indicated by the large extinction ratio of ~22 dB between the two orthogonal polarization axes at the output of the fibre when linearly polarized light was launched in one of the principal axes, was anticipated to ensure the realization of a stable and robust KS.

A limiting factor in the performance of a KS is modal birefringence. In particular, when a birefringent fibre is used in a KS configuration, the difference between the propagation constants of the two principal fibre polarization axes poses a fundamental limit to the timing window, as it affects the group-velocity characteristics of the two axes (while the second-order dispersion remains unaffected) [4, 11]. Hence, in a way, the effect of modal birefringence is similar to chromatic dispersion induced walk-off, however it appears between components orthogonally polarized to each other. As expected, the effect is more severe in highly birefringent fibres. The polarization induced walk-off is expressed in ps/km and can be derived from the fibre modal birefringence [4, 11]. The measurement of the fibre beat length, as reported in section 2.3.3.4, yielded a relative delay between the two polarization components of ~0.86 ps/m at 1550 nm. Although this time delay seems substantial, it will be shown that, for the actual experimental conditions, this relative delay did not introduce broadening of the pulse at the output of the KS.

To perform the KS experiment, a free-space polarizer (Fig. 3.9) was initially inserted before the fibre and the two principal polarization axes of the fibre were determined using the procedure described in section 2.2.2. After the principal axes were identified, the axis of the input polarizer was set at 45° relative to them and the probe was turned on. By placing a power meter just after the input polarizer and with suitable adjustment of the polarization controller at the probe port, it was straightforward to align the probe signal to the axis of the polarizer, i.e. the probe signal at the input of
the fibre had a linear polarization at 45° relative to the fibre principal axes, as required for KS operation. At the output of the fibre, the probe was selected by the use of a 3 nm BPF and was passed through two successive stages, each consisting of a polarization controller, an EDFA, a BPF and a polarizer. By adjustment of the polarization controllers PC3 and PC4, the polarizers at the output of the fibre (polarizers 1 and 2, Fig. 3.9) blocked the probe transmission in the absence of the pump. The polarizers employed in the two stages had an extinction ratio of 18 dB and 24 dB respectively; hence it was essential to use both of them for sufficient suppression of the CW probe component. The axis of the input polarizer was then adjusted so as to become aligned to one of the fibre principal axes and the pump was turned on. By adjustment of the polarization controller at the pump port (PC2, Fig. 3.9), a linear polarization aligned to one of the fibre principal polarization axes was achieved for the pump signal. It should be noted that, for this experiment, it was not critical to identify the fast/slow axis of the fibre, although this could easily have been achieved by slightly modifying the setup to an interferometric configuration [20]. The input polarizer was then removed and the signal at the output of the setup was examined. After propagation through the SF57-HF, the pump caused an intensity dependent change in the state of polarization of the probe, therefore a wavelength-converted signal at the probe wavelength was obtained at the output of the setup.

3.2.3 Experimental results

The received spectrum at the output of the SF57-HF is presented in Fig. 3.10. Clear sidebands arising from XPM are observed at the probe wavelength. For comparison, the output probe spectrum in the absence of the pump is also shown.
The received spectra after each of the two polarizers are shown in Fig. 3.11. It can be seen that the combination of the two polarizers could effectively suppress the CW probe beam, in the absence of the pump, and transform the XPM-induced nonlinear phase shift to intensity modulation, hence a wavelength-converted signal at the probe wavelength was obtained at the output of the setup. The pulsewidth of the wavelength-converted output was determined through the use of SHG-based autocorrelation measurements. An output pulse of 2.2 ps FWHM, i.e. almost identical to the input pump pulsewidth, was measured (Fig. 3.12).
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Figure 3.11: The received spectra prior to the two polarizers and after each one of them. The combination of the two polarizers effectively suppresses the CW probe.

The short width of the output pulses can be understood by considering the chromatic dispersion induced walk-off in the fibre. The low GVD, in combination with the low dispersion slope of the fibre used in the experiment, yields a walk-off length of ~12 m, i.e. much longer than the physical length of the SF57-HF. (Note that, even if the wavelength separation between the pump and probe was 30 nm, the walk-off length would be only 6 m). The significance of these figures can be appreciated when compared to the values exhibited by other highly nonlinear soft-glass fibres. For
example, the walk-off length of a step-index bismuth-oxide fibre, similar to the one used in [18] would be just \( \sim 30 \text{ cm} \) for the same conditions as those considered in our experiment, and the pulse-width at the output would inevitably be broadened in KS devices of a similar length to those considered here.

![Figure 3.12: SHG intensity autocorrelation traces of the input pump and output wavelength-converted pulses.](image)

The experimental results indicated that the modal birefringence of the employed SF57 HF did not significantly affect the timing window of the KS. To verify this, numerical simulations, which solved the coupled NLSEs by applying the split-step Fourier method (SSF) [4], were carried out. The electric field of the probe was analyzed into two polarization modes, one parallel and one perpendicular to the pump. In this way, three coupled NLSEs, describing the propagation of the pump beam and the two orthogonal components of the probe beam, were formed [4, 16]

\[
\frac{\partial A_p}{\partial z} + \frac{i}{2} \beta_{2,p} \frac{\partial^2 A_p}{\partial T^2} + \frac{\alpha}{2} A_p = i \gamma A_p \left( |A_p|^2 + \frac{2}{3} |A_{pr(y)}|^2 + 2 |A_{pr(x)}|^2 \right) \tag{3.10a}
\]

\[
\frac{\partial A_{pr(x)}}{\partial z} + d_{pr(x)} \frac{\partial A_{pr(x)}}{\partial T} + \frac{i}{2} \beta_{2,pr(x)} \frac{\partial^2 A_{pr(x)}}{\partial T^2} + \frac{\alpha}{2} A_{pr(x)} = i \gamma A_{pr(x)} \left( |A_{pr(x)}|^2 + \frac{2}{3} |A_{pr(y)}|^2 + 2 |A_{pr(z)}|^2 \right) \tag{3.10b}
\]
\[
\frac{\partial A_{pr(y)}}{\partial z} + d_{pr(y)} \frac{\partial A_{pr(y)}}{\partial T} + i \frac{\beta_{2pr(y)}}{2} \frac{\partial^2 A_{pr(y)}}{\partial T^2} + \frac{\alpha}{2} A_{pr(y)} = i \gamma A_{pr(y)} \left( \left| A_{pr(y)} \right|^2 + \frac{2}{3} \left| A_{pr(x)} \right|^2 + \frac{2}{3} \left| A_{pr(x)} \right|^2 \right) \tag{3.10c}
\]

where \( A_j \) is the slowly varying field, \( \alpha \) is the propagation loss, \( \gamma \) is the nonlinear parameter, \( \beta_{2j} \) is the second order derivative of the propagation constant, \( T \) is time measured in a reference frame moving with the pump pulse, i.e. \( T = t - \beta_{1p} \) where \( \beta_{1p} \) is the first order derivative of the propagation constant at the pump wavelength, \( d \) is the relative group-velocity mismatch, i.e. \( d = \beta_{1j} - \beta_{1p} \), and the index \( j = p, pr(x), pr(y) \) denotes the pump wave, the parallel to the pump probe wave and the perpendicular to the pump probe wave respectively. It was assumed that the strength of the XPM effect was twice as effective as SPM for parallel polarization couplings. For orthogonal-polarization couplings, the relative factor was considered to be 2/3 [4, 16]. Furthermore, the coherent coupling between the two polarization components of the probe leading to degenerate FWM was ignored, on the basis that in highly birefringent fibres, with a beat length much smaller than the fibre length, its contribution averages to zero [ref. 4, pages 206-208]. Since the fibre employed in the experiment had a very small beat length \( (L_B \sim 6 \text{ mm}) \), almost 350 times less than the actual fibre length, this was considered as a valid assumption. Moreover, due to the low intensity of the probe relative to the pump and the reduced efficiency of the XPM effect for orthogonal polarization couplings, the contribution of the nonlinear terms originating from XPM between the orthogonal polarization probe components was ignored in Eq. 3.10b-c. For the same reasons, the contribution of the nonlinear terms originating from the probe on the pump pulse propagation could also be ignored in Eq. 3.10a. In this way, Eq. 3.10a-c could be decoupled, taking the simplified form [4, 16]

\[
\frac{\partial A_p}{\partial z} + i \frac{\beta_{2p}}{2} \frac{\partial^2 A_p}{\partial T^2} + \frac{\alpha}{2} A_p = i \gamma A_p \left( \left| A_p \right|^2 \right) \tag{3.11a}
\]

\[
\frac{\partial A_{pr(x)}}{\partial z} + d_{pr(x)} \frac{\partial A_{pr(x)}}{\partial T} + i \frac{\beta_{2pr(x)}}{2} \frac{\partial^2 A_{pr(x)}}{\partial T^2} + \frac{\alpha}{2} A_{pr(x)} = i \gamma A_{pr(x)} \left( \left| A_{pr(x)} \right|^2 + 2 \left| A_{pr(x)} \right|^2 \right) \tag{3.11b}
\]
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By numerically solving Eq. 3.11a, the propagation of the pump pulses was simulated. The parallel and perpendicular components of the probe could then be estimated by solving Eq. 3.11b-c using the calculated propagation profile of the pump pulses. The wavelength-converted pulse waveform was then obtained from the probe transmissivity function $T$, which is provided by the relation [4, 11, 16]

$$T = \sin^2(\Delta\phi / 2)$$  \hfill (3.12)

where $\Delta\phi$ is the phase difference between the two orthogonal components. To solve Eq. 3.11a-c, it was assumed that the modal birefringence resulted in different group-velocities for the two orthogonal probe components, i.e. $\beta_{1pr(x)} \neq \beta_{1pr(y)}$, while the second order derivative of the propagation constant remained unaltered. Furthermore, the chromatic dispersion of the differential group-delay (DGD) was ignored. In this way, the absolute value of the difference between $\beta_{1pr(x)}$ and $\beta_{1pr(y)}$ was equal to the DGD. Under these assumptions and using parameter values corresponding to the actual experimental conditions and measured fibre characteristics, the pulse-width of the wavelength-converted signal was numerically estimated.

Assuming the pump was aligned to the fast axis of the fibre, the simulations yielded a wavelength-converted pulse of ~2 ps FWHM at the output of the polarizer (an infinite extinction ratio was assumed for the polarizer), as shown in Fig. 3.13a. Note that the pulse in Fig. 3.13a is offset in time, since Eq. 3.11a-c were solved for a time frame moving with the group-velocity of the pump. A slight asymmetry in the pulse and a ringing near the trailing edge are evident. Both features can be attributed to the DGD induced walk-off between orthogonal polarization couplings. In the case that the pump was aligned to the slow axis of the fibre, the corresponding FWHM value of the output pulses was again ~2 ps (Fig. 3.13b). The pulse was again slightly asymmetric, but the ringing near the trailing edge disappeared, since the chromatic dispersion induced walk-off between the pump and probe wavelengths partially compensated for the DGD-induced walk-off (note that the fibre had a normal dispersion in the C-band and the pump was placed at a longer wavelength relative to the probe). When the
effect of DGD was not included, a wavelength-converted pulse showing no evidence of asymmetry was obtained (Fig. 3.14a). For optimum probe transmittance (theoretically reaching 100% if fibre propagation loss is neglected) to be achieved, a phase difference of $\pi$ between the two orthogonal polarization components of the probe would be required. Simulations predict that a pump peak power of $\sim$12.4 W would be sufficient to induce complete switching, resulting in an output pulse with a FWHM of $\sim$2.4 ps (Fig. 3.14b).

The difference between the simulated and experimental wavelength-converted pulse-widths can be attributed to the assumptions of the numerical modelling and the conditions of the performed experiment, i.e. the propagation of the wavelength-converted pulses through additional SMF length and spectral filters. The numerical simulations confirmed that the low dispersion of the fibre ensured negligible pump pulse broadening, therefore favouring the realization of a short timing window. This is a major advantage of compound-glass HF s over step-index compound-glass HNLFs; the high dispersion of compound-glass HNLFs in the C-band induces a rapid pump pulse broadening that inhibits the formation of short wavelength-converted pulses [16].
Figure 3.13: Output wavelength-converted pulse predicted from numerical simulations for the case when (a) the pump is aligned to the fast axis of the fibre and (b) the pump is aligned to the slow axis of the fibre. The values of the parameters used in the simulations correspond to the experimental conditions.
The performance of the wavelength converter was experimentally assessed both in terms of eye diagrams and BER tests. In Fig. 3.15a the eye diagram corresponding to the input pump is compared to the received eye diagram at the probe wavelength. A clear converted eye diagram is observed, with some intensity noise that can be attributed to the accumulation of ASE through the two amplification stages at the
output of the system. The corresponding BER tests are presented in Fig. 3.15b. The power penalty of the wavelength-converted signal relative to the input signal is $\sim 3$ dB at a BER of $10^{-9}$. Since the operation in the normal dispersion regime of the fibre discourages the onset of any modulation instability effects, this power penalty is associated with a leakage CW power at the probe wavelength due to the finite extinction ratio of the polarizers and the accumulation of ASE noise induced from the two amplifiers at the output of the system, as mentioned above.

It is anticipated that improvements in the fabrication process of compound-glass HFs can significantly decrease the propagation losses and enable the realization of designs with higher $\gamma$ values, hence decreasing the length requirements even further. Using the SEST approach, it is possible to fabricate fibres with even lower dispersion and dispersion slope in the C-band, thus reducing the time window even further. Furthermore, since the non-optimised light coupling into and out of the SF57 SEST HF dictates the use of two optical amplifiers at the output of the set-up, it is expected that the utilization of compound glasses which can be spliced to standard SMFs for the fabrication of compound-glass HFs will greatly improve the BER performance of future KS configurations.

![Input and Output Eye Diagrams](image)

**Figure 3.15:** (a) Eye diagrams of the input and output pulses (b) Corresponding BER curves.
3.3 Conclusions

In this Chapter, the use of a 2.1 m-long SF57 SEST HF in two particularly attractive XPM-based wavelength conversion configurations was presented.

The first technique relied on the use of optical filtering for the transformation of XPM-induced phase modulation to intensity modulation. Tunable, error-free operation with a power penalty in the receiver’s sensitivity below 1 dB was demonstrated. The normal dispersion of the employed fibre in the C-band favoured the performance of the wavelength converter, since it avoided signal degradation from modulation instability issues. Furthermore, the low dispersion and relatively low dispersion slope of the employed fibre, in combination with the short length used, eliminated the effects of walk-off and resulted in similar behaviour for large pump-probe detunings. The simplicity and robustness of this scheme, in combination with the compactness offered by compound-glass HF technology, make it a good candidate for practical all-optical wavelength conversion applications.

The second approach was based on the nonlinear birefringence induced by XPM. To transform XPM-induced nonlinear phase-shift into intensity modulation, a KS configuration was implemented. The short length of the fibre in combination with its low dispersion resulted in a performance extremely tolerant to walk-off, hence allowing for a timing window as small as 2.2 ps to be achieved in our experiment.

Between the two configurations, the one based on XPM and optical filtering is simpler and easier to implement and monitor. More importantly, for suitably chosen peak power conditions, this scheme provides the opportunity to combine wavelength conversion with amplitude noise suppression [6]. On the other hand, this approach requires the generation of sufficiently wide XPM-induced sidebands, so as to allow positioning the optical filter far enough to ensure effective suppression of the CW probe, while at the same time enabling the use of an optical filter with a bandwidth wide enough to achieve a narrow output pulsewidth (ideally similar to the input pulsewidth). Moreover, the converted signal is wavelength shifted compared to the input probe signal, and this might be undesirable in real applications. With regard to the KS configuration, it is more demanding in terms of implementation complexity
and performance monitoring, especially since random variations of temperature and pressure may cause fluctuations of the linear phase shift, hence requiring continuous adjustment of the output polarization controller employed for linear phase shift compensation. Nevertheless, the KS configuration allows for short timing windows to be achieved, while at the same time enables the generation of a wavelength converted signal at the exact probe wavelength, without imposing an undesirable wavelength shift.

In conclusion, both configurations highlight the potential of compound-glass HF technology in the realization of compact and ultrafast time response XPM-based applications. It is anticipated that improvements in the fabrication process of SEST compound-glass HFs can significantly decrease the propagation losses and enable the realization of designs with even higher $\gamma$ values, hence further decreasing the power-length requirements of such devices. By identifying suitable fibre designs that can combine a higher nonlinear coefficient with a flat dispersion profile, so as to eliminate walk-off effects, a wavelength-insensitive operation can potentially be realised.
References


Chapter 4

Parametric processes based on four-wave mixing in lead-silicate holey fibres

4.1 Wavelength conversion based on stimulated four-wave mixing

In Chapter 3, the XPM effect in optical fibres was employed for the realization of all-optical wavelength conversion. While the demonstrated devices were simple and relatively robust, operation at higher bit rates raised the power demands dramatically, since intensity-modulated signals were required. FWM in optical fibres is an alternative nonlinear effect that can be exploited for the implementation of all-optical wavelength conversion. The main advantage of FWM-based approaches is the transparency they offer, both in terms of modulation format and bit rate [1].

Key parameters contributing to a broadband and highly efficient FWM process are a high effective nonlinearity per unit length, a low GVD with a low dispersion slope and a short fibre length [2, 3]. A high effective nonlinearity provides the means for a highly efficient FWM process, leading to enhanced conversion efficiency. By operating close to the ZDW of a fibre with a low dispersion slope, the linear phase mismatch between the interacting waves is decreased, hence operation over a broad wavelength region can be achieved. With regard to the fibre length, it is important to use as a short fibre piece as possible, so as to avoid the longitudinal variance of the ZDW, which is rather unavoidable in long fibres and can greatly deteriorate their FWM response. Furthermore, by using short fibre lengths, the phase decoherence of the interacting waves due to propagation through the fibre is reduced, since the parameter $d\beta L$, which expresses the phase shift acquired by the interacting waves of different propagation constant $\beta$ as they propagate through a fibre length $L$, is reduced. Moreover, the acquired polarization mismatching between the probe and signal beams, which is induced in non-polarization maintaining fibres and leads to degradation of the
conversion efficiency, is greatly reduced when a short fibre is employed in FWM-based applications.

Three different fibre technologies have achieved significant advances in optimizing these key parameters for an efficient FWM process in recent years, namely highly nonlinear silica-based DSFs, silica-based HFs and step-index compound-glass HNLFs. Highly nonlinear DSFs represent the most mature technology, and impressive results have been achieved in terms of the dispersion profiles, leading to the demonstration of FWM-based parametric amplifiers with broad wavelength conversion bandwidths and very high conversion efficiencies [3, 4, 5, 6, 7]. Due to the moderate values of $\gamma$ of highly nonlinear DSFs, several tens of meters are normally required and hence compactness and stability are an issue. Furthermore, local variations in the ZDW throughout the length of the highly nonlinear DSF, which are expected to arise during the fibre fabrication process, drastically decrease the efficiency of the FWM process [8]. The emergence of HF technology has allowed for the fabrication of fibres with a very small effective area, thus enabling an almost four-fold improvement in the achievable values of $\gamma$ and leading to significantly reduced fibre length requirements [9, 10, 11, 12]. Furthermore, the flexibility that HF technology offers ensures that, for suitable fibre designs, this nonlinear coefficient $\gamma$ improvement can be combined with novel dispersion properties. Therefore, broadband and compact FWM-based wavelength converters, using silica based HFs, have been successfully reported. A further drastic increase in $\gamma$, by as much as three orders of magnitude relative to conventional SMFs, has been achieved using compound-glass HNLF technology. This has allowed the required fibre lengths to be reduced to only a few meters (limited by the much higher propagation loss and/or chromatic dispersion in such glasses), offering significant advantages for the system stability and compactness. However, the ZDW of such glasses lies typically at far longer wavelengths than the telecoms band, therefore limiting the bandwidth of the FWM devices to just a few nanometres [13].

Compound-glass HF technology has the potential to become an alternative candidate in FWM-based applications. As presented in Chapter 2, the strand-on-air design (triangular-core design fibres) has enabled the fabrication of fibres with ultra-high values of $\gamma$, albeit with a large anomalous dispersion and/or a large dispersion slope at the 1.55 $\mu$m telecommunications window that is due to the large waveguide dispersion
resulting from the extreme fibre design [14, 15, 16]. Such fibres can lead to conversion efficiency enhancement at the expense of a reduced wavelength conversion bandwidth. On the other hand, the SEST approach (section 1.2.2) has provided the advantage of accurately tailoring the fibre refractive index profile, allowing the fabrication of compound-glass HFs with low dispersion at 1.55 µm (section 2.3.3.3) [17]. Although the achievable $\gamma$ values of these fibres are substantially lower than the corresponding $\gamma$ values of the strand-on-air designs (even for a similar core diameter), the superior dispersion properties of the SEST fibres represent a good performance trade-off.

In this Chapter, experiments on FWM-based wavelength conversion and parametric amplification are presented. At first, a simplified model of FWM under CW or quasi-CW conditions is presented, so as to identify the parameters that determine the efficiency of a parametric amplifier. Emphasis is placed on the different behaviour of a parametric amplifier in the normal and anomalous dispersion region. Then, parametric amplification using a 1 km-long, commercially available, HNLFs of conventional design is experimentally demonstrated and the validity of the approximate derived solutions is verified. The advantages of compound-glass HF technology in FWM-based wavelength conversion and parametric amplification applications are subsequently demonstrated. Using just a 2.2 m-long lead-silicate HF, fabricated with the SEST approach and exhibiting a low dispersion in the C-band (section 2.3.3.3, fibre band #1), a FWM bandwidth of ~30 nm with a conversion efficiency of -6 dB is achieved for pump pulses of the order of 6.2 W. Numerical simulations are used to support the experimental findings and to predict the fibre behaviour for different experimental conditions and fibre parameters. Furthermore, the performance of HF designs, optimized for FWM applications, are presented and the particular implications associated with the design of short-length, compound-glass FWM devices are revealed.
4.1.1 Phase matching and gain profiles in the normal and anomalous dispersion regimes

Quantum-mechanically, FWM occurs by annihilation of two photons from one or two waves and the generation of two new photons at different frequencies. The energy and momentum are conserved during this interaction. In the degenerate case, on which this Chapter will be focused, a single pump is used. If only a pump wave at a frequency $\omega_p$ is incident on the nonlinear medium, then two new waves at frequencies $\omega_s$ and $\omega_i$ can be generated by noise [18]. If a weak signal is launched on the nonlinear medium together with a strong pump, then the signal is amplified and a new wave at frequency $\omega_i$ is generated. Thus, FWM has been used both in wavelength conversion applications, for the generation of new frequencies, and parametric amplification applications [19, 20].

To study the stimulated FWM process in the degenerate case, we assume that a pump wave at frequency $\omega_p$ is launched on a fibre together with a weak signal at frequency $\omega_s$. For the FWM process to be efficient, both a frequency condition and a phase-matching condition have to be satisfied. The frequency condition yields that

$$2\omega_p = \omega_s + \omega_i$$

(4.1)

where $\omega_i$ is the angular frequency of the generated idler wave. Thus, the position of the idler is dictated by the position of the pump and the signal. For the determination of the evolution of the pump, signal and idler fields in the fibre, three coupled equations are derived from the basic propagation equation of electromagnetic waves in a nonlinear dispersive fibre. The resulting NLSEs are quite complex and normally a numerical approach is necessary for their solution. A simplified analysis is possible if CW or quasi-CW conditions are assumed, so that the GVD can be neglected. A further simplification is introduced by assuming that the overlap integrals of all the participating waves are similar. This assumption is normally valid in SMFs. In this way, if the wavelengths of the interacting waves are close enough so that the nonlinear parameter $\gamma$ can be considered to be constant, the resulting NLSEs, written in terms of power and phase, take the following form:

$$\frac{dP_p}{dz} = -aP_p - 4\gamma(P_s^2 P_i) \frac{1}{2} \sin \theta$$

(4.2)
\[
\frac{dP_s}{dz} = -aP_s + 2\gamma (P_p^2 P_s P_i) \frac{1}{2} \sin \theta \\
\frac{dP_i}{dz} = -aP_i + 2\gamma (P_p^2 P_s P_i) \frac{1}{2} \sin \theta \\
\frac{d\theta}{dz} = \Delta \beta_i + \gamma (2P_p - P_s - P_i) + \gamma \cos \theta \left[ \left( \frac{P_p^2 P_i}{P_s} \right)^{\frac{1}{2}} + \left( \frac{P_p^2 P_s}{P_i} \right)^{\frac{1}{2}} - 4(P_s P_i) \frac{1}{2} \right] 
\]

where \( P_s, P_i, P_p \) are the power levels of the signal, idler and pump respectively, \( \alpha \) is the loss parameter and \( \Delta \beta_i \) is the linear phase mismatch [21, 22]. The parameter \( \theta \) represents the relative phase difference between the interacting waves and is provided by the equation

\[
\theta(z) = \Delta \beta_i \cdot z + [ \phi_s(z) + \phi_i(z) - 2 \phi_p(z) ] 
\]

where \( \phi_j(z) \) includes the initial phase at \( z = 0 \) and the acquired nonlinear phase shift. For the special case where an intense pump is launched on a fibre together with a weak signal, in the absence of an idler wave \( (P_i(0)=0) \), it can be proven that \( \theta \) is equal to \( \pi/2 \) at the fibre input port [21]. Thus, power is immediately transferred from the pump to the signal and the idler. Furthermore, assuming that the parametric amplifier is operating close to the phase-matched condition of \( \theta = \pi/2 \), the second term on the right hand of the equation can be neglected, hence \( d\theta/dz \) can be approximated by

\[
\frac{d\theta}{dz} = \Delta \beta_i + \gamma (2P_p - P_s - P_i) \approx \Delta \beta_i + 2\gamma P_p 
\]

If the propagation constant \( \beta(\omega) \) is expanded in Taylor series up to the third order around the ZDW (i.e. the fourth-order dispersion is ignored), then the following approximate relation for the linear phase mismatch \( \Delta \beta_i \) can be reached

\[
\Delta \beta_i = -\frac{2c \pi}{\lambda^2} \frac{dD}{d\lambda} (\lambda_p - \lambda_0)(\lambda_p - \lambda_s)^2 
\]

where \( D \) is the dispersion of the fibre, \( \lambda_0 \) its ZDW and \( \lambda_p, \lambda_s \) the pump and signal wavelength respectively [2, 22]. An analytical solution can then be realized under the assumption that the propagation loss of the signal (and idler) wave through the fibre is negligible compared to its FWM-induced gain, while at the same time the gain of the signal (idler) is such that pump depletion is not reached, i.e. \( P_p >> P_s \) through the whole amplifying process. Setting \( dP_p/dz = 0 \) in Eq. 4.2 (i.e. ignoring both pump loss
and pump depletion), the following equations for the signal and idler waves are reached [2, 23]

\[ P_s(L) = P_s(0) \left( \frac{\gamma P_p}{g} \sinh(gL) \right)^2 + 1 \]  
\[ P_i(L) = P_i(0) \left( \frac{\gamma P_p}{g} \sinh(gL) \right)^2 \]

where \( L \) represents the length of the fibre and the parameter \( g \), which controls the parametric gain, is provided by the expression

\[ g = \sqrt{(\gamma P_p)^2 - \left( \frac{1}{2} \frac{d}{dz} \right)^2} = \sqrt{(\gamma P_p)^2 - \left( \frac{1}{2} (\Delta \beta + 2\gamma P_p) \right)^2} \]

The signal gain is thus provided by the expression

\[ G_s = \frac{P_s(L)}{P_s(0)} = 1 + (\gamma P_p L)^2 \left( \frac{\sinh(gL)}{gL} \right)^2 \]

while

\[ G_i = \frac{P_i(L)}{P_i(0)} = (\gamma P_p L)^2 \left( \frac{\sinh(gL)}{gL} \right)^2 \]

Using the simplified set of equations, some useful conclusions can be drawn with regard to the behaviour of a parametric amplifier in the normal and anomalous dispersion regimes. The case of a typical germanosilicate, HNLF with a nonlinear parameter \( \gamma \) of 18 W\(^{-1}\)km\(^{-1}\), a ZDW lying inside the C-band, a dispersion slope of 0.028 ps/nm\(^2\)/km and a length of 1 km is now considered. Setting the pump position in the anomalous dispersion regime at a wavelength detuning of 2 nm relative to the ZDW, the signal and idler gain profiles are examined for various pump powers. It can be seen in Fig. 4.1a and 4.1b, which are based on solving the Eq. 4.12 and 4.13, that both the gain of the signal \( G_s \) and the idler \( G_i \) are largely dependent on the pump power, increasing dramatically as the pump power is increased. It is also important to note the characteristic shape of the gain profiles when the pump is placed in the anomalous dispersion regime. For signals placed in the proximity of the pump wavelength, \( \Delta \beta_i \) is approximately equal to zero (Eq. 4.8), hence \( g \approx 0 \) (Eq. 4.11) and since
the signal gain (Eq. 4.12) is approximately equal to

$$G_s = (\gamma P_p L)^2$$

(4.15)

As the detuning of the signal from the pump is increased, it is obvious from Eq. 4.8 that the negative value of $\Delta \beta_l$ that gradually increases in magnitude will compensate for the positive value of the nonlinear phase mismatch, resulting in reduced net phase mismatch (Eq. 4.7). A reduced net phase mismatch is translated into an increased value of the gain parameter $g$ and hence the gain of the signal (or idler) increases as the signal wavelength is placed further from the pump. This is the case until perfect phase-matching is reached, i.e. $\Delta \beta_l = 2 \gamma P_p$ and $d\theta/dz = 0$. At this point, $g$ is optimized and equals $\gamma P_p$, hence the signal gain $G_s$ reaches its maximum value:

$$G_s = \left[ 1 + \left[ \sinh \left( \gamma P_p L \right) \right]^2 \right] = \left[ 1 + \left[ \frac{e^{(\gamma P_p L)} - e^{(-\gamma P_p L)}}{2} \right]^2 \right] \approx \left[ 1 + \frac{1}{4} e^{2(\gamma P_p L)} - 1 \right]$$

(4.16)

This maximized value of $G_s$ (and $G_i$) causes the peak that is observed in the gain profiles of the signal and the idler in Fig. 4.1a and 4.1b, respectively. Moving to greater signal wavelength detunings, relative to the pump, the magnitude of the net phase mismatch (which now becomes negative) increases and the gain drops again. Furthermore, it is obvious from Eq. 4.7 and 4.8 that the position of the signal wavelength where zero net phase mismatch (and hence optimum signal and wavelength gain) is achieved moves further from the pump as the pump power is increased. Defining the bandwidth of the parametric process as the width of the area between the two lobes where phase-matching is achieved, it becomes apparent that the bandwidth of the amplifier is increased with power. This trend is also confirmed by Fig. 4.1a and 4.1b. In terms of bandwidth efficiency, it is also of critical importance to place the pump wavelength as close to the ZDW as possible. This can be seen in Fig. 4.1a and 4.1b, which show the gain profiles the signal and idler waves as the position of the pump is placed further from the ZDW, from 2 nm up to 5 nm. It is obvious that the lobes where absolute phase-matching is achieved are moved further from the pump wavelength as the pump is placed closer to the ZDW, hence the
bandwidth efficiency of the amplifier is increased for low detunings of the pump relative to the ZDW.

The shape of the signal and idler gain profiles is different when the pump is placed inside the normal dispersion region. This situation is depicted in Fig. 4.2a and 4.2b, where the pump is placed at a negative wavelength detuning of 2 nm relative to the ZDW. Since both the linear and the nonlinear phase mismatch terms (Eq. 4.7 and 4.8) have the same sign when the pump wavelength is in the normal dispersion region, the net phase mismatch increases as the signal wavelength moves far from the pump wavelength. Hence, the signal and idler gains fall monotonically as the detuning of the signal wavelength from the pump wavelength is increased. In this case, it is common to define the bandwidth of the amplification process as the width between the signal wavelength positions where the gain is 3 dB less than its maximum value [10]. As in the case where the pump is placed in the anomalous dispersion region, the gain is
greatly dependent on the pump power, improving dramatically with the pump power. However, this increase in gain comes at the expense of a reduced conversion efficiency bandwidth when the pump wavelength is positioned in the normal dispersion region, as shown in Fig. 4.2a and 4.2b. This behaviour is due to the fact that in the normal dispersion regime, both the linear phase mismatch and the nonlinear power-dependent phase mismatch have the same sign. With regard to the position of the pump wavelength, once again it is of critical importance that this is placed close to the ZDW. This is demonstrated in Fig. 4.2a and 4.2b, where a very sharp decrease of the gain bandwidth is observed as the pump is placed further from the ZDW.

![Figure 4.2: FWM gain profiles when the pump is placed in the normal dispersion region. The FWM gain profiles of (a) the signal wave and (b) the idler wave in relation to (i) the pump power and (ii) the position of the pump relative to the ZDW are presented. The fibre parameters are the same as in Fig. 4.1.](image)

All the simulations presented in this section have neglected any fourth-order dispersion terms. However, it should be noted that the phase-matching behaviour of a fibre with significant fourth-order dispersion exhibits some interesting characteristics. This will be examined in some detail in section 4.1.3.2, where it will be shown that, phase-matching due to the fourth-order dispersion can generate two peaks at the FWM...
gain profiles, which normally appear far away from the main lobes in Fig. 4.1 or the main lobe in Fig. 4.2.

4.1.2 Parametric amplification through four-wave mixing in a highly nonlinear fibre with conventional design

The FWM-induced amplification of low-power signals and the generation of idler wavelengths was studied initially on a germanosilicate HNLF of conventional design. The purpose of the experiment was to validate the simplified FWM model presented in the previous section, as well as to acquire familiarity with parametric effects in fibres, before experimenting with the HFs of particular interest for this project. The HNLF provided a more controlled environment for this purpose. The experimental setup is presented in Fig. 4.3.

![Figure 4.3: Experimental setup for the demonstration of FWM-based parametric amplification in a HNLF with a conventional design. PC: polarization controller.](image)

Two CW lasers that could be tuned inside the C-band were used as the pump and signal sources. The pump was modulated using a LiNbO$_3$ MZM with 100 ps rectangular pulses at a duty cycle of 1:4. The modulated pump passed through an amplification stage, which consisted of a high power amplifier and a 1 nm BPF for out-of-band ASE suppression, and was then combined with the CW signal beam through a 90-10 coupler. At the output of the coupler, the average signal power was –7 dBm while the pump power could be amplified up to an average pump power of 16 dBm, i.e. a peak pump power of 22 dBm. The resulting beam was launched on a 1 km-long HNLF, with nonlinear parameter $\gamma$ of 18 W$^{-1}$km$^{-1}$, a loss of 0.65 dB/km, a dispersion slope of 0.028 ps/nm$^2$/km and a ZDW lying at 1537 nm. For the maximum available pump average power, it was confirmed through spectral measurements that the Brillouin threshold was not reached.
To study the behaviour of the implemented amplifier in the anomalous dispersion regime, the pump was placed at 1540.5 nm. The gain profile of the signal was taken by changing the position of the signal wavelength and measuring the output signal power recorded on an OSA (resolution of 0.2 nm) with and without the pump. The gain profiles were taken for two different peak powers, namely 21.4 dB, and 20.7 dBm, as shown in Fig. 4.4. An improvement in the signal gain of more than 2.5 dB is observed for an increase of 0.7 dB in the pump peak power showing clearly the strong dependence of the FWM gain on the pump peak power. In both cases, the maximum signal gain was more than 11 dB and the FWM bandwidth over 14 nm.

![Figure 4.4](image)

*Figure 4.4:* FWM signal gain profiles of a 1 km-long HNLF with conventional design for a pump peak power of 21.4 dBm (red squares) and 20.7 dBm (blue triangles). A pump increase of 0.7 dB improves the conversion efficiency by ~2.9 dB.

The generation of the idler wave, and hence the use of the setup for wavelength conversion, was also examined. The maximum gain of the idler for a pump power of 21.4 dBm was ~14 dB, with a FWM bandwidth over 16 nm (Fig. 4.5). Therefore, for the powers used in this experiment, the signal and the idler gains are of a similar magnitude, hence the setup could be used equally as an amplifier or a wavelength converter.

Although the HNLF used in this experiment could lead to significant signal amplification and idler wave generation at moderate pump powers, the FWM bandwidth was relatively small. A significant improvement in the fibre performance, in terms of FWM bandwidth, could be achieved by increasing the nonlinearity per unit
length, for example by increasing the concentration of Ge in conventional HNLFs, so as to decrease the required fibre length; or by realizing an appropriate fibre design to further flatten the dispersion slope of the fibre, in order to improve the linear phase mismatch response. With the SEST SF57 HF it was aimed to address both these issues, as will become evident in the following section.

4.1.3 **FWM-based wavelength conversion using a lead-silicate based holey fibre**

4.1.3.1 **Experimental results and fitting with numerical simulation**

The experimental setup for the demonstration of FWM in a SF57 SEST-HF is shown in Fig. 4.6. The setup was slightly different to the one used for the demonstration of FWM in a conventional HNLF (Fig. 4.3), since a free-space launching configuration was employed. Two CW lasers, tunable inside the C-band, were used as the pump and signal sources. In order to achieve peak pump powers of the order of a few watts using a moderate average-power fibre amplifier, the pump was modulated by a LiNbO$_3$ MZM with 100 ps rectangular pulses at a duty cycle of 1:64. The modulated pump and the CW signal beams were amplified by two separate fibre amplifiers. This configuration allowed the independent control of the power of the two beams, and ensured that nonlinear interaction of the two signals occurred only in the SEST-HF. In contrast, if both the pump and the signal were amplified from the same high power
amplifier, a significant FWM effect would have taken place inside the amplifier, inhibiting the correct interpretation of the observed FWM efficiency. After amplification, the pump and signal waves were combined through a 3-dB coupler. The resulting beam was free-space coupled into 2.2 m of the SEST-HF. As reported in section 2.3.3, the loss of the fibre (fibre band #1) was determined to be ~3.2 dB/m, while the value of $\gamma$ was estimated as ~164 W$^{-1}$km$^{-1}$. The estimated coupling efficiency into the SEST-HF was ~28%, leading to a peak pump power into the fibre of ~6.2 W, while the power of the signal was 2.4 mW. At the output of the system, the FWM-induced interaction between the pump and the signal in the SEST-HF gave rise to a clear idler - wavelength converted beam, as shown in Fig. 4.7a. The polarizer was aligned to one of the principal polarization axes of the fibre and the polarization controllers in the signal and pump ports were appropriately adjusted so that the power through the polarizer was maximised, in which case the wavelength conversion efficiency was optimized. As mentioned in section 2.3.3.4, the fibre had the ability to preserve linear polarization along any of its principal polarization axes, with an extinction of ~22 dB between the signals received on the two orthogonal polarization axes at the output of the fibre.

![Figure 4.6: The experimental set-up for the demonstration of FWM in a 2.2m-long SF57 SEST-HF.](image)

The conversion efficiency of the FWM process was measured for two different pump wavelengths, namely 1559.7 nm and 1563.0 nm, and for several signal wavelengths in each case, in order to get a clear measurement of the bandwidth of the FWM process. The selection of the pump wavelengths was based on predictions relying on SEM characterization, numerical modelling and attempted dispersion measurements (section 2.3.3.3), according to which the fibre ZDW lied a little further from the C-band, inside
the L-band. Therefore, to achieve optimum FWM conversion efficiency with the available pump source, the pump wavelength was placed as close to the edge of the C-band as dictated from the source tunability range. Following a definition commonly used in research literature, the conversion efficiency herein is expressed as the ratio of the peak power of the generated idler at the output of the fibre to the power of the input signal (i.e. propagation losses in the fibre are taken into account) [10]. The accuracy of the measurement was improved by subtraction of the leakage ASE power at the idler wavelength induced by the two EDFAs used in the experiment [19]. Since the pump, and hence the idler too, were modulated at a duty cycle of 1:64, the peak power of the idler was ~18 dB greater than the average power recorded on the OSA. The conversion efficiency curves were then obtained from OSA traces after taking into account the attenuation of the signal due to propagation through the fibre (~7 dB in total). The results of the measurements are presented in Fig. 4.7b.

A maximum conversion efficiency of -6 dB was achieved with a 3-dB bandwidth of ~30 nm. The shape of the obtained conversion efficiency curves, i.e. the monotonic decrease of the conversion efficiency with the signal wavelength detuning from the pump, indicates that the fibre dispersion was normal at the pump wavelength, further suggesting that the fibre dispersion was normal throughout the C-band.

The retrieved FWM conversion efficiency curves were fitted using numerical simulations of the FWM process, based on solving the set of Eq. 4.2-4.5. The use of these equations for simulating the FWM behaviour of the fibre is valid under the assumptions that pulse broadening due to second-order dispersion in the fibre was negligible and the parameter $\gamma$ did not change substantially in the wavelength region where the measurements were performed. Indeed, the combination of the low fibre dispersion in the C-band, which was confirmed from independent dispersion measurements using the interferometric set-up (section 2.3.3.3), the short length of fibre employed and the relatively long duration of the input pulses (100 ps) minimized the effect of pulse broadening in the performed FWM experiment. Moreover, the ~28 nm wavelength span over which the measurements were performed justified the approximately constant value of $\gamma$ used to derive the theoretical predictions.
Figure 4.7: (a) Typical spectral trace obtained at the output of the SEST–HF (b) Experimental (symbols) and fitted numerical (solid lines) conversion efficiency curves for a pump power of 6.2 W and two different pump wavelengths (1563.0 and 1559.7 nm).

For the numerical simulation of the FWM system, the same parameters as in the performed experiments were used for the pump power, signal power, fibre length, propagation loss and nonlinear coefficient. As mentioned in section 2.3.3.3, the dispersion of the fibre could not be accurately determined with the interferometric technique. Numerical simulations, based on a full vector finite element method modal solver, revealed that the fibre had a dispersion slope of 0.2 ps/nm²/km around its ZDW, which, unlike the exact ZDW position that was within the range 1530-1600 nm, was largely insensitive to small structural variations. It was hence expected that any uncertainties in the estimation of the sizes of either the core or the holes would affect the accurate determination of $\lambda_0$ of the fibre, while it would leave the dispersion slope unaffected. For this reason, the fitting of the numerical results to the experimental measurements was performed by using the second-order dispersion of the fibre as the
free parameter (a third-order dispersion of 0.2 ps/nm²/km was assumed). A $\lambda_0$ value of ~1582 nm was obtained from this process, fitting well with the values predicted from the SEM characterization of the SEST-HF profile and the associated modelling.

### 4.1.3.2 Numerical simulations of the fibre performance for different parameters

As mentioned in the introduction of section 4.1, parameters such as the length and loss of the fibre or the pump power and wavelength detuning relative to the fibre ZDW can greatly affect the performance of FWM-based applications. In order to gain a better understanding of how the various parameters of the FWM system employing the SF57 SEST HF could be optimized, numerical simulations of its performance for different operation conditions were carried out. The simulations were based on the power-phase form of the coupled Eq. 4.2-4.5. The predicted linear dispersion slope of the fibre in the region 1500-1620 nm justified approximating the fibre dispersion with terms up to the third order, in which case the simplified Eq. 4.8 could be used to describe the linear phase mismatch $\Delta \beta_l$. Subsequent consideration of the fourth-order dispersion term, as presented later in this paragraph, validated this approximation for wavelengths lying inside or close to the C-band.

Initially, the effect of the fibre length $L$ in the performance of the system in terms of conversion efficiency and 3-dB conversion bandwidth was investigated. The simulations were carried out for a pump wavelength of 1563 nm and a pump power similar to the pump power used in the experiment. It becomes apparent from Fig. 4.8a that the propagation loss of the SEST-HF sets an optimum value $L_{opt}$ of the fibre length for maximum conversion efficiency to be realized. This optimum in terms of conversion efficiency $L_{opt}$ value does not depend on the applied pump power but explicitly on the loss of the fibre, representing a trade-off between the FWM-induced conversion efficiency and the loss of the fibre. An approximate analytical expression for $L_{opt}$ can be derived by assuming that the pump wavelength is set close to the ZDW, where the linear phase mismatch is approximately equal to zero (section 4.1.1). Under this assumption and provided that pump depletion can be ignored, it can be shown that the idler gain is maximized for [24]
\[ L_{opt} = \frac{\ln(3)}{a} \]  

Due to the high propagation loss of the employed fibre, \( L_{opt} \) is of the order of just a few meters. In particular, for the fabricated fibre, this optimum length \( L_{opt} \) is \( \sim 1.5 \) m. For the pump conditions used in the experiment, the use of the optimum fibre length corresponds to a maximum conversion efficiency of \(-5.5\) dB. On the other hand, regarding the achievable 3-dB bandwidth of the FWM process, it becomes apparent from Fig. 4.8a that a reduction in the fibre length drastically increases the operational bandwidth, since it improves the phase-matching response of the system. Thus, the use of just \( \sim 0.5 \) m of SEST-HF in the experiments described in the previous section would result in a FWM bandwidth of \( \sim 79 \) nm, which would be enough to cover the entire C-band, however the conversion efficiency in this case would be reduced down to \(-9\) dB. On the other hand, we also observe that the use of \( \sim 0.9 \) m of fibre would result in the same conversion efficiency as we achieved in our experiments, but with an even broader 3-dB bandwidth of \( \sim 53 \) nm.

It has been shown in section 4.1.1 that at the proximity of the pump wavelength, the FWM gain is approximately a function of the square of the pump power. Hence, the conversion efficiency can be greatly improved by increasing the input pump power. However, this increase in conversion efficiency comes at the expense of reduced bandwidth, as shown in Fig. 4.8b (see also Fig. 4.2). This behaviour is due to the operation of the wavelength converter in the normal dispersion regime, where both the linear phase mismatch and the nonlinear power-dependent phase mismatch have the same sign (section 4.1.1).
Figure 4.8: Dependence of the conversion efficiency (solid lines) and the 3 dB-wavelength conversion bandwidth (dashed lines) on: (a) the SEST-HF length for a 6.2 W pump placed at 1563 nm (b) the pump power for a 2.2 m-long SEST-HF and a pump wavelength of 1563 nm. The experimentally measured values of conversion efficiency and bandwidth are also presented (triangular symbols). The following colour convention applies to the graphs: red lines -> fabricated 3.2 dB/m loss SEST-HF, blue lines -> 2.0 dB/m loss SEST-HF.

The bandwidth of the FWM process can be greatly improved if the pump wavelength is positioned closer to the fibre’s ZDW $\lambda_0$. This is demonstrated in Fig. 4.9a. Placing the pump 5 nm away from the ZDW, a 3-dB bandwidth over 50 nm can be achieved for pump peak powers of a similar order to the pump power used in the experiments presented.

It should be noted that in the simulations used to obtain the results of Fig. 4.9a, the approximation of a linear dispersion slope has been considered, hence the fourth-order dispersion term has not been taken into account. Due to the fourth-order dispersion term, two narrow phase-matching peaks are expected to appear in the conversion efficiency curves. For the case when the pump wavelength is placed far from $\lambda_0$, these two peaks, corresponding to phase-matching due to the fourth-order dispersion, normally appear far from the pump wavelength. On the other hand, these peaks appear inside the main lobe of the conversion efficiency curves when the pump is placed very close to $\lambda_0$, in which case it is difficult to define a 3 dB conversion efficiency bandwidth.
The validity of the linear dispersion slope approximation in the case of the SF57 SEST HF was tested by performing numerical simulations where the exact fourth-order dispersion term was considered, as predicted from numerical simulations based on a full vectorial finite element method modal solver. In Fig. 4.9b and 4.9c, the cases of a pump detuning of 19.5 nm, corresponding to the experimental measurements for a pump placed at 1563 nm, and 5 nm are presented for the fabricated fibre. The phase-matching peaks are not incorporated into the main lobe, hence the approximation of linear dispersion slope can be considered valid. Therefore, for the pump peak power-fibre loss scenarios presented in Fig. 4.9a, the fourth-order dispersion does not lead to significant alteration of the conversion efficiency curves. On the other hand, in the vicinity of \(\lambda_0\) (<3 nm), the fourth-order dispersion term significantly affects the shape of the obtained conversion efficiency curves. This is shown in Fig. 4.9d, where the case of a pump detuning of 2 nm is considered. Clearly, it is difficult to define a 3 dB conversion efficiency bandwidth in this case.

With regard to phase-matching due to the fourth-order dispersion term, it should be noted that it has been proposed by M. Hirano et. al. to use the associated phase-matching peaks for selective wavelength conversion [25]. Indeed, by changing the position of the pump, the position of the phase-matching peaks can be tuned over a broad wavelength region. In Fig. 4.9e, the expected positions of the phase-matching peaks for three different pump positions are presented, showing clearly that SEST SF57 HFs could be used in tunable selective wavelength conversion applications. It is important to note that in such applications stability in the position of the ZDW is of critical importance. By using highly nonlinear soft-glass HFs, the fibre length requirements could be minimized, ensuring better core diameter and environmental stability, hence a more accurate prediction of the fibre response.
Figure 4.9: (a) Dependence of the 3 dB conversion bandwidth on the pump wavelength for a 2.2 m-long SEST-HF and pump powers of 6.2 W (blue and red lines) and 2 W (pink and cyan lines). The red and pink lines correspond to the fabricated 3.2 dB/m loss SEST-HF, while the blue and cyan lines correspond to a 2.0 dB/m loss SEST-HF. The measured values of 3 dB-bandwidth are also presented (triangles); Conversion efficiency curves for a 2.2 m-long SEST-HF and a pump of 6.2 W placed at (b) 1563 nm, (c) 1577.5 nm and (d) 1580.5 nm, with (red line) and without (blue line) the inclusion of the fourth-order dispersion parameter; (e) Phase-matching peaks appearing due to the fourth-order dispersion term for different pump power positions.
It has been shown in section 2.3.2.1 that the fabrication of SF57 HFs, with much smaller core diameters compared to the HF used here and a propagation loss as low as 2 dB/m, is possible. It is therefore reasonable to expect that improvements in the fabrication process can result in similar loss performance for SF57 HFs fabricated using the SEST method. For this reason, numerical simulations of the FWM-induced wavelength conversion were performed for a fibre with similar characteristics to the one used in the experiments but considering a lower propagation loss of 2.0 dB/m. It can be seen from Fig. 4.8a that, for the same fibre length and experimental conditions, an improvement of ~4.8 dB in the conversion efficiency could be achieved compared to the experimental results. It should be noted that for such a propagation loss performance the fibre length for optimum conversion efficiency becomes ~2.4 m, very close to the actual length used in our experiments and in agreement with Eq. 4.17. For this fibre, a conversion efficiency of 0 dB could be achieved for a pump power of 7.2 W. With regard to the 3-dB conversion efficiency bandwidth, the performance of this lower loss fibre would be only slightly degraded compared to the one used in the experiments for the same pump power and wavelength (Fig. 4.8a, 4.8b and 4.9a). This behaviour stems from the fact that for the lower loss fibre and for the same dispersion characteristics, the nonlinear phase becomes larger, therefore the phase mismatch deteriorates more rapidly.

4.1.3.3 Numerical simulations of the four-wave mixing performance of improved fibre designs

By small modifications of the structural parameters of the fibre design compared to the fabricated SEST-HF, fibres with a $\lambda_0$ wavelength inside the C-band, a low dispersion slope and higher values of nonlinearity per unit length can be realized. Using an inverse design procedure, several such SEST designs were identified. A good compromise between dispersion slope and nonlinearity could be offered by a fibre with a design similar to the fabricated one but with a hole-to-hole distance $\Lambda$ equal to 1.15 µm and a hole size $d$ of 0.65 µm. This fibre would exhibit a $\lambda_0$ at 1550 nm, a dispersion slope of -0.2 ps/nm$^2$/km, a dispersion profile as shown in Fig. 4.10b, and a $\gamma$ value of 763 W$^{-1}$km$^{-1}$. Numerical simulations were performed to assess the performance of this fibre, assuming a loss of 2 dB/m and a length of 2.2 m. Higher
order dispersion terms were more significant in this case, and hence they were taken into account in these simulations. For a 2 W pump placed at 1547.5 nm, a positive conversion efficiency up to 7.2 dB could be achieved over a bandwidth sufficiently broad to cover the entire C-band (Fig. 4.10a). Such a fibre could be used both in wavelength conversion and parametric signal amplification applications, enabling the realization of compact broadband nonlinear devices.

![Figure 4.10](image)

**Figure 4.10:** (a) Conversion efficiency curves of the optimized SEST-HF for a pump placed at 1547.5 nm and pump powers of 1.5 W (dashed line) and 2 W (solid line). The inset depicts the microstructure design of the fibre. (b) The dispersion profile of the optimized SF57 SEST HF.

Using the SEST approach, fibre designs optimized in terms of dispersion flatness inside the C-band can also be realized. Such a design, as identified by using an inverse design procedure, would be similar to the inset of Fig. 4.10a, but with a hole-to-hole distance $\Lambda$ equal to 1.31 $\mu$m and a hole size $d$ of 0.63 $\mu$m. A fibre with this design parameters would exhibit two closely spaced ZDWs, positioned at 1440.5 and 1598.5 nm, and a very flat profile in the C-band, ranging from 2.7 ps/nm/km at 1530 nm
down to 1.8 ps/nm/km at 1565 nm (Fig. 4.11a). Having a small core, the fibre would be highly nonlinear, with an expected $\gamma$ value of $\sim 526$ W$^{-1}$km$^{-1}$. Such a fibre would be ideal for XPM-based applications, where the walk-off effect between the pump and probe signals can significantly affect the system performance. The FWM performance of this design was assessed from numerical simulations, assuming a loss of 2 dB/m and a length of 2.2 m. A dual-pump configuration was considered, with the two pumps placed at 1540 nm and 1557 nm and carrying a power of 1 W each. It can be seen in Fig. 4.11b that this fibre would be able to provide transparent wavelength conversion over the entire C-band, while for even higher pump powers it could also be used for signal amplification.

![Figure 4.11:](image)

**Figure 4.11:** (a) Dispersion profile of a SEST-HF exhibiting a flat dispersion inside the C-band and (b) numerically predicted conversion efficiency curve for a dual-pump configuration, with the pumps placed at 1540 nm and 1557 nm and having a power of 1 W each.
4.2 Generation of correlated photons based on spontaneous four-wave mixing in a lead-silicate holey fibre

4.2.1 Generation of quantum entanglement using optical fibres

Quantum cryptography has recently attracted much attention, since it promises extremely secure and robust communications [26, 27]. In traditional cryptography, security is largely dependent on the generation of a key under the application of complex mathematical algorithms. The computational complexity of the key minimises the probability of an eavesdropper deciphering the encrypted messages. On the other hand, in quantum cryptography security is based on the fact that any eavesdropper attempting to read the transmitted information would inevitably disturb its state, hence any attempt of eavesdropping could be detected. In quantum cryptography eavesdropping is viewed essentially as a measurement that is performed on a system and alters the transmitted data (due to the non-cloning theorem), hence malicious interception of the transmitted information is detected and communication can be ceased [28].

The generation of quantum entanglement between physically separated systems is of prime importance for the realization of quantum cryptography applications [26, 27, 28]. The majority of the demonstrated quantum cryptography applications have relied on polarization entanglement through the creation of correlated photons by spontaneous parametric downconversion in $\chi^{(2)}$ crystals [29, 30]. The high nonlinearity of $\chi^{(2)}$ crystals favours the production rate of correlated photons. However, the wideband behaviour of such crystals results in low brightness per nanometre per single-mode correlated photon sources, while mode mismatching seriously affects the coupling efficiency to optical fibres, impeding the application of $\chi^{(2)}$ crystals in quantum communication applications [31]. The coupling problem can be obviated if the correlated photons are generated in the optical fibre itself. Furthermore, although the $\chi^{(3)}$ nonlinearity of optical fibres is normally small compared to the $\chi^{(2)}$ nonlinearity of crystals, optical fibres can combine tight light confinement with long interaction lengths, giving rise to strong nonlinear effects.
For correlated photons generation in optical fibres, the nonlinear effect of spontaneous FWM has been recently proposed. By using long lengths of DSFs, correlated photon sources of high production rates have been demonstrated [32, 33, 34, 35]. Initial approaches relied on pumping these fibres close to the ZDW in the anomalous dispersion regime. In these implementations, a big number of accidental coincidences, i.e. simultaneous detection of photons that do not belong in a correlated pair, was observed. These high accidental coincidence rates arise mainly due to the fact that for peak powers in the order of a few Watts, spontaneous FWM gives rise to an idler and a signal wave that are placed relatively close to the pump wavelength. Therefore, accidental coincidences can be generated from mechanisms such as pump leakage due to imperfect filtering, spontaneous emission of the pump and mainly spontaneous Raman scattering [31]. A high rate of accidental coincidences limits the quality of the correlated photons generated by spontaneous FWM and hence it is detrimental to quantum cryptography applications. The accidental coincidence counts could be significantly reduced if the generated signal and idler photons lied at wavelengths far from the pump wavelength [31]. For example, a signal- and idler- to- pump detuning exceeding 100 nm would result in photon pairs being generated away from the peak of the Raman gain and, with appropriate tuning, away from high-order Raman gain peaks as well. Such a wavelength separation between the pump and signal/idler wavelengths would also enable efficient filtering of the idler and signal photons from each other as well as from the pump photons.

A correlated photons fibre-based source would greatly benefit from the use of fibres with a high nonlinear parameter $\gamma$. Compared to SMFs or DSFs, HNLFs enhance the correlated photon pairs’ production rate [36] and, when pumped close to their ZDW in their anomalous dispersion region, allow for a larger wavelength separation between the signal and idler beams. Under the assumption that a classical treatment of the spontaneous FWM effect can degenerate into the case of stimulated FWM initiated by noise [18, 36], the higher production rate of correlated photon pairs in HNLFs can be justified from Eq. 4.12 and 4.13, which show that the signal and idler gain greatly benefit from a high nonlinear parameter $\gamma$. Moreover, it has been recently shown that it is possible to generate very widely spaced parametric gain peaks by pumping fibres in their normal dispersion regime, close to their ZDW $\lambda_0$ [31]. The generated signal and idler wavelengths in this case can have a separation exceeding several hundred
nanometres. The freedom to shift the ZDW of fibres, so as to generate nonlinear processes by pumping from available laser sources, and to choose specific phase matched idler and signal wavelengths by adjustment of the fibre parameters, in order to avoid high order Raman bands, requires accurate tailoring of the fibre dispersion properties. Therefore, the use of small-core HF s has been recently proposed for the generation of correlated photons [31, 37, 38, 39, 40]. The high achievable $\gamma$ in these fibres allows for a large correlated photons production rate [36], while the design flexibility of MOFs enables accurate dispersion tailoring, hence fibres with a ZDW lying at convenient wavelengths, where high power lasers are available, can be realized.

Compound-glass HF s could in principle greatly enhance the performance of correlated photons fibre-based sources. For example, a compound-glass HF with a nonlinear coefficient a thousand times greater than a SMF would require a thousand times less power to achieve the same correlated photon pairs production rate [31]. This reduction in pump power is effectively translated into a reduced number of Raman scattered photons, hence both the power requirements and the performance of the correlated photons source is improved. In this section, a study of the use of compound-glass HF s with an ultra-high nonlinearity over 1000 $W^{-1}km^{-1}$ for the generation of correlated photons through spontaneous FWM is provided. The theoretical predictions regarding the phase-matching curves are presented and an experimental demonstration of the wide wavelength separation between the signal and idler wavelengths that such a fibre can provide is demonstrated. Finally, the practical issues regarding correlated photon generation using compound-glass fibres are identified and solutions are proposed.

The experiments presented in this section were performed in collaboration with Dr. Alan Migdall and Dr. Jay Fan, members of the Optical Technology Division group of the National Institute of Standards and Technology (NIST-USA), with research experience in the area of correlated photons. The implementation of the experimental set-up and the acquisition of the presented measurements were performed by me and Dr. Fan at the optical technology laboratory of NIST, in USA, during a short-term visit.
4.2.2 Theoretical prediction of the performance of small-core lead-silicate holey fibres in a spontaneous four-wave mixing based correlated photons application

The production rate of correlated photons at the signal and idler wavelengths through spontaneous FWM in an optical fibre depends on the pump power, the length of the employed fibre and its nonlinearity. In particular, for a lossless fibre, a CW single pump configuration and low signal gain conditions, it can be shown that a quantum mechanical treatment of spontaneous FWM for vacuum input signal and idler waves gives an average photon number per mode of \((\gamma P_p L)^2\) for both the signal and idler beams in the case of absolute phase-matching \((d\theta/dz = 0\) in Eq. 4.7) [36]. Therefore, HNLFs are desired in correlated photons applications since they enable high production rates of correlated photons to be achieved for lower pump powers and/or shorter fibre lengths, thus favouring the compactness, robustness and environmental stability of the implemented correlated photon sources.

Amongst the various fabricated compound-glass fibres presented in Chapter 2, the triangular-core SF57 HFs had the highest nonlinearity, combining the high nonlinear refractive index of SF57 glass with the tight mode confinement offered by the triangular-core HF design. Indeed, as it can be seen in Fig. 4.12a, where the predicted by numerical simulations nonlinear parameter \(\gamma\) is plotted as a function of the core diameter of SF57 HFs, extreme values of \(\gamma\) can be achieved in small-core SF57 HFs. Note that these calculations were performed using a full-vector modal solver, based on the finite element method, with data acquired from real SEM images of the fabricated fibres (simulations performed by Dr. Finazzi). Furthermore, the fabricated triangular-core SF57 HFs also exhibited the lowest propagation loss among the various fabricated fibres. In Fig. 4.12b, the measured loss profile of the 1.2 \(\mu\)m core fibre over the wavelength range spanning from \(\sim 600\) nm to \(\sim 1600\) nm is presented. Due to their high nonlinearity and relatively low loss, the use of these fibres in a correlated photons generation application was studied.
Figure 4.12: (a) Predicted nonlinear parameter $\gamma$ of SF57 triangular-core fibres at 1.0 $\mu$m and 1.55 $\mu$m (b) Experimental loss profile of the SF57 HF with triangular-core design and a core diameter of 1.2 $\mu$m. (c) Predicted dispersion characteristics of the triangular-core HF for different core diameters (courtesy of Dr. Julie Leong).
In Fig. 4.12c, the predicted dispersion characteristics of triangular-core SF57 HFs of different core diameters are presented. It can be seen that, as the core diameter is increased, the ZDW is moved towards longer wavelengths. For enclosed core diameters in the region between 0.9 to 1.4 µm, the ZDW lies between 950 nm-1080 nm. Hence, a tunable source operating in the region between 0.9-1.1 µm would be suitable for pumping these fibres, leading to efficient generation of correlated photons.

If a single CW source is launched on a fibre, the idler and signal waves generated from spontaneous FWM appear at those wavelengths for which phase-matching is achieved, i.e. $\Delta \beta_l = 2\gamma P$, where $\Delta \beta_l$ is the linear phase mismatch caused by the dispersion of the fibre, $P$ is the pump power and $\gamma$ is the nonlinear coefficient [39, 40]. Normally, in correlated photons generation applications, a pulsed pump source is used, so as to increase the ratio of correlated to uncorrelated photons. This improved performance stems from the reduction of the SBS effect, which is greatly decreased as the bandwidth of the pumped source increases. SBS gives rise to uncorrelated photons, hence it should be avoided in quantum entanglement applications [36].

To study the behaviour of the SF57 HFs in correlated photons applications, their phase-matching response was simulated for different peak pump powers and pump wavelengths positions. Higher order dispersion terms up to the sixth-order (i.e. $\beta_6$) were considered in the numerical simulations. The results are presented in Fig. 4.13a. It can be seen that the fibre phase-matching response greatly depends on whether the pump is placed in the anomalous or the normal dispersion regime. In the anomalous dispersion region, the separation between the signal and idler wavelength is relatively small and it is only loosely dependent on the pump wavelength position. However, it changes substantially with the peak pump power, increasing as the pump power is increased. On the other hand, if the pump is placed inside the normal dispersion regime, the separation between the signal and idler wavelengths is weakly power-dependent, especially when operating deep in the normal dispersion region (Fig. 4.13b), but it is greatly affected by the position of the pump wavelength and can be even wider than a few hundred nanometres. This region is ideal for the generation of correlated photons, since the idler and signal waves can be tuned at wavelengths far from the pump and away from the first order or higher order Raman gain bands. Hence, it becomes apparent from the phase-matching curves that small-core, highly
nonlinear triangular core SF57 HFs can be effectively used for the generation of widely-spaced in terms of wavelength correlated photon pairs by pumping at wavelengths in the region between 900-1100 nm (depending on the actual core diameter).

![Diagram](image)

**Figure 4.13:** (a) Predicted spontaneous FWM phase-matching curves of SF57 triangular-core HFs of different enclosed core diameters for an input pump peak power of 12 W; (b) Comparison of the spontaneous FWM phase-matching curves of two SF57 triangular-core HFs for input pump peak powers of 12 W (solid) and 120 W (dotted). The dashed lines represent the position of the ZDW.

For applications involving quantum cryptography and quantum communications, it would be desirable to have at least one of the two photons of a correlated pair generated in a typical optical communications wavelength band. In Fig. 4.14, the
pump wavelength position required for the generation of a signal beam at 1312 nm for different triangular-core SF57 HF core diameters and an input peak power of 12 W is presented. It is shown that by appropriate pump wavelength adjustment, signal photons at the 1300 nm window can be obtained. The relationship between the fibre core diameter and the required pump wavelength position is approximately linear for the range of core diameters considered. The case of a 1.34 µm core fibre is of particular interest, since a commercially available neodymium-doped yttrium aluminum garnet (Nd:YAG) laser operating at 1.064 µm could be used for the generation of a signal photon at 1312 nm. Furthermore, it is important to note that for core diameters ranging between 0.9-1.1 µm, the matched pairs of the produced 1312 nm photons lie in the region of 700-800 nm, where highly efficient Si photon detectors are available.

![Graph](image)

**Figure 4.14:** Required pump wavelength position for the generation of a signal photon at 1312 nm using a triangular-core SF57 HF. The input peak power is considered to be 12 W.

### 4.2.3 Phase-matching experiment using a small-core highly nonlinear lead-silicate holey fibre

The spontaneous FWM response was experimentally studied for the lead-silicate HF with a triangular-core design and enclosed core diameter of ~0.9 µm. As reported in section 2.3.2.2, this fibre had a nonlinear coefficient \( \gamma \) of 1860 W\(^{-1}\)km\(^{-1}\) at 1550 nm. The experimental setup is presented in Fig. 4.15. The IR light from a Nd:YAG laser operating at 1064 nm was frequency doubled to obtain optical pulses at a central wavelength of 532 nm with a repetition rate of 80 MHz and an average power of ~4
W. These pulses were used as a pump source for the realization of a widely tunable optical parametric oscillator (OPO), as presented in detail in Fig. 4.15. The OPO was based on parametric down conversion enabled by a Type-1 phase-matching in a LBO crystal. By appropriate adjustment of the cavity length and the temperature applied on the LBO crystal, pulses tunable in the wavelength region between 800-1050 nm with a FWHM of ~5 ps and an average power up to ~70 mW were obtained. These pulses were launched on a 1m-length of the 0.9 µm-core SF57 triangular-core HF using a x40 microscope objective. The coupling efficiency into the fibre was ~8%. At the output of the fibre, the resulting signal was collected and its spectrum was examined on an OSA. Spectra were obtained for various pump wavelength positions and pump powers.

In Fig. 4.16, the received spectra for a pump wavelength of 960 nm and 996 nm are presented. For the pump wavelength of 996 nm, a broad continuum that was greatly dependent on the pump power was obtained. The shape of the spectrum suggests the existence of the self-frequency shifting effect, an indication of operating deep in the anomalous dispersion regime [41]. In particular, as will be explained in greater detail in Chapter 5, for a central pump wavelength lying in the anomalous dispersion regime of a fibre, a higher-order soliton ($N>>1$) launched into the fibre decays into its constituents. These constituent solitons can appear as distinct red-shifted peaks in the output spectrum of the fibre, while at high pump powers these peaks spectrally merge together forming a continuum. This is exactly the situation in Fig. 4.16, hence it can be concluded that operation in the anomalous dispersion regime of the fibre takes place. This pump wavelength region would likely be unsuitable for a correlated photons
experiment, since a plethora of nonlinear phenomena give rise to uncorrelated photons events that would inhibit the collection of the produced correlated photon pairs.

The pump wavelength was then set to ~956 nm and the spectra at the output of the fibre for two different pump powers were obtained (Fig. 4.17). It can be seen that the received spectra changed substantially with power, with successive distinct Stokes and anti-Stokes peaks appearing at low pump peak powers. The first Stokes and anti-Stokes peaks for an average input pump power of ~2.6 mW appeared at ~945 nm and ~975 nm respectively. However, for large peak powers, the peaks merged together, forming a continuum as in the case of Fig. 4.16 due to solitonic effects.
When operating at wavelengths below \(~945\) nm, clear FWM peaks appeared (Fig. 4.18). As expected from theory, the phase matched wavelengths (FWM peaks) appeared to be relatively insensitive to power variations. Changing the input power in the fibre by 3 dB did not significantly change the position of the FWM peaks. Furthermore, the phase matched wavelengths moved far from each other as the pump wavelength was placed deeper into the normal dispersion regime (i.e. towards shorter wavelengths). For a pump wavelength of 941.6 nm, the spontaneous FWM peaks, appeared approximately at 912 nm and 976 nm, having a wavelength separation over \(~64\) nm. For a pump wavelength of 936.8 nm, the spontaneous FWM peaks, appearing approximately at 1018 nm and 870 nm, had a wavelength separation of \(~150\) nm. Therefore, by appropriate tuning of the pump wavelength position and using suitable narrowband filtering, widely spaced signal and idler correlated photons could be generated and collected. Although it was expected that by pumping at wavelengths slightly shorter than 935 nm, a FWM peak should appear close to 1.3 \(\mu\)m, such a peak (as well as the corresponding from FWM blue-shifted anti-Stokes component) was not visible. This can be attributed to the instability of the pump source. As it becomes apparent from the phase-matching curves in Fig. 4.13, when operating deep in the normal dispersion region, a very stable source is essential to achieve phase-matching at specific wavelengths, since even small changes of the pump wavelength can severely affect the position of the phase matched wavelengths. Furthermore, the large frequency shift associated with this FWM process involving the generation of a photon at \(~1.3\) \(\mu\)m and its twin at \(~730\) nm (Fig. 4.13) can be responsible for a dramatic reduction in the FWM parametric gain, since it enhances the sensitivity of the phase-matching condition to deviations in the core diameter along the fibre length [42].
Figure 4.18: Received spectra when pumping in the normal dispersion regime of the SF57 triangular-core HF. The separation of the FWM peaks depended greatly on the pump wavelength position, as expected from theory.

Although the received spectrum at a pump wavelength position of 936.8 nm seemed promising for a correlated photons generation experiment, since the generated idler and signal beams seemed to be far apart from each other, an actual counting rate experiment was not performed. This was mainly for two reasons. Firstly, the objectives of the collaboration from the perspective of NIST researchers were clearly identified as the generation of pairs of correlated photons at the matched wavelength regions of ~800 nm, where highly efficient Si photon detectors are available, and ~1320 nm, where the GVD of SMFs is minimized, so as to demonstrate the suitability of the system for use in an optical communication system context. The fact that the stability of the pump was not sufficient to clearly view the generation of photons at the wavelength region ~1320 nm, discouraged the acquisition of a set of complete measurements. The second reason was the limited time-frame of the experiments. In particular, the experiments were performed at NIST in a short period of four weeks, and the experimental set-up, including the design and the implementation of the pulsed laser source, its alignment, and the arrangement for launching into the HF were realized during this period. Unfortunately, the optimization of the laser source occupied a great deal of the available time.

It has to be noted that, even in case that a photon could be produced from spontaneous FWM at the 1.3 μm region, the performance of the system would be degraded from the poor collection efficiency of the generated photons from the SF57 HF. It was
estimated that the coupling efficiency from the output of the compound-glass HF to a silica SMF fibre was about 10%, without considering the transmission of any necessary filters (typically about 70%) and gratings/prisms to get rid of the pump wavelength and separate the signal/idler wavelengths before the detectors. This poor collection efficiency is attributed to the mode mismatch between the SMF/compound glass HF, both in terms of shape (triangular versus circular) and NA difference (large NA of small-core HF versus an NA of 0.1 for SMF fibres). A poor collection efficiency greatly deteriorates the received photon-pair count-rate, since

\[
\text{photon-pair count-rate} = n_{\text{det1}} \cdot n_{\text{det2}} \cdot n_{\text{coupling1}} \cdot n_{\text{coupling2}} \cdot R
\] (4.18)

where \( R \) is the rate of pair photon generation (source repetition rate), \( n_{\text{det1}} \) and \( n_{\text{det2}} \) the efficiencies of the two detectors and \( n_{\text{coupling1}}, n_{\text{coupling2}} \) the coupling efficiencies from the compound-glass HF to the SMF fibres connected to the detectors [31]. Hence, although the count rate \( N_{\text{det}} \) of each detector could be quite large (\( N_{\text{det}} = n_{\text{det}} \cdot n_{\text{coupling}} \cdot R \)), it would mostly be formed by single photon events, unable to provide correlated photon pairs at the output of the system, where an AND gate between the two detectors for the signal and idler beam would be used to indicate correlation. This count rate of the detectors stemming from single photon events would appear as background noise (increase in the accidental coincident rates) due to random overlap of single photon events, i.e. events not generated by photon pairs. The use of specialized high NA and mode-shaping lenses or the use of tapered silica fibres for the collection of the photons at the output of the HF could potentially improve the collection efficiency, resulting in a sufficient photon-pair count-rate.

It is worth mentioning that, provided the issue of the collection efficiency of correlated photons is addressed, SF57 HFs can give rise to high photon-pair count rates at greatly reduced pump power and length requirements, since their ultra-high nonlinearity enables very high signal/idler photon generation rates. Ultimately, the only factor limiting the received count rates would be the dead time of the photon counters used, which determines the shortest possible time between two photon counting events. The count rate capability of commercially available detectors currently reaches a few MHz, thus GHz pair photon generation rates cannot currently be exploited.
4.3 Conclusions

In this Chapter, parametric processes based on FWM were studied for lead-silicate HFs. In the first section, the potential of dispersion tailored lead-silicate-based HFs in FWM-based wavelength conversion applications was numerically and experimentally examined. Using a 2.2 m-long SF57-HF fabricated following the SEST technique, a -6 dB conversion efficiency over a 3-dB bandwidth of ~30 nm was experimentally demonstrated. Simulations revealed that by careful selection of parameters such as the fibre length, the pump power and the pump position, optimization of the FWM performance in terms of bandwidth and conversion efficiency can be achieved. It is reasonable to expect that further improvements in the fabrication process of SEST fibres would lead to decreased fibre loss and accurate manipulation of the fibre structural parameters. Such improvements would enable the realization of fibre designs that combine a high nonlinearity with a low dispersion slope and a ZDW shifted inside the C-band, or even designs that exhibit two closely spaced ZDWs and are therefore suitable for a dual pumping scheme. Numerical simulations performed for a design with a ZDW at 1550 nm and a higher effective nonlinearity of 763 W⁻¹ km⁻¹ revealed that SF57-HFs can become an excellent candidate for the realization of broadband, highly efficient and compact parametric devices.

The second section of the Chapter regarded the potential use of compound-glass HFs in the new and rapidly growing field of quantum cryptography. Using spontaneous FWM in such fibres, efficient generation of correlated photons can be achieved. In a preliminary experiment, the generated spontaneous FWM spectra for various pump wavelength positions were studied for a SF57 triangular-core HF with a nonlinear parameter \( \gamma \) of 1860 W⁻¹ km⁻¹. It was shown that such fibres can generate widely spaced signal and idler correlated photons when pumped close to their ZDW in the normal dispersion regime, thus avoiding the detrimental effect of spontaneous Raman scattering. Furthermore, the ultra-high nonlinearity of compound-glass fibres can give rise to a very large correlated photons production rate at significantly lower power and/or length requirements compared to other fibres. However, a significant issue that has to be solved in order for such fibre to become applicable is the coupling efficiency into SMFs. The fabrication of fibres with a suitably designed core diameter and core shape that would represent an ideal trade off between mode-mismatch to SMFs and
nonlinearity, together with the use of specialized high NA and mode-shaping lenses can potentially greatly improve the coupling into SMFs, making the use of compound-glass HF{s} for the generation of correlated photons a reality.
Chapter 4: Parametric processes based on FWM in lead-silicate HFs

References


Chapter 5

Supercontinuum generation in short lengths of lead-silicate holey fibres

When optical pulses of very high intensity propagate through nonlinear media, the interplay of various nonlinear phenomena taking place during pulse propagation can generate a broad, continuous spectrum of high spectral intensity spanning more than an octave. This broadened spectrum is referred to as a “supercontinuum” (SC) [1] and has found many applications, with optical coherence tomography [2], spectroscopy [3], optical metrology [4] and WDM-based high-speed communications [5] being the most prominent.

The quality of the SC is assessed by its flatness, brightness and coherence [6]. Since the SC is the product of a plethora of nonlinear phenomena, its quality depends on the relative significance of the interacting nonlinear effects. Therefore, the properties of the nonlinear medium, such as its nonlinear response and its dispersion profile, and the launched pulse characteristics, especially the pulse peak power and the pulse duration, determine the SC formation. In general, for a broad SC to be realised, it is desirable to employ materials of high nonlinearity. Highly nonlinear materials can lead to significant spectral broadening at reduced pulse peak powers and pulse duration requirements, enabling the use of cheaper and less bulky laser sources. Furthermore, another parameter of critical importance is the position of the ZDW of the nonlinear medium with respect to the central wavelength of the launched pulse. For a pump central wavelength positioned close to the ZDW, the dispersion is small and the input pulse can sustain a high peak power over a substantial length, enhancing nonlinear effects. By employing a nonlinear medium that exhibit a ZDW close to the wavelength of operation of available high power laser sources, such as at 1064 nm for Nd:YAG laser sources or in the region between 800-950 nm for titanium-sapphire laser sources, broad SC spectra can be realised.
Optical fibres are an ideal nonlinear medium for the generation of SC, since they can combine tight light confinement with long interaction lengths and novel dispersion properties. Tapered SMFs and dispersion-optimised fibres have therefore been employed successfully in broad SC generation applications [7, 8]. Recently, HFs have attracted significant attention, due to the flexibility they offer in terms of tailorable dispersion and nonlinear properties. Employing optimised HF designs, which combine a high nonlinearity with novel dispersion characteristics at regions where convenient laser sources are available, can lead to the formation of a broad, flat and bright SC [9, 10]. Furthermore, combining HF technology with compound glasses can lead to ultra high values of nonlinearity, therefore significantly reducing the pump power requirements for SC generation.

With regard to the nonlinear propagation of short pulses of the order of a few hundred femtoseconds in optical fibres, the shape of the formed SC depends greatly on the dispersion regime on which the central wavelength of the pump pulses lie. In the normal dispersion regime, SPM broadens the spectrum symmetrically around the central wavelength of the pump pulses, while SRS leads to spectral broadening in the longer wavelength side [6, 10]. The resulting spectrum is smooth, hence suited for such applications as optical coherence tomography. In the anomalous dispersion regime, SPM, soliton fission, Raman-induced SSFS and dispersive wave generation mediated by solitons are the dominant processes [10, 11]. The formed SC has a very wide wavelength span, but it is normally quite structured. When pumping close to the fibre ZDW, all the above-mentioned nonlinear effects participate in the formation of the SC, while FWM effects also become very important, since FWM phase-matching conditions are normally satisfied close to the ZDW [11].

Non-silica glasses have recently emerged as potential candidates for the background material of HFs. Typically, compound glasses exhibit a high transparency from the near-IR to the mid-IR, high rare-earth solubility and a very high nonlinear refractive index [12]. By suitable control of the fibre structure, and material choice, it is possible to envisage compound-glass fibre designs with ultra-high nonlinearities, orders of magnitude higher than silica-based HFs, while at the same time ensuring suitable dispersion properties [13]. The high nonlinearity offered by compound-glass HFs enables the generation of a broad SC at reduced power and length requirements. On
the other hand, HF technology offers the particularly attractive option to shift the fibre zero dispersion to 1.0 and 1.5 µm, so as to offer the potential to use Nd:glass femtosecond lasers (or ytterbium-doped fibre-lasers) and erbium-doped fibre-lasers respectively to generate the SC. The combination of high nonlinearities with unique dispersion properties could ultimately allow for the realization of practical, compact, diode-pumped nonlinear devices using very short fibre lengths and operating at low powers.

In this Chapter, the use of compound-glass HFs in SC applications, with SC generated with seed pulses at the wavelength regions of ~1 µm and ~1.5 µm, is demonstrated. Femtosecond-range pulses are launched into small pieces of compound-glass HFs and the formed SC is examined for different pulse peak powers and pulse central wavelength positions. The experimental results are qualitatively justified and compared to numerical simulations. The employed fibres were suitably designed so as to exhibit a ZDW close to the wavelength regions of the pump pulses, in order for the spectral broadening of the formed SC to be optimised.

5.1 Numerical modelling of the supercontinuum generation

The experimental results which are reported in this Chapter have been supported by numerical simulations, carried out by Dr. J. Price. The simulations were based on solving the modified NLSE, taking into account the nonlinear contribution of both the instantaneous electronic and the delayed ionic response (section 1.1.2.1).

The numerical model included the effects of loss, Kerr and Raman nonlinearity and dispersion. To improve the accuracy of the model, the full wavelength dependent loss and dispersion profile of the fibre under test was taken into account. For the estimation of the nonlinear parameter $\gamma$, the effective mode area at the central wavelength of the seed pulses was used, as obtained from numerical modelling of the fibre frequency dependent mode distribution of the fundamental mode. It was assumed that only the fundamental fibre mode participated in the SC generation, while propagation of higher-order modes was not taken into account. For simplicity, the effects of two-photon absorption and polarization mixing were not included in the
model. For an accurate prediction of the contribution of the Raman effect, the delayed temporal response of the employed fibres was calculated from uncalibrated spontaneous Raman spectra [14] and was included in the numerical calculations. The fraction of the ionic-vibrational contribution to the nonlinear polarization was assumed to be 0.2 for the SF57 lead-silicate fibres, based on the known fraction of 0.18 for silica fibres.

A detailed and accurate study of the generated SC would require repeated, computational-intensive calculations for different input pulse parameters, such as pulse duration, power and chirp. This approach would accurately simulate the measured SC spectrum, which results from the contribution of a large number of pulses having slightly different characteristics. To avoid complex calculations, a rolling average was applied to smooth the numerically acquired spectra, so as to simulate the measured, time-average spectra of several pulses, obtained by use of an OSA.

5.2 Experimental setup for supercontinuum generation

The experimental setup for the generation of SC is shown in Fig. 5.1. Femtosecond pulses were generated from a modelocked laser system, which in our experiments was either an ultra-broadband, titanium-sapphire, laser system (COHERENT-Mira) (utilizing passive modelocking in the form of the Kerr-lens modelocking) or a Nd:glass laser system. The beam passed through a variable optical attenuator, based on metallic neutral density filter technology, and was guided through the rest of the set-up by a combination of mirrors. To reduce the divergence of the laser beam, expansion and recollimation was performed through a combination of plano-convex lenses in a Keplerian telescope configuration. A small circular aperture was placed at the focal point of the telescope, so as to smooth the radial intensity profile of the beam through spatial filtering. The collimated beam had its polarization aligned to one of the principal axes of the employed compound-glass HF by suitable adjustment of a halfwave plate. The pump beam was subsequently coupled into a small piece of compound-glass HF through the use of either a standard x60 microscope objective or a high NA (≈0.68) aspheric lens, depending on which of the two would give a higher coupling efficiency in the experiment. After propagation through the fibre, the beam
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was collected from the fibre exit facet and was coupled to a high sensitivity OSA, which recorded the spectrum of the formed SC.

Figure 5.1: Experimental setup for the demonstration of SC using SF57 lead-silicate HFs.

5.3 Supercontinuum generation in lead-silicate holey fibres with triangular-core design by pumping at \( \sim 1.06 \, \mu m \)

5.3.1 Experimental results

As mentioned in the introduction of this Chapter, fibre-based SC is greatly affected by the fibre dispersion profile. It is generally advantageous to operate close to the fibre ZDW in order to achieve a broad SC. Therefore, for SC generation at the 1.06 \( \mu m \) region, the triangular-core fibres \#3 and \#4, as described in section 2.3.2, were employed. A diode-pumped, Nd:glass laser system capable of producing nearly transform-limited, 300 fs Gaussian pulses at a central wavelength of 1055 nm, with a repetition rate of 80 MHz, was used as a source. The average power received from the laser was \( \sim 100 \, mW \). Therefore, assuming a perfect Gaussian shape, the peak power of the pulses exiting the laser system was \( \sim 4 \, KW \). The coupling efficiency into the fibre was estimated to be \( \sim 20\% \) (based on the fibre loss measured at 1055 nm) hence pulses with energies up to \( \sim 240 \, pJ \) could effectively be launched into the fibres.

For the SC generation studies, a \( \sim 60 \, cm \)-long piece of the triangular-core fibre with a core diameter of \( \sim 0.9 \, \mu m \) (fibre band \#4 in section 2.3.2) was employed. By adjustment of the variable attenuator, the spectrum of the generated SC was recorded for several input pulse peak powers (Fig. 5.2). For pump pulse energies below 20 pJ, a multi-peaked spectrum on the longer wavelength side (compared to the central wavelength of the input pulses) was obtained. At the same time, the generation of new
spectral components at the shorter wavelength side was observed. As the pulse energy was increased, the obtained spectrum became broader and smoother, particularly at the longer wavelength side. For a pulse energy of ~100 pJ, the SC extended over one octave, extending significantly into the visible and the near-IR region and exhibiting an almost flat top in the region between 1100-1450 nm.

![Figure 5.2: Experimental and simulated SC spectra for a ~60 cm long SF57 HF with triangular-core design and a core diameter of ~0.9 µm.](image)

The SC generation from a ~6.8 cm piece of the triangular-core fibre with a core diameter of ~1.2 µm (fibre band #3 in section 2.3.2) was also studied for various pump pulse energies (Fig. 5.3). The SC spectra obtained in this case were flatter and much more symmetric, as compared to the spectra obtained with the ~0.9 µm core diameter fibre, and spanned a few hundred nanometres. For pulse energies higher than ~180 pJ the SC spanned over 600 nm, but the broadening was profound at the longer wavelength side, similar to the case of the ~0.9 µm core diameter fibre.
5.3.2 Analysis of the supercontinuum generation and supporting numerical simulations

SC generation in optical fibres is determined by the magnitude and the relative significance of the various nonlinear effects taking place during pulse propagation. Obviously, the high nonlinearity of the employed SF57-based fibres (Fig. 4.12a), greatly enhances nonlinear effects, leading to a spectral broadening over an octave for moderate pump pulse energies of the order of ~100 pJ. These pulse energy levels should be compared to the case femtosecond pulse pumping of silica fibres, where, even in tapered SMFs, pump energies of the order of ~1 nJ are required for an octave SC to be generated [7]. However, the shape and quality of the generated SC is ultimately determined by the type of nonlinear effects contributing to the generated SC. Apart from the fibre propagation loss profile, which can hinder the generation of frequencies lying inside bands where absorption is high, the fibre dispersion profile is the determining factor of the phenomena participating in the SC generation. Therefore, in order to interpret the obtained SC spectra, the dispersion profile of the employed fibres and the position of the pump pulse central wavelength relative to the fibre ZDW have to be considered.
In this section, the observed SC spectra are qualitatively interpreted. The main features of the spectra are justified in terms of participating nonlinear phenomena, and the discrepancies between numerical simulations and measurements are explained.

### 5.3.2.1 Pumping in the anomalous dispersion regime

With regard to the fibre with a triangular-core design and a core diameter of ~0.9 μm, its ZDW was predicted by FEM-based numerical simulations to lie at ~960 nm (Fig. 4.12c). Therefore, the fibre dispersion was expected to be anomalous at the central wavelength of the pump pulse and soliton effects were anticipated. Indeed, the multi-peaked nature of the received spectra, for moderate pump peak powers, can be attributed to the Raman-scattering induced decay of femtosecond higher-order solitons in combination with the SSFS effect.

In particular, for a central pump wavelength lying in the anomalous dispersion regime of a fibre, i.e. $\beta_2 > 0$, where $\beta_2$ is the second order propagation constant of the fibre, and for high pump peak powers, a higher-order soliton can be formed. A higher-order soliton obeys the relation

$$N = \sqrt{\frac{\gamma P_0 T_0^2}{|\beta_2|}}$$

(5.1)

where $N$ is the soliton order, $\gamma$ is the nonlinear parameter, $P_0$ is the pump pulse peak power and $T_0$ is the pulse duration [15]. It becomes apparent that for the same pulse characteristics and dispersion profile, a high fibre nonlinearity favours the formation of a higher-order soliton. A higher-order soliton is generally an unstable entity; its constituents, known as sub-solitons, are bound together solely because their propagation speeds, as dictated by the real part of their eigenvalues, are similar [15, 16, 17]. Under energy preserving perturbations, such as birefringence and dispersion, the bound state can propagate as an entity, with periodical changes in its spectrum. On the other hand, non-Hamiltonian type perturbations, where pulse energy is not preserved, can break the degeneracy, leading to the decay of a higher-order soliton of order $N$ into its $N$ fundamental constituents [16, 17]. The relative group velocities and amplitudes of the constituents are dictated by the real and imaginary part of their eigenvalues, which can be obtained using the inverse scattering method [18]. The individual solitons are stripped off from the input pulse one by one, with the shortest-
duration and therefore highest peak power solitons ejected first and exhibiting the largest group-velocity difference relative to the input pulse pump wavelength [1, 17]. The peak powers and widths of the constituents are provided by the expressions

\[ P_k = \frac{(2 \cdot N - 2k + 1)^2}{N^2} P_0 \]  
\[ T_k = \frac{T_0}{2 \cdot N - 2k + 1} \]

respectively, where \( k \in [1, N] \) corresponds to the \( k \)-th constituent [1]. Two effects that might cause this bound state destruction is self-steepening and Raman scattering. At femtosecond scales, RS dominates over self-steepening [15].

In the performed experiment, taking into account the nonlinearity and dispersion profiles of the fibre (Fig. 4.12) as well as the duration of the input pulses, a second-order soliton could be excited in the \( \sim 0.9 \) µm core diameter fibre for an input pulse energy as low as \( \sim 0.3 \) pJ. Therefore, for the range of launched peak pump powers used in the SC experiments, the fibre could support the formation of a higher-order soliton. For example, considering the loss of the fibre, \( N \approx 16 \) for 20 pJ pulses and \( N \approx 37 \) for 100 pJ pulses [1, 15]. It is therefore safe to assume that RS-induced pulse decay was expected in this fibre.

To understand the evolution of each constituent soliton after the decay of a higher-order soliton, the effect of intra-pulse RS has to be considered [15]. Due to the broadband nature of the pulses, low frequency components of the pulse can experience gain at the expense of high frequency components, which act as a pump. This energy enhancement of the red components can appear in the form of a Raman pulse, which propagates as a soliton and is therefore commonly referred to as Raman soliton. The enhancement of the red components takes place all along the fibre length, leading to a corresponding continuous red-shift of the Raman soliton, according to the SSFS effect [10].

In the case of a decay of a \( N \)th-order soliton, each of the \( N \) sub-solitons would experience the SSFS effect. Since, as it becomes apparent from Eq. 5.2 and 5.3, each sub-soliton has a different amplitude and duration, the central frequencies of the different solitons undergo different frequency shifts. Due to the fibre dispersion, the
fundamental solitons propagate at different speeds and therefore separate from each other in time. In the spectral domain, they form separate spectral bands, appearing as distinct Stokes components in the received spectrum [1]. This is exactly the case observed in the ~0.9 µm core diameter fibre for pulse energies of the order of a few tens of pJ. Separate Stokes components are formed, with each one corresponding to a sub-soliton of the initial \(N\)th-order soliton. Ideally, the number of separate Stokes components that appear in the spectrum should be equal to the order of the initial higher-order soliton. However, a fundamental requirement for all \(N\) components to be observed in the received spectrum is a sufficient fibre length [1, 17]. In fact, the required fibre length increases with \(N\), and for very large \(N\) values becomes tens of times the soliton period \(z\) [17], where \(z\) is provided by the relation [15]

\[
z = \frac{\pi}{2} L_p = \frac{\pi}{2} \frac{T_0^2}{|\beta_2|}
\]

(5.4)

In the performed experiment, the employed fibre length was almost equal to the fundamental soliton period (~0.64 m). Therefore, even for moderate pulse energies, not all the \(N\) fundamental solitons could be observed.

The combination of soliton decay and SSFS can successfully interpret the form of the received SC spectra at longer wavelengths for moderate peak powers. With regard to the new frequencies generated at shorter wavelengths, they can be attributed to the high-order dispersion seeded radiation of energy from the generated sub-solitons [1, 19, 20, 21]. Higher-order dispersion terms perturb the sub-solitons, which respond by radiating energy in order to maintain their shape. This energy appears in the form of dispersive waves. For each formed sub-soliton, the corresponding dispersive wave, usually referred to as non-solitonic radiation, appears at a frequency where phase-matching with the sub-soliton phase is achieved [1, 19]. In the received spectra, a dispersive wave appears as an anti-Stokes component that lies in the normal dispersion regime and normally has an intensity much lower than the intensity of the associated to the sub-soliton Stokes component [1]. While the Stokes components shift towards longer wavelengths with an increase in the input power, the anti-Stokes lines shift towards shorter wavelengths [19]. This process is illustrated in Fig. 5.4.
Since the Stokes components generate anti-Stokes components at phase-matched frequencies, when pumping in the anomalous dispersion regime and far from the ZDW, a dip is expected to appear in the SC spectrum. The furthest from the ZDW the pump wavelength is placed, the greatest the span of the generated SC becomes, at the expense, however, of a wide gap between the generated red and blue components [17]. Pumping closer to the ZDW and employing fibres with a very flat dispersion profile can smooth the spectrum and eliminate the dip. With regard to the experimentally observed SC using the ~0.9 µm core diameter fibre, a gap is indeed observed in the received spectrum close to the numerically predicted ZDW, both for moderate (20 pJ) as well as for strong input pulse energies, as expected from theory. Furthermore, the anti-Stokes peaks lie at the wavelength region between 650-850 nm, in agreement with theoretical predictions stemming from numerical simulations.

For strong input pulse energies, the distinctive spectral components in the SC spectra received for the ~0.9 µm core diameter fibre became smoother on the longer wavelength side, while the gap between the blue and red bands started to get filled. The smoother spectrum at red wavelengths for high pump powers can be attributed to degenerate FWM. In particular, each of the formed Raman solitons can seed a degenerate FWM process, resulting in the generation of new frequencies lying in the vicinity of its spectrum, as expected from FWM processes in the anomalous dispersion regime [17]. The sidebands formed by spontaneous FWM can effectively fill the gaps between the spectral components of the Raman solitons, since, for pumping in the

**Figure 5.4:** Diagram showing the combined effects of soliton decay, soliton shifting and dispersive wave generation.
anomalous region, the generated by FWM waves appear relatively close to the pump wavelength. FWM is therefore expected to lead to the spectral merging of the Raman solitons [17], resulting in a smoother spectrum in the longer wavelength regime. This is the situation for pump pulse energies of the order of \( \sim 100 \) pJ. A degenerate FWM process can also be seeded by the blue-shifted frequencies stemming from soliton phase-matched radiation (dispersive waves). However, the relatively low power of the anti-Stokes components, in combination with the large wavelength separation of the generated by FWM frequencies, when pumping in the normal dispersion regime of fibres (see Fig. 4.13), makes this process very weak [17]. Moreover, a FWM process can be initiated between the Raman solitons and the generated blue-shifted components [17, 22]. This process can result in the amplification of the components lying between the Stokes and anti-Stokes line, thus filling the observed gap at the region close to the ZDW [17]. Such a process is not observed in the SC spectra obtained with the \( \sim 0.9 \) \( \mu \)m core diameter fibre, possibly because pump pulses of a higher energy would be required for such an effect to appear.

It becomes apparent that the combined effects of soliton decay, SSFS and FWM that dominate femtosecond pulse propagation in the anomalous region of optical fibres can effectively justify the main features observed in the SC spectrum obtained using the \( \sim 0.9 \) \( \mu \)m core diameter fibre. Numerical simulations of pulse propagation were performed to substantiate the experimental findings. Indeed, the main features such as the formation of Raman solitons, the short-wavelength anti-Stokes peaks lying at the wavelength region between 650-850 nm and the dip in the spectral region at the close proximity of the ZDW can be observed in the simulated spectrum. In general, since the participating nonlinear processes greatly depend on the actual fibre dispersion profile, it is expected that differences between the fibre simulated dispersion profile and the exact dispersion profile might be causing some discrepancies. It has to be appreciated that even small differences in the fibre core size of the order of \( \sim 0.05 \) \( \mu \)m can change the ZDW position by as much as 20 nm (Fig. 4.12c), therefore an accurate estimation of the fibre core diameter is of critical importance. However, some important differences between the simulated and the experimentally acquired spectra should be further justified. In particular, a peak appears at the central wavelength of the input pump pulses in the experimental SC spectra, which is not present in the spectra obtained from simulations. This peak can be associated with a residual pump power
that did not participate in the generation of nonlinear phenomena and might be attributed to light propagating in the cladding of the employed uncoated compound glass HF. The presence of cladding light probably hindered the exact estimation of the coupling efficiency into the fibre, and might have caused the discrepancy between the experimentally acquired pulse energies and those expected by numerical simulations to be required to form similar SC spans. Moreover simulations predicted the formation of sharp, well-resolved peaks, each corresponding to a frequency shifted Raman soliton rather than a smooth spectrum, as obtained in the experiments. The flatter experimental spectrum at the longer wavelength can be possibly attributed to the time averaging applied by the spectrum analyser. The time averaging period generally includes the effect of several pulses, and even a slight energy jitter can change the spectral extent of the Raman shifting, therefore leading to a smoother SC spectrum (however, the amplitude jitter of the pump pulses was not measured, thus it is difficult to substantiate this comment further).

The numerical model was employed to predict the SC generation for similar pump characteristics but using triangular-core SF57 HFs of different core diameters, which exhibited an anomalous dispersion at 1.05 \( \mu \)m. For a 5 cm-long fibre of a 0.8 \( \mu \)m core diameter, the SC generated from \( \sim 100 \) pJ pulses exhibited blue shifted components below 700 nm and a gap in the spectral region lying between 700 and 900 nm, while the SSFS effect favoured the generation of longer wavelengths beyond 1600 nm. Fibres with core sizes between 1.0-1.1 \( \mu \)m were particularly suitable for SC generation using a 1.05 \( \mu \)m pump, since they exhibited a small anomalous dispersion at this wavelength. Simulations revealed a relatively flat and broad SC, spanning from 750 nm up to 1500 nm [23].

### 5.3.2.2 Pumping in the normal dispersion regime

The numerically predicted ZDW for the \( \sim 1.2 \) \( \mu \)m core diameter fibre was at \( \sim 1070 \) nm (Fig. 4.12c). Therefore, at the pump central wavelength of 1055 nm, the fibre was expected to have a normal dispersion. For propagation in the normal dispersion regime of fibres, SPM is expected to be the dominant effect, at least for low pulse energies. Indeed, it can be seen in Fig 5.3 that at pulse energies up to \( \sim 180 \) pJ, SPM leads to a
relatively symmetrical spectral broadening. A good agreement between simulation results and experimental observations is evident for low pump energies (Fig. 5.3).

As the power is increased, Raman scattering effects are initiated, leading to the generation of new frequency components on the longer wavelength side. Therefore, the SC spectrum becomes asymmetric. Such is the case observed for a pulse energy of 232 pJ, which corresponds to the maximum possible launched pulse energy in the performed experiment. The obtained SC for such a pulse energy had a relatively flat profile, extending over 600 nm. However, the observed spectral broadening was asymmetric. Furthermore, a significant portion of the new frequency components generated by SPM lay over the ZDW, in the anomalous dispersion regime. Therefore, it was expected that for even higher pump pulse peak powers, the energy transferred to the anomalous dispersion regime would evolve into the formation of solitons. The SSFS effect could subsequently lead to further spectral broadening, with new frequencies generated in the longer wavelength region, similar to the case described in the previous section. For the case of high pulse energies, a relatively good agreement between the values theoretically predicted by simulations and those experimentally acquired is evident. Minor differences observed in the two spectra are attributed to discrepancies between the actual and the simulated fibre dispersion profile.

5.4 Supercontinuum generation in lead-silicate holey fibres with a hexagonal lattice design by pumping at ~1.5 µm

5.4.1 Experimental results

While triangular-core SF57 HFs with core diameters of ~1.0 µm are suitable for SC generation by pumping at ~1.0 µm, appropriately designed hexagonal lattice SF57 HFs exhibiting a ZDW close to the C-band can be very effective for SC generation by pumping at the 1.5 µm region. The tailorable dispersion and nonlinearity properties of such fibres, designed by the SEST approach, can enable the realization of fibres that combine a ZDW near the C-band with a very low and flat dispersion profile, which are parameters extremely desirable for efficient SC generation.
For the demonstration of SC generation by pumping at 1.5 µm, the SEST fibre #1, described in section 2.3.3 was employed. The COHERENT-Mira laser system was used as a source. The laser was capable of producing 200 fs, nearly transform-limited, Gaussian pulses at the 1.5 µm wavelength range with a repetition rate of 250 kHz. The central wavelength of the pulses was set to ~1490 nm in the performed experiment. Considering a coupling efficiency of ~20% into the fibre, pulse energies up to ~23 nJ could be launched on a ~1.02 m-long piece of the 4.3 µm core SEST fibre.

By adjustment of a variable attenuator, the spectrum of the generated SC could be recorded for different input pulse energies. These spectra are presented in Fig. 5.5a and Fig. 5.5b.
Figure 5.5: Experimentally acquired spectra using ~1.02 m of the SEST SF57 HF with a hexagonal hole arrangement. (a) Formation of a flat spectrum at the longer wavelengths side (b) SC spectra obtained for different input pulse energies. Blue-shifted peaks can be clearly observed.

For pump pulse energies in the range of 0.4-0.8 nJ (Fig. 5.5a and 5.5b), the output spectrum extended mainly to longer wavelengths, compared to the pump pulse central
wavelength, exceeding 1600 nm. When the pulse energy was increased to ~1.7 nJ, the SC spectra extended even further to the longer wavelength side, while well-resolved spectral components were also generated at shorter wavelengths, peaking at ~1.0 µm (Fig. 5.5b). A clear gap was formed at the region between the peak at the blue and the pump wavelength. For even higher pulse energies (~3 nJ) the received spectra in the longer wavelength side spanned up to ~1750 nm, forming a relatively flat top that extended over 150 nm and was reaching the upper limit of the OSA’s wavelength range of operation (Fig. 5.5a). Since the cut-off wavelength of lead-silicate glass is at around 3 µm, it can be assumed that spectral components were generated beyond ~1750 nm, but could not be monitored by the OSA. Unfortunately, a grating monochromator able to diffract and detect wavelengths longer than the upper limit of the employed OSA was not available at the time when the experiment was conducted.

With regard to blue components, the peak in the shorter wavelength side was blue-shifting as the pump power was increased, reaching ~940 nm for an input pulse energy of ~6 nJ (Fig. 5.5b). The increase in pulse energy also led to the generation of new frequency components lying between the peak at the shorter wavelength side and the central wavelength of the input pulses. Therefore the observed gap was gradually filled, leading to the formation of a broad SC for pump pulse energies greater than ~11 nJ (Fig. 5.5b). The power variation of the various spectral components across the 800-1700 nm was ~15 dB.

5.4.2 Analysis of the supercontinuum generation and supporting simulations

The ZDW of the SEST fibre employed was estimated from FWM experiments to be ~1582 nm. Therefore, the fibre was pumped at the normal dispersion regime and SPM was expected to dominate the SC formation, leading to a symmetric spectrum. However, the spectral broadening seemed to be extending mainly towards longer wavelengths for pulse energies below ~1 nJ, a behaviour that implies the existence of Raman effects, while the formation of strong blue-shifted peaks at the SC spectra and relatively far from the central pump wavelength was observed for pulse energies over ~1.7 nJ.

To explain the observed spectral features, it has to be appreciated that the input pump pulse energies to the HF were relatively high, while the ZDW lied about ~90 nm away
from the central pump wavelength. For a pump pulse with energy below ~1 nJ, the formed SC extended towards longer wavelengths over 1600 nm, both due to SPM and Raman-induced spectral broadening, therefore a portion of energy was already in the anomalous dispersion regime. At even higher pump pulse energies, considerable energy was transferred in the anomalous dispersion regime and higher-order soliton effects were expected to appear. In fact, it was anticipated that soliton fission, accompanied by the SSFS effect, would have led to further spectral broadening, with new frequencies being generated in the longer wavelength region. Indeed, a significant spectral broadening, characterized by the presence of successive peaks, was evident in the longer wavelength region; unfortunately, due to the limited measurement range of the OSA employed (up to 1750 nm), the spectral broadening extending beyond 1750 nm could not be studied. The occurrence of the intense peak at shorter wavelengths, which seemed to be shifting even further towards the blue with an increase in the input pulse energy, can be interpreted to be the result of the formation of dispersive waves from the $N$ fundamental solitons resulting from higher-order soliton fission in the anomalous dispersion region. The shortest and strongest fundamental soliton stemming from soliton fission, which is the first to be ejected from the initial higher-order soliton pulse, determines the position of the peak at the shorter wavelengths region [1, 19, 20]. As the power was increased, the spectral gap between the pump wavelength and the formed blue-shifted peak started to disappear and a smooth continuum spectrum was formed, an effect attributed to FWM between the red-shifted Raman solitons and the dispersive waves [17].

In order to support the interpretation of the blue-shifted peaks as a result of soliton fission of higher-order solitons, formed in the anomalous dispersion regime of the fibre under test, and subsequent non-solitonic radiation, numerical simulations of the expected formation of dispersive waves were undertaken. Both the numerical modelling and the simulations were performed by Peter Horak. The numerical model made several assumptions. First, the central wavelength position of the formed higher-order soliton was considered to be at 1590 nm, i.e. very close to the expected ZDW. Numerical simulations revealed that the exact position of the soliton central wavelength did not affect the results substantially (deviations of the order of ~50 nm from the ZDW were simulated). However, it was considered reasonable to assume that the higher-order soliton was formed close to the ZDW; after all, the efficiency of the
generation of non-solitonic radiation becomes substantial when the process is seeded by the wing of the soliton spectrum itself, which, when the soliton lies close to the ZDW, extends to the normal dispersion region and can stretch as far as the resonance wavelength of non-solitonic radiation [1, 17, 19, 20]. A second assumption regarded the sole consideration of the shortest and most powerful sub-soliton for the generation of dispersive waves. Although the rest of the sub-solitons are also expected to generate non-solitonic radiation, resulting in substantial spectral broadening of the blue-shifted dispersive wave components in the SC spectra, this is a reasonable assumption [1, 17, 19, 20]. A third assumption, expected to affect the results substantially, regarded the power concentrated in the formed higher-order soliton. Although the central wavelength of the pump pulse lay in the normal dispersion regime, in the simulations it was assumed that the whole pump power was transferred to a higher-order soliton in the anomalous dispersion regime. This is a weak assumption, and probably the main source of discrepancies between the predicted by numerical modelling behaviour and the experimental results.

The results from the simulations are presented in Fig. 5.6. In Fig. 5.6a, the phase mismatch between the shortest soliton, stemming from soliton fission, and non-soliton radiation is shown for various pulse energies. It can be seen that for a specific input pulse energy there is a certain non-soliton radiation wavelength position for which the phase mismatch is minimised. This phase-matched wavelength is shifted towards shorter wavelengths as the pump energy is increased. Therefore, the phase-matched non-soliton radiation appears to be at ~1000 nm for an input pulse energy of ~3.8 nJ, while it shifts to ~860 nm for an input pulse energy of ~11 nJ. In Fig. 5.6b, the phase-matched dispersive wavelength position is presented as a function of the input pulse energy. Considering the assumptions involved in the numerical model, there is a reasonable agreement between the predictions of the simulations and the behaviour observed in the acquired SC spectra (Fig. 5.5b).
Chapter 5: SC generation in short lengths of lead-silicate HFs

5.5 Conclusions

In this Chapter, SC generation in lead-silicate based HFs was studied for femtosecond input pulses. The fabricated SF57 triangular-core HFs and hexagonal hole arrangement SEST HFs were employed in these experiments. The high nonlinearity of lead-silicate glass favoured nonlinear effects in those fibres and hence enhanced the SC formation. The SF57 triangular-core fibres with a core diameter of ~1.0-1.3 µm were suitably designed to exhibit a ZDW close to the convenient, in terms of high-power laser availability, wavelength regime of ~1.0 µm. Similarly, the ~4.3 µm core SEST fibre favoured SC generation at 1.5 µm. Pumping the fibres near their ZDW yielded a broad SC.

A significant parameter determining the characteristics of the formed SC was the dispersion profile of the employed fibre, especially the sign of the dispersion at the central wavelength of the input pulse. When the central wavelength of the input pulses lay in the anomalous dispersion regime of the fibre, the SC generation process was governed by the combined effect of soliton fission, SSFS and dispersive wave generation. The formed SC was broad but highly asymmetric, extending mainly...
towards longer wavelengths and characterised by successive peaks. On the other hand, pumping in the normal dispersion regime gave rise to a more symmetric spectrum, since SPM was the dominant effect leading to SC generation. However, when pumping in the normal dispersion regime but very close to the ZDW, even for moderate input peak powers a substantial part of the pulse energy appeared in the anomalous dispersion region after SPM-induced spectral broadening. Therefore, soliton effects were initiated and the observed output spectrum had similar characteristics to the spectrum obtained by pumping in the anomalous dispersion regime.

The experimentally acquired spectra clearly revealed that compound-glass HF technology represents a promising route towards the generation of extremely broad SC spectra for moderate powers and fibre lengths. For example, for the case of a triangular-core fibre with a core diameter of ~0.9 µm and an ultra-high nonlinearity of 1860 W⁻¹ km⁻¹ at 1.55 nm, the generated SC spectrum in a 60-cm piece of this fibre spanned over one octave for pump pulse energies of ~100 pJ. Using the SEST fabrication approach, the realization of fibres with a suitable design, so as to simultaneously exhibit a high nonlinearity and a flat dispersion profile over a broad wavelength region, might lead to a SC optimized in terms of broadness and flatness.

It has to be appreciated that despite the wide span of the experimentally acquired SC spectra presented in this Chapter, their coherence properties were not evaluated. In principle, SC spectra generated with femtosecond pulses under normal GVD conditions are highly coherent, albeit at the cost of reduced spectral width compared to the case of pumping in the anomalous dispersion regime (at the same peak power), due to the rapid initial temporal spreading of the pump pulses [24]. On the other hand, when pumping in the anomalous dispersion region, noise on the input pulses could perturb higher-order soliton propagation through modulation instability, resulting in an incoherent SC spectrum [25]. Nevertheless, it can be shown that by appropriately choosing the required fibre length for given input pulse characteristics or by placing constraints on the input soliton order for a given fibre length, high coherence SC can be achieved even when pumping in the anomalous dispersion regime [24].
Finally, it should be mentioned that compound-glass fibres are extremely promising for mid-IR SC applications. In contrast to silica glass, where transmission is limited up to ~3.5 µm due to the intrinsic vibrational absorption [12], several compound glasses such as tellurite [26], chalcogenide [27] and lead-silicate [28] glasses can guide effectively in the mid-IR, hence they can be particularly attractive for generating spectral components in this region.
Chapter 5: SC generation in short lengths of lead-silicate HF

References


Chapter 5: SC generation in short lengths of lead-silicate HFs


Chapter 6

All-optical regeneration using a step-index bismuth-oxide highly nonlinear fibre

All-optical regenerators are regarded as key components in future high bit rate optical communication systems, allowing for significant transmission distance enhancement. In their simplest form, regenerators compensate the effect of propagation loss and reshape the transmitted signal by cancelling the detrimental effects of amplitude noise accumulation, pulse distortion due to nonlinear effects and dispersion (2R-regenerators). For the realization of all-optical regenerators, fast nonlinear elements are normally used [1]. In particular, fibre-based regenerators have drawn significant attention, since they can support very high bit rates, exceeding 40 Gb/s. To date, fibre-based all-optical regenerators have been demonstrated by utilization of various different nonlinear phenomena, such as SRS [2], SPM [3], XPM [4] and FWM [5].

The SPM-based schemes are particularly attractive due to their simplicity, since they eliminate the need for a pump-probe configuration in the regenerator. Among the SPM-based regenerator configurations [3, 5, 6, 7, 8], the regeneration scheme relying on spectral broadening in a fibre and subsequent offset filtering yields the strongest noise suppression capabilities, while simultaneously achieving a very robust operation [3, 9]. A typical 2R regenerator utilizing the SPM and offset filtering technique is shown in Fig. 6.1a. The operation of such a regenerator is based on the use of a narrow-band optical filter, with its central wavelength offset (detuned) relative to the central wavelength of the signal, as a decision gate. Pulses with sufficient peak power generate substantial spectral broadening due to SPM and can pass through the filter. On the other hand, noisy ‘zero’ signals (spaces) are unable to produce considerable spectral broadening and therefore they are largely rejected by the filter. In general, the filter bandwidth is determined by the requirement that the width of the pulses coming out of the regenerator should have the same width as the initial signal pulses. By proper selection of the filter offset, the launch power and the fibre length and
dispersion characteristics, the 2R regenerator can exhibit a nonlinear transfer function as shown in Fig. 6.1b [10]. If such a response is achieved, the transmission through the regenerating system of pulses with peak powers close to zero is rejected, while the power at the output of the regenerator is almost unvarying for pulses with peak powers over a certain threshold. Such a response is extremely desirable, since it can lead to substantial noise suppression and hence improved received signal quality [11].

![Diagram of 2R regenerator](image)

**Figure 6.1:** (a) 2R regenerator based on SPM induced broadening in a highly nonlinear fibre and subsequent offset filtering and (b) typical nonlinear transfer function of a suitably designed regenerator of this type.

It is important to note that, for this type of regeneration, HNLFs with normal dispersion at the operating wavelength are preferred [5, 9]. This is due to the pulse evolution under normal dispersion conditions. Assuming Gaussian or soliton pulses, the chirp induced by the combined effect of dispersion and SPM in a normal
dispersive fibre results in the formation of almost rectangular pulses. For low peak-power signals, the spectrum of the pulses is not significantly broadened. As the power of the pulses increases, a strong dependence of the bandwidth and the shape of the spectrum on the pulse peak power is observed. However, for pulses with peak powers over a certain threshold, the power of the spectral components in the vicinity of the wavelength of operation changes only slightly with the input pulse peak power. This spectral behaviour is advantageous for a good regenerative performance.

In Fig. 6.2, an application example of a conventional Ge-doped HNLF used in a 2R regeneration configuration based on SPM broadening and offset filtering is simulated. The physical parameters set for the simulations correspond to typical parameters of highly nonlinear Ge-doped silica fibres [9]. The fibre is assumed to have a loss of 0.5 dB/km, a nonlinear coefficient of $16 \text{ W}^{-1}\text{km}^{-1}$, a dispersion slope of $0.02 \text{ ps/nm}^2/\text{km}$ and a dispersion of $-0.25 \text{ ps/nm/km}$ at the central wavelength of the input pulses. The length of the fibre is set to 2 km. Considering only the effects of SPM and dispersion, the output spectra of 3.5 ps Gaussian pulses, after propagation through 2 km of fibre for various pulse input peak powers, are shown in Fig. 6.2a. The band-pass filter employed as a decision gate is considered to be Gaussian, with a 3-dB bandwidth of 1 nm. This bandwidth is chosen so as to ensure that the pulses received after the filter have a FWHM similar to the input pulses. The filter position is selected to be offset by 2.5 nm compared to the central wavelength of the input pulses and is marked with a dashed line in Fig. 6.2a. It can be seen that, for low pulse peak powers ($<100 \text{ mW}$), the power of the spectral components around the filter position is very low, while it becomes almost independent of the input pulse peak power for input peak powers in the range from ~350 up to 800 mW. This spectral behaviour provides the desirable step-like transfer function response, as shown in Fig. 6.2b.
Chapter 6: All-optical regeneration using a step-index Bi-HNLF

Figure 6.2: Simulated (a) spectral traces for various input peak powers and (b) nonlinear transfer function of a 2R regenerator based on the use of a highly nonlinear Ge-doped silica based fibre. The fibre parameters considered were: Length = 2 km, Loss = 0.5 dB/km, Nonlinear coefficient $\gamma = 16 \text{ W}^{-1} \text{km}^{-1}$, Dispersion = -0.25 ps/nm/km. The filter was assumed to be Gaussian with a 3 dB bandwidth of 1.0 nm and was set to be offset to the input pulse central wavelength by 2.5 nm (dashed line with magenta circles in (a)).
It should be appreciated that the presence of chirp in the input pulses can greatly influence the transfer function shape, since it affects the SPM-induced spectral broadening. For example, compared to the SPM spectral behaviour of unchirped input pulses, a negative chirp (downchirp) leads to the generation of more intense peaks, while a positive chirp (upchirp) reduces the number of peaks appearing in the spectrum of the output pulses. Therefore, careful monitoring of the quality of the input pulses is essential for a stable and robust operation. Furthermore, if such 2R regenerators are to be used in long optical links in a cascading configuration, it is essential that the quality of the pulses entering each regenerator stage is similar, both in terms of pulse width and chirp profile. The most common approach to resolve this issue is to make sure that the BPFs employed as decision gates have a bandwidth that matches the bandwidth of the input pulses. Moreover, in real applications timing jitter can severely degrade the optical signal quality, therefore 2R-regenerators might have to be accompanied by an all-optical retiming device. It should, however, be noted that the regeneration scheme based on SPM broadening in the normal dispersion regime and offset filtering has an increased timing-jitter tolerance compared to other types of 2R-optical regenerator schemes, hence it can increase the spacing between subsequent retiming devices.

The use of conventional Ge-doped silica HNLFs in 2R-regeneration applications based on SPM and offset filtering has been extensively reported both theoretically and experimentally [12, 13, 14, 15]. However, long lengths of fibre are normally required for a good regenerative performance to be achieved. HFs have allowed for a reduction in the length requirements [16], while compound-glass fibres represent a promising alternative route for the realisation of meter-long nonlinear devices with improved performance in terms of stability and input power requirements [17].

In this Chapter, the potential of a bismuth-oxide-based nonlinear fibre with an effective nonlinear coefficient of 1100 W⁻¹km⁻¹ and a simple step-index design in an all-optical 2R application is examined. Using just a few meters of this fibre, clear 2R signal regeneration is demonstrated at pulse repetition rates of 10 and 40 GHz. The implemented 2R regenerators exhibit a low power $\times$ length product and provide great resilience to amplitude noise, leading to a substantial improvement in the receiver sensitivity.
6.1 Characteristics of the highly nonlinear bismuth-oxide based fibre employed in the experiments

The fibre sample used for the demonstration of 2R regeneration was fabricated by the Asahi Glass Company. Tab. 6.1 summarizes the characteristics of the bismuth-oxide based fibre at 1550 nm. The fibre is single-mode in the C-band, and cladding modes are effectively eliminated [18]. The ultra-high value of the nonlinear coefficient $\gamma$ in the bismuth fibre stems from the combination of the high intrinsic nonlinearity of bismuth-oxide glass, which has a nonlinear refractive index ~40 times greater than silica, and the small-core fibre design that yields an effective mode area of the order of $3 \mu m^2$.

Perhaps the most promising advantage of bismuth-oxide glass over other highly nonlinear glasses in terms of applicability is the fact that bismuth-based fibres can be spliced to silica-based fibres. With regard to the small-core bismuth fibre employed in the 2R regeneration experiment, the difference between its small mode field diameter and the mode field diameter of a SMF dictated the use of an ultra-high NA silica based fibre (UHNA4, Nufern) as a buffer stage [18]. Through the use of the intermediate fibre, which had a NA of 0.35, the bismuth fibre was pigtailed to SMFs, with a typical total splicing loss of ~2-3 dB at each input port. It should be noted that the use of a tapered waveguide structure could potentially decrease the splicing loss of small-core bismuth fibres to SMFs even further. In Fig. 6.3, the spliced bismuth-oxide highly nonlinear fibre (Bi-HNLF) employed in the experiment is shown.
Chapter 6: All-optical regeneration using a step-index Bi-HNLF

Figure 6.3: Photograph of the connectorised Bi-HNLF employed in the 2R regeneration experiments.

<table>
<thead>
<tr>
<th>Core diameter (µm)</th>
<th>Core refractive index at 1550 nm</th>
<th>Cladding refractive index at 1550 nm</th>
<th>Effective Mode Area at 1550 nm (µm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.97</td>
<td>2.219</td>
<td>2.13</td>
<td>3.04</td>
</tr>
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Table 6.1: Characteristics of the fibre used in the 2R regeneration scheme. The values marked with an asterisk were measured, while the rest were provided by Asahi Glass Company.

The large normal dispersion of the bismuth-oxide based step-index fibre in the C-band allows for the implementation of all-optical devices free from modulation instability induced noise. In particular, it enables its use in a 2R regeneration scheme based on SPM and offset filtering, where a normal dispersion is required, as described in the previous section. Furthermore, the relatively low loss of the bismuth-oxide fibre in combination with its high nonlinearity yields a FOM $\gamma x L_{eff} @1m = 1$ (see Tab. 2.8), which is ~50 times greater than the FOM of a typical highly nonlinear silica based fibre with a loss of 0.5 dB/km and a nonlinear coefficient of 20 W⁻¹km⁻¹. Hence, in general, when compactness is an issue, bismuth based nonlinear fibres have an edge over conventional HNLFs in all-optical signal processing applications. In our
experiments, the large FOM was anticipated to lead to reduced \textit{power x length} product requirements compared to 2R regenerators using silica-based HNLFs or silica HF\textls{[3, 16].}

6.2 Performance of the regenerator at 10 Gb/s

6.2.1 Experimental setup

The performance of the Bi-HNLF was initially assessed in a 10 Gb/s system. The schematic of the experimental setup is shown in Fig. 6.4.

![Figure 6.4: Experimental setup of the regenerator. PC: Polarization controller, BERT: BER Tester.](image)

The transmitter was based on a 10 GHz actively mode-locked EFRL which generated \(~2.2\) ps FWHM pulses at a central wavelength of 1555.7 nm. The pulses were modulated with a \(2^{2^{31}-1}\) PRBS using a lithium-niobate MZM.

Amplitude noise was intentionally introduced in the pulses in a controlled fashion using a second modulator, which was driven by a 15 MHz sinusoidal signal. The amplitude jitter could be varied by adjustment of the modulation depth of the sinusoidal signal and modification of the bias voltage of the modulator to a non-optimum position, so as to degrade the extinction ratio between marks and spaces. Using this approach, it was possible to add intensity noise to the ‘zero’ and the ‘one’ levels of the input pulses in a deterministic and flexible way, which allowed for the assessment of the performance of the regenerator in terms of amplitude equalization and ghost pulse suppression individually.
The signal, degraded by amplitude noise, exiting the second modulator was amplified up to 2 dBm using an EDFA and was intentionally broadened to 5 ps using a BPF with a 3 dB bandwidth of 0.7 nm. The resulting signal was subsequently amplified by a high power Er/Yb amplifier and launched into the 2-m-long connectorized Bi-HNLF. A tunable bandpass grating filter, with a 3 dB bandwidth of 0.6 nm, was used as a decision gate at the output of the regenerator. The filter bandwidth was selected on the grounds that the output pulse width should be similar to the input pulse width of 5.0 ps entering the regenerator.

6.2.2 Results

As mentioned in the Introduction of this Chapter, it is considered advantageous for a regenerator based on the SPM and offset filtering technique to operate in the normal dispersion regime, since for input peak powers over a threshold $P_{thres}$, the combined effects of nonlinearity and normal dispersion lead to the formation of a flat-topped spectrum that changes only slightly with the input power. Such a spectral behaviour is desirable, as it has been shown to be directly connected to a flatter transfer function and hence a better pulse amplitude equalization performance. In Fig. 6.5, the measured spectral profiles of the pulses at the output of the Bi-HNLF are presented for various input peak powers. The almost flat-topped spectra acquired for launched peak powers over ~16 W, indicated that a good regenerative performance should be feasible using the Bi-HNLF. Note that the power levels quoted herein refer to the launched optical power at the input of the Bi-HNLF patchcord and not the optical power in the Bi-HNLF itself, which was significantly reduced due to splicing losses between the SMF patchcord and the Bi-HNLF.
However, despite the generally flat spectral profile of the output pulses, a slight spectral asymmetry between the longer and shorter wavelengths regime (with reference to the central wavelength of the input pulses) was observed. This behaviour was attributed to the slightly asymmetric (in time) and nonlinearly chirped (in frequency) nature of the pulses input to the Bi-HNLF, which was revealed by the SHG-based frequency-resolved optical gating (FROG) characterization performed, as shown in Fig. 6.6(a).

![Figure 6.6](image)

**Figure 6.6:** Intensity and instantaneous frequency profile of the pulses at the (a) input and (b) output of the regenerator measured using SHG-FROG.
The asymmetry of the input pulses observed in the time domain is associated to the mode-locked EFRL transmitter used in the experiment, since the mode-locked generated slightly asymmetric pulses. The high order chirp components evident in the input pulses were attributed to the 0.7 nm BPF employed in the input port. To verify this, the reflectivity of the filter and its group-delay profile were measured (Fig. 6.7).

![Figure 6.7: Reflectivity and group-delay characteristics of the BPF employed at the input of the set-up for pulse broadening.](image)

Indeed, an abrupt change of both the sign and the absolute value of the slope of the group-delay at the central position of the filter was revealed through these characterization measurements. This feature was expected to generate high order chirp components, which would significantly affect the shape of the SPM broadened spectrum. To confirm this, the effect of the filter was taken into account in numerical simulations of the pulse evolution in the Bi-HNLF. The simulations approximated the system’s behaviour by solving the NLSE using the SSF method. The effects of attenuation, SPM and dispersion (up to the third order term) were considered in the simulations. The results are presented in Fig. 6.8, for a launched average power of 31 dBm. A splicing loss of ~2.2 dB, as indicated by experimental evidence, was assumed between the Bi-HNLF and the SMF patchcords.
Chapter 6: All-optical regeneration using a step-index Bi-HNLF

Figure 6.8: Optical spectra at the input of the Bi-HNLF, after propagation through the Bi-HNLF and at the output of the BPF filter. The simulated SPM spectrum at the output of the fibre is also shown.

An ideal transform limited pulse with a width similar to the experimentally measured input pulse width would result in the formation of an almost perfectly symmetric (only slightly degraded by the third order dispersion of the Bi-HNLF) spectrum. However, it can be seen in Fig. 6.8 that the incorporation of the phase modulation imposed by the filter generated an asymmetric output spectrum, with ripples at shorter wavelengths and a flat profile at longer wavelengths (with respect to the central wavelength of the signal), in close agreement with the measured spectrum.

In order to optimize the noise suppression performance of the implemented system, the high power amplifier was operated at its maximum available average power level of ~31 dBm, corresponding to a launched peak power of 44 W. In this way the output filter could be placed at a large offset from the input signal central wavelength, thus ensuring excellent suppression of ghost pulses (noise in the ‘zero’ level) as well as a flat transfer function at high powers. This behaviour is demonstrated in Fig. 6.9a, where the transfer functions obtained numerically for various filter offsets are presented. It can be seen that operating at a larger filter offset results in better noise suppression and amplitude equalization performance at the expense of an increased input pulse peak power required to reach the plateau of stable output power. Due to the
asymmetric nature of the SPM spectrum, the regenerative performance varies, depending on whether the filter is placed at shorter or longer wavelengths with respect to the input. Simulations reveal that regeneration could be achieved by operation at a negative filter offset as well, and this behaviour was also verified experimentally. However, the obtained transfer functions exhibit a narrower plateau stemming from the deep spectral ripples, as shown in Fig. 6.5. Therefore, it was considered advantageous in terms of performance to operate the regenerator at a positive filter offset.

Figure 6.9: (a) Simulated transfer functions for various filter offsets (b) Simulated and measured transfer function of the regenerator for an average launched power of 31 dBm and a positive filter offset of 6.1 nm.
It was experimentally determined that for the maximum available input power, optimum regenerative performance could be achieved for a filter offset of +6.1 nm. Note that SHG-based FROG characterization of the output pulses revealed good quality pulses, with a FWHM of ~6.0 ps and a fairly unchirped profile (Fig. 6.6b). The measured transfer function of the regenerator for this filter offset is presented in Fig. 6.9b together with the corresponding transfer function obtained from numerical simulations. Although a generally good agreement is verified, there is an evident discrepancy between the values obtained in the experiment and the simulation at low peak powers. This is attributed to the ASE noise of the high power amplifier, which allowed some leakage power to pass through the filter even for relatively low peak powers. This behaviour could have been avoided by employing an ASE rejection filter after the high power amplifier.

To verify that the regeneration system did not in itself introduce any additional noise, its performance was examined for a high-quality input signal, in absence of the noise generator. As it can be seen in Fig. 6.10a and 6.10c, eye diagrams of similar quality were obtained both at the input and output of the regenerator. The noise reduction performance of the implemented Bi-HNLF regenerator was tested by artificially inducing noise to the input signal. Measured from the received eye diagrams, the rms standard deviations of the amplitude in the one and zero levels were 11% and 7% of their mean values respectively, while the Q-factor of the signal (assuming Gaussian noise distribution) was only 5.6. The corresponding eye diagram of this input noise-degraded signal is shown in Fig. 6.10b and a significant eye-closure is evident. For comparison, Fig. 6.10d shows the eye diagram of the received signal at the output of the BPF, after regeneration has taken place. Clearly, noise at the spaces has been suppressed, while amplitude equalization has been performed at the marks. The Q-factor of the regenerated signal was ~20, very close to the Q-factor value of 22 that was measured in a back-to-back configuration for the nominally noise-free signal produced by the EFRL-based transmitter. The normal dispersion of the Bi-HNLF, at the wavelengths of operation, has a significant contribution to this behaviour, since it can suppress the detrimental effects of nonlinear phenomena such as modulation instability, that can give rise to additional amplitude noise on the signal [19]
In Fig. 6.11, the amplitude noise intensity histograms prior and after the regeneration process are compared. Clearly, the regenerated signal has a greatly reduced amplitude jitter distribution, similar to the noise distribution of a noise-free input signal. It should be noted that due to noise restrictions imposed by the measuring system used, a 2% standard deviation in amplitude was measured for both the zero and one levels for a nominally noise-free signal.

![Figure 6.10: Eye diagrams of the input and the regenerated signal for the case of a noise-free (a, b) and a noise-contaminated (c, d) input signal.](image)

![Figure 6.11: Amplitude jitter distribution (a) before and (b) after the regeneration process.](image)

To assess and quantify the improvement in the receiver sensitivity introduced by the 2R fibre-based regenerator, BER measurements were performed. The measured BERs are presented in Fig. 6.12 as a function of the launched average optical power into the receiver. For a noise-free input, it was confirmed that the regenerator did not introduce any power penalty. In the case of the noise-contaminated signal, an improvement in
the sensitivity of the receiver of over 5 dB at a BER of $10^{-9}$ resulted from the regenerative process, leading to a similar performance as in the back-to-back case.

The impressive noise suppression performance of the implemented system in combination with its environmental stability, due to the short length of fibre employed and the weak polarization dependence of the SPM induced broadening, clearly reveal the potential of the Bi-HNLF in fibre-based regeneration applications. However, a disadvantage inherent to 2R SPM-based fibre regenerators is their poor power efficiency. This is due to the fact that only a small portion of the SPM-generated spectrum received after the nonlinear fibre element is selected by the decision-gate-equivalent output filter. The overall power loss induced by the Bi-HNLF-based system, defined as the ratio of the average output power to the power input to the Bi-HNLF, was 24 dB. A decrease in the propagation loss of the Bi-HNLF as well as its splicing loss to silica SMFs would lead to a significant improvement in terms of power efficiency.

![Figure 6.12: BER measurements of the input and the regenerated signal for the case of a noise-free and a noise-contaminated input signal.](image)

With regard to the power requirements of the regenerator, the peak power $\times$ length product of this device was just 0.09 W·km, much lower than the relevant figure for
similar devices relying on silica-based HNLFs or even silica based HFs (see Tab. 6.2, section 6.4). Clearly an even lower power x length product could be achieved by choosing to operate at lower powers, however this would be at the expense of noise-suppression performance. It is expected that a further decrease in the splicing losses between the Bi-HNLF and silica fibres or even the combination of the high material nonlinearity that Bismuth glass offers with HF technology can lead to optimised performance with extremely lower power requirements.

### 6.3 Performance of the regenerator at 40 Gb/s

#### 6.3.1 Experimental setup

The performance of the Bi-HNLF in a 2R regeneration scheme was also examined at 40 Gb/s. The experimental set-up is presented in Fig. 6.13 and is similar to the configuration of the 10 Gb/s experiment with the exception of the multiplexing and pulse compression sections.

![Experimental setup of the Bi-HNLF 2R regenerator at 40 Gb/s](image)

**Figure 6.13:** Experimental setup of the Bi-HNLF 2R regenerator at 40 Gb/s. MUX: Multiplexer, POL: Polarizer, ATT: Attenuator, EAM: Electro-absorption modulator.

The 40 Gb/s data signal was obtained by multiplexing the 2 ps pulses generated from the EFRL transmitter by means of a 1:4 passive fibre delay line based multiplexer. The dispersion induced to the signal by the use of the passive multiplexer was compensated from a 10-m long DCF. In order to increase the peak power of the pulses
launched to the Bi-HNLF while keeping the same high-power amplifier as in the 10 Gb/s case, a pulse compression stage, based on the use of a 1.5 km-long dispersion-decreasing fibre (DDF), was realized. The pulses at the output of the DDF had a FWHM of 1.4 ps and exhibited a fairly linear change in the instantaneous frequency as well as a clear pedestal 12 dB lower than the pulse peak power (Fig. 6.14a). These pulses were amplified using a high power Er/Yb amplifier and launched to the 2-m long Bi-HNLF. A 0.6 nm tunable bandpass grating filter was employed as a decision gate at the output of the regenerator and an EAM-based demultiplexer was used for obtaining the four 10 Gb/s constituents of the 40 Gb/s signal. It should be noted that despite the poor quality of the input pulses, the pulse-reshaping capability of the implemented regenerator provided almost unchirped and pedestal-free pulses at the output of the system (Fig. 6.14b).

![Figure 6.14: Intensity and instantaneous frequency profile of the pulses at the (a) input and (b) output of the 40 Gb/s regenerator measured using SHG-FROG.](image)

### 6.3.2 Results

As in the previous experiment, in order to optimize the performance of the regenerator in terms of noise suppression and amplitude equalization, the high-power EDFA was operated at its maximum average output power point (~31 dBm). As shown in section 6.2.2, the input pulse characteristics significantly affect the shape of the SPM broadened spectrum received at the output of the Bi-HNLF. Indeed, the difference between the input pulse characteristics of the 40 and 10 Gb/s regenerator configurations lead to qualitatively dissimilar SPM-induced spectral shapes. In figure
6.15a, the SPM spectrum received at the output of the Bi-HNLF, for the 40 Gb/s case, and with an input average power of ~31 dBm, is presented. Numerical simulations performed using the obtained pulse profile measured by the SHG-FROG system (Fig. 6.14a) yielded a SPM broadened spectrum in good agreement with the experimentally acquired one, as shown in Fig. 6.15a. In the 40 Gb/s regeneration configuration it was considered advantageous to operate the regenerator at a negative filter offset, so as to decrease the effect of the EDFA-induced ASE noise, which peaked towards longer wavelengths compared to the input signal central wavelength. Assessing the performance of the regenerator in the presence of noise and in terms of the eye-opening of the received pulses, it was found that, for the experimental conditions used, the optimum filter offset relative to the central wavelength of the input pulses was 3.9 nm. For this filter position, the obtained transfer function of the regenerator is presented in Fig. 6.15b.
Figure 6.15: (a) Optical spectra at the input of the Bi-HNLF, after propagation through the Bi-HNLF and at the output of the BPF filter (b) Measured transfer function of the regenerator for the 40 Gb/s experiment.

Compared to the transfer function obtained in the 10 Gb/s case, the plateau of the regenerator implemented at 40 Gb/s appears at lower input peak powers at the expense of a degraded suppression ratio at the zero level. This behaviour is in agreement with the discussion in section 6.2.2 (Fig. 6.9a). With regard to the output pulse characteristics, SHG-FROG measurements revealed an intensity and chirp profile similar to the case of the 10 Gb/s configuration (compare Fig. 6.14b to Fig. 6.6b). This implies that the output pulse characteristics are predominantly determined by the optical BPF employed at the output of the setup as the decision gate.
The noise suppression performance of the regenerator was assessed both in terms of eye diagrams and BER measurements. Initially it was confirmed that the system did not, in itself, introduce any noise on the input signal when the noise generator stage was removed, Fig. 6.16a_i and Fig. 6.16a_ii. Subsequently, amplitude noise was added and the behaviour of the system was examined. It should be noted that, due to the 20 GHz bandwidth of the receiver employed for the acquisition of the eye diagrams, it was difficult to assess the induced noise by direct measurement of the amplitude histograms, especially since severe ringing was evident. Therefore, the induced noise was assessed by measurements performed on the initial 10 Gb/s signal, prior to multiplexing. It should be appreciated that this approximation led to an underestimation of the noise that was present in the input signal, since both the EDFA’s noise and the pulse propagation through the DDF were expected to further degrade the SNR of the input pulses. Histogram measurements of the 10 Gb/s pulses revealed a standard deviation of ~4% and ~11% at the spaces and marks respectively. The corresponding eye diagram of the 40 Gb/s input signal is presented in Fig. 6.16a_iii, while the received eye diagram after regeneration is shown in Fig 6.16a_iv. An improvement in the eye opening, stemming from the regenerative process, is evident. To quantify the regenerative performance of the system, the 40 Gb/s signal was demultiplexed into its four 10 Gb/s tributaries using an EAM, and BER measurements were carried out on each of them. Error-free operation was achieved for all channels after the regeneration process, with an improvement in the receiver sensitivity of over 2 dB (Fig.6.16b).
Figure 6.16: (a) Eye diagrams of the input and the regenerated signal for the case of a noise-free (i, ii) and a noise-contaminated (iii, iv) input signal. (b) Corresponding BER measurements for all the constituent channels of the 40 Gb/s signal.

6.4 Conclusions

In this Chapter the use of a 2 m-long Bi-HNLF in a 2R regeneration scheme based on SPM-induced spectral broadening and offset filtering was reported at rates of 10 Gb/s and 40 Gb/s. The ultra-high nonlinearity per unit length of the Bi-HNLF enabled the employment of a fibre piece as short as 2m, which ensured both the compactness and
environmental stability of the system. Furthermore, the normal dispersion of the Bi-HNLF in the C-band favoured the performance of the system by suppressing the detrimental effect of Modulation Instability, which leads to coherence degradation and hence the induction of amplitude noise. The 2R regenerator formed by the Bi-HNLF showed excellent performance, as it was revealed by BER measurements and eye diagram quality evaluations. For an average launched power of \(\sim31\) dBm and RZ pulses with a duty cycle of \(\sim1:20\), the improvement in the sensitivity of the receiver that resulted from the regenerative process was found to be \(\sim5\) dB for a 10 Gb/s input signal and \(>2\) dB for a 40 Gb/s signal. The power length product of the regenerator was just 0.09 W km, much lower compared to the power length products of similar devices based on SMFs, DSFs and even silica-based HF, as shown in Tab. 6.2. Although a direct comparison between the reported results should be avoided, since performance in terms of BER improvement is a critical issue for a fair assessment, the table clearly demonstrates the potential of CG-HNLFs in reducing the power and length requirements for effective all-optical regeneration.

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Fibre Characteristics</th>
<th>Length (km)</th>
<th>Peak Power (W)</th>
<th>Power x Length (W km(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard DSF</strong></td>
<td>45 (\mu)m(^2) effective mode area ([3])</td>
<td>8.0</td>
<td>0.9</td>
<td>7.20</td>
</tr>
<tr>
<td><strong>Highly Nonlinear DSF</strong></td>
<td>(D= -0.5) ps/nm/km (40) Gb/s RZ 1.5 nm offset ([13])</td>
<td>2.0</td>
<td>2.14</td>
<td>4.14</td>
</tr>
<tr>
<td></td>
<td>(\gamma = 8.4) W(^{-1}) km(^{-1}) ([14]) (D= -0.25) ps/nm/km 80 Gb/s RZ pulses 2.8 nm offset</td>
<td>2.7</td>
<td>1.25</td>
<td>3.37</td>
</tr>
<tr>
<td></td>
<td>(\gamma = 8.4) W(^{-1}) km(^{-1}) ([15]) (D= -0.7) ps/nm/km 40 Gb/s RZ 2 nm offset</td>
<td>2.5</td>
<td>1.16</td>
<td>2.90</td>
</tr>
<tr>
<td><strong>Si-HF</strong></td>
<td>(\gamma = 35) W(^{-1}) km(^{-1}) 1.93 nm offset ([16])</td>
<td>0.0033</td>
<td>40</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Bi-HNLF</strong></td>
<td>(\gamma = 1100) W(^{-1}) km(^{-1}) 0.0020</td>
<td>40</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

**Table 6.2:** Typical examples of demonstrated fibre based regenerators.

For the operation of the regenerator, a commercially available high power amplifier was employed. Targeting at optimum performance, the high power amplifier was operated at its maximum output power point. Although it is appreciated that the
average power of ~31 dBm used is still considered high for practical applications, it should be noted that the regenerator could readily operate at lower average powers, however at the expense of degraded noise suppression and amplitude equalization performance. Moreover, it is expected that further improvement in the fabrication process of Bi-HNLFs would lead to a drastic reduction of the propagation loss and the splicing loss to SMFs, or even the realization of designs with an even higher nonlinearity per unit length, thus enabling operation at lower average powers and ultimately the employment of conventional EDFAs. Similarly, higher nonlinearity and reduced losses would also improve the power efficiency of Bi-HNLF based regenerators, which is currently worse than the power efficiency of devices based on SMFs and DSFs.

It has to be noted that since SPM has a femtosecond response time, the 2R-regeneration technique based on SPM and offset filtering is readily scalable to ultra-high bit rates, e.g., 160 Gb/s and beyond [20]. Although general guidelines for optimal regenerative performance have been proposed and simple scaling rules concerning the choice of pulse and fibre characteristics apply when moving to higher bit-rates [21, 22], it is generally considered difficult to operate at ultra-high speeds. This is mainly due to limitations imposed by fibre dispersion and required pulse peak power. In particular, the rapid pulse-broadening of the very short pulses required when operating at high speeds can lead to degraded performance due to interference of adjacent bit-slots [22], while the use of high peak power pulses might stimulate undesirable higher order nonlinear effects, such as intrapulse Raman scattering and self-steepening.

The results of this Chapter clearly demonstrate the potential of compound-glass technology in all-optical signal processing applications. As the fabrication process of such fibres matures, their use in practical high-speed all-optical networks is expected to become feasible. Ultimately, the combination of the high material nonlinearity offered by compound glasses with the rapidly evolving HF technology can result in optimised device performance, leading to the realization of devices with greatly reduced power and/or length requirements.
Chapter 6: All-optical regeneration using a step-index Bi-HNLF

References


Chapter 7

Pulse compression in a step-index bismuth-oxide highly nonlinear fibre

The generation of ultrashort optical pulses with sub-picosecond width is desirable for a number of applications, such as optical coherence tomography [1], metrology [2], terahertz imaging [3] and ultra-high bit-rate optical communications [4]. In particular for optical communications, the generation of pedestal-free, chirp-free, sub-picosecond RZ pulses at repetition rates over 10 GHz inside the C-band would be essential for the realization of future ultrafast OTDM systems.

Mode-locked fibre ring lasers, using either an Er-doped fibre [5] or a SOA [6] as gain medium, have been able to generate pulses in the picosecond range when operating at high repetition rates. Although the direct generation of sub-picosecond pulses should be possible at high repetition rates using techniques such as hybrid mode-locking [7] or asynchronous hybrid mode-locking [8], picosecond-range pulses generated from actively-mode locked lasers still exhibit superior timing jitter performance and chirp characteristics. Therefore, instead of directly generating femtosecond pulses at a high repetition rate, it is considered advantageous to generate high-quality picosecond pulses from conventional mode-locked fibre-lasers and to apply an external pulse compression scheme to obtain sub-picosecond pulses.

Amongst the various pulse compression schemes demonstrated, perhaps the most widely known and one of the earliest reported is the nonlinear propagation of higher-order solitons in optical fibres [9]. This technique exploits the periodical change of the pulse shape of a higher order soliton propagating through an optical fibre for the generation of a compressed pulse. Impressive compression ratios have been obtained using this scheme. For, example, in Ref. [10], pulse compression of 3.6 ps pulses down to 185 fs is demonstrated by propagation along 30 m of fibre. However, the quality of the received pulse at the optimum compression point is low, since a broad pedestal carrying most of the initial soliton energy accommodates the compressed
pulse [9, 10]. Furthermore, high powers are required for large pulse compression ratios to be achieved and, as a rule of thumb, larger pulse compression ratios lead to lower pulse quality.

A different approach relies on the adiabatic compression of solitons when propagating through DDFs. Provided that the decreasing dispersion of such fibres is adiabatic, a propagating fundamental soliton will retain its solitonic nature and adjust its pulsewidth as a response to the dispersion-induced perturbation of its energy. Under the assumption of lossless propagation at a constant nonlinear coefficient, the achieved pulse compression using this technique can be determined by the ratio of the DDF’s output to input dispersion. High-quality, low-pedestal compressed pulses, at powers relatively low compared to the technique relying on the nonlinear propagation of higher-order solitons in constant dispersion fibres, have been achieved using DDF-induced adiabatic soliton compression [11, 12]. For example, in [12], a 950 m-long dispersion-flattened DDF was employed for the compression of 2.4 ps pulses down to 100 fs pulses using this approach. However, the strict fabrication requirements of DDFs in combination with the required fibre length for large compression ratios hinders the applicability of this technique. A variation of the adiabatic soliton compression technique relies on launching higher order solitons in DDFs [13]. Although theoretically this scheme offers a pulse quality similar to the adiabatic soliton compression technique at reduced power and fibre length requirements, DDFs with very accurate dispersion profiles are required, hence the fabrication requirements are still limiting the applicability of this technique. To avoid the demanding fabrication requirements that the DDFs design impose, the use of comb-dispersion profiled fibres, comprising of the alternate concatenation of low and high dispersion segments of different fibres, so that the dispersion-decreasing profile of a DDF is effectively simulated, has been proposed [14]. By combining this comb-like dispersion profile with a comb-like profile of the nonlinear coefficient, so that alternating regions of high nonlinearity-low dispersion and low nonlinearity-high dispersion regions are formed [15], impressive pulse compressions have been demonstrated [16, 17]. For example, in [17], the pulse compression of a 40 GHz pulse sequence from 7 ps down to 375 fs has been demonstrated by realising such a comb-like nonlinearity and dispersion profile. However, strict requirements regarding the properties and the
length of the alternating segments of fibre, as well as the required fibre length, which normally exceeds a kilometre, limit the practical application of this technique.

An alternative approach, capable of providing a pulse quality better than the compression scheme based on nonlinear propagation of higher-order solitons, which does not require labour-intensive specialized DDFs, relies on the nonlinear propagation of pulses in the normal dispersion regime of optical fibres [18]. In this regime, when high intensity pulses are launched into the fibre, the combined effect of GVD and nonlinearity leads to the formation of almost rectangular pulses, characterized by a linear change in the instantaneous frequency throughout the duration of the pulse. These rectangular pulses can be readily compressed if they are propagated linearly through a suitable length of an anomalously dispersive fibre or a properly designed FBG [19, 20]. High quality compressed pulses have already been demonstrated using this approach, for example in [20], the compression of 1.8 ps pulses down to 320 fs was demonstrated at a repetition rate of 10 GHz. However, if normal-dispersion fibres with a low nonlinearity are used, high powers or long fibre lengths are normally required. The power and length requirements can be greatly reduced if fibres with a high nonlinearity and a strong normal dispersion are employed [21, 22].

In this Chapter, the bismuth-oxide based fibre with an ultra-high nonlinearity and a normal dispersion in the C-band presented in Chapter 6 is used in a similar compression scheme. The combination of the large normal dispersion and the high nonlinearity of this fibre favours the formation of highly chirped pulses at relatively low peak powers, even when a piece of fibre as short as 2m is used. Due to propagation in the normal dispersion regime, the formed pulses exhibit a linear change in the instantaneous frequency, hence they can easily be transformed to a compressed pulse by propagating through a suitable length of anomalously dispersive in the C-band (conventional SMF). Pulses with a duration of ~1.5-1.9 ps and at a repetition rate of 10 GHz are compressed down to ~400 fs using this technique for launched powers into the Bi-HNLF as low as ~24.5 dBm. The compressed pulses are characterized using a linear variation of the FROG technique. The suitability of the linear FROG (L-FROG) in accurately retrieving both the intensity and the phase information of sub-
picosecond pulses is verified by comparing the experimentally acquired results with numerical simulations.

### 7.1 Nonlinear propagation in the bismuth-oxide highly nonlinear fibre

Prior to the experimental demonstration of pulse compression using the Bi-HNLF, the nonlinear propagation of sech-profile pulses in this fibre was simulated using the SSF method. This was necessary to provide an estimation of the appropriate length of SMF that had to be used for chirp compensation of the pulses exiting the Bi-HNLF. The fibre characteristics used in the simulations have been provided in Chapter 6, Tab. 6.1. To account for the experimental conditions set by the available components, the input sech pulsewidth was set to 1.6 ps FWHM and the average pump power, input to the Bi-HNLF, to 25 dBm. The input pulses were assumed to be unchirped and their central wavelength was set to 1548 nm. The repetition rate of the pulses was assumed to be 10 GHz. In Fig. 7.1 the simulated pulse shape and instantaneous frequency profile of the output pulses from the 2 m-long Bi-HNLF are shown. In the simulations, the effects of fibre loss, dispersion up to the third-order term and Kerr nonlinearity were taken into account. Almost rectangular shaped pulses are obtained, with a linear change in the instantaneous frequency throughout the greatest part of the pulse duration.

![Figure 7.1: Simulated intensity (normalised to the input pulse peak power) and instantaneous frequency profile of the output pulses from the 2 m-long Bi-HNLF, assuming ideal sech-profile input pulses with 1.6 ps FWHM, a central wavelength of 1548 nm, a repetition rate of 10 GHz and an average power of 25 dBm.](image)

The chirped rectangular pulses obtained at the output of the Bi-HNLF favour the use of a conventional SMF to achieve pulse compression. In Fig. 7.2, the shape of the
compressed pulses received after propagation through various lengths of SMF is presented.

Figure 7.2: Simulated compressed pulse shape for different lengths of SMF, assuming the input pulse characteristics described in Fig. 7.1. The duration and shape of the compressed pulses is greatly dependent on the length of SMF used.

For the case considered, the SMF length required for maximum pulse compression is \( \sim 30 \text{ m} \). It should be noted that the received pulse shape is greatly dependent on the actual length of SMF used: deviations from the optimum length as small as a meter can lead to a compressed pulse with drastically different profile.

7.2 Characterisation of short pulses using the FROG technique

Spectrographic pulse characterization techniques are based on the acquisition of spectrograms, i.e. time-frequency distributions of a pulse or a pair of pulses. A spectrogram is acquired by measuring the intensity spectrum of a pulse, described by an electric field \( E(t) \), after gating it with a function \( G(t) \), for various delays \( \tau \) between the pulse under test and the gating function. Mathematically, a spectrogram is described by the relation

\[
S(\tau, \omega) = \left| \int E(t) G(t - \tau) e^{i\omega t} dt \right|^2
\]  

(7.1)

and is a function of both the time delay and the frequency. From the obtained spectrogram, the phase and intensity profile of both the pulse and the gate function can be reconstructed by applying iterative numerical calculations [23, 24].
The SHG-FROG technique represents the most popular implementation of spectrographic pulse-characterisation techniques [24]. It is based on splitting the pulse under test into two replicas and passing one of them through a delay line. The two replicas are subsequently recombined in a SHG crystal, generating photons at the sum-frequency of the two participating photons. Using a spectrometer, the resulting SHG pulse is spectrally resolved. Repeating this process for various time delays between the two replicas, a spectrogram can be obtained.

The biggest advantage of SHG-FROG is the fact that it is an inherently self-referenced technique, hence timing jitter effects are eliminated. However, a severe limitation stems from the fact that the employed nonlinear crystal has to be able to frequency double over the entire pulse bandwidth. An increased bandwidth of the SHG crystal comes at the expense of reduced efficiency. Further disadvantages of the SHG-FROG method concern the difficulty in carefully aligning the free-space optics involved in the measurement, as well as the fact that, since SHG-FROG relies on a nonlinear process, the sensitivity of the approach scales with the peak power.

It was recently shown that, by applying a suitable deconvolution algorithm, it is possible to predict the pulse characteristics from a spectrogram, even if the relation between the pulse and the gate function is unknown [23]. Hence, any gate function, instead of a replica of the original pulse employed in the SHG-FROG technique, can suffice for a FROG-based characterization. Instead of using nonlinear effects, a linear pulse characterisation measurement can therefore be applied by employing a modulator for the realization of the gating function [24]. Such a set up is shown in Fig. 7.3. The pulses under test pass through an optical splitter and two replicas are created. One of them passes through an optical modulator, while the other experiences a variable time delay and is subsequently detected by a photodiode. The produced electric signal drives the modulator, which provides the gating function. Using this approach, the system becomes self-referenced. Moreover, the set-up is robust, since no precise alignment of free-space optic components is required. The sensitivity of the L-FROG measurement is greatly dependent on the bandwidth of the modulator, as it will be shown later in this Chapter. Broadband optical modulators can therefore be employed for an accurate characterisation of the pulse characteristics.
7.3 Demonstration of pulse compression using a 2 m-long bismuth-oxide highly nonlinear fibre

In Fig. 7.4, the experimental set-up for the demonstration of pulse compression using the Bi-HNLF is shown.

A 10 GHz actively mode-locked EFRL able to generate 1.4 -2.5 ps FWHM sech$^2$ pulses at a central wavelength tunable in the range 1530-1560 nm was used as a transmitter. In our experiment the central wavelength of the pulses was set to 1548.6 nm. The pulse train was amplified by a high power Er/Yb amplifier up to 24.45 dBm.
and launched into a 2 m-long Bi-HNLF with its polarization state adjusted so that optimal SPM-induced spectral broadening was obtained at the output of the fibre. A ~31.5 m-long section of SMF accommodated compression of the chirped, square-profiled pulses, which were obtained at the output of the Bi-HNLF.

The phase and intensity characteristics of the input and output pulses were obtained using L-FROG, where the gating was performed by a commercial LiNbO$_3$ MZM. L-FROG was preferred over the more conventional SHG-FROG, since it has the advantage of a higher sensitivity (section 7.2), thereby allowing an improved characterization of the formation of any pedestal features on the pulses.

The intensity and instantaneous frequency profile of the launched pulses to the Bi-HNLF, retrieved using the L-FROG technique, are presented in Fig. 7.5. A FWHM of ~1.47 ps was obtained. However, a small asymmetry in the pulse shape was evident. This asymmetry, together with the third order dispersion of the Bi-HNLF, was expected to lead to the generation of an asymmetric spectrum at the output of the Bi-HNLF, which indeed was observed (Fig. 7.6b).

![Figure 7.5:](image)

**Figure 7.5:** Intensity and instantaneous frequency profile of the pulses launched into the Bi-HNLF. The intensity profile of an ideal sech pulse with the same FWHM is also shown.

Since the length of SMF that had to be chosen for maximum pulse compression was dictated by the actual experimental launched pulse characteristics (pulsewidth and peak power) to the Bi-HNLF, the calculated SMF length of 30 m (section 7.1) served only as an estimated starting point. By adjustment of the SMF length by ~0.5 m increments, it was experimentally determined that a fibre length of ~31.5 m was close to the required for maximum pulse compression. In Fig. 7.6a, the characteristics of the
compressed pulse retrieved by the L-FROG method are presented and compared to the output pulse characteristics obtained by numerical simulations.

![Graph](image)

**Figure 7.6:** (a) Compressed pulse intensity (solid lines) and instantaneous frequency profile (dotted lines) comparison between numerical simulations (red lines) and retrieved pulses (blue lines) using MZM-based L-FROG, for an average launched power into the Bi-HNLF of 24.45 dBm (SMF length: 31.5 m, pulse central wavelength: 1548.6 nm, repetition rate: 10 GHz, input pulse profile as shown in Fig. 7.5) (b) Comparison of the retrieved, measured and simulated spectra of the compressed pulses.

The simulations were performed using the intensity and instantaneous frequency profile of the launched pulses, as obtained from the L-FROG (Fig. 7.5). The very good agreement between the simulated and the experimental spectral profiles validates the measured dispersion and nonlinear characteristics of the Bi-HNLF. A compressed pulse with a FWHM of ~ 385 fs was retrieved, which is in good agreement with that
predicted by numerical simulations (395 fs). The small, residual chirp evident in the central pulse portion indicates that, although optimum pulse compression was not accurately achieved, the employed SMF length was very close to the length required for maximum pulse compression.

The same analysis was performed for an average launched power of 23.80 dBm (Fig. 7.7). The FWHM of the retrieved pulse in this case was 405 fs, in good agreement with the predicted by numerical simulations pulse width of 420 fs (Fig. 7.7a).
Chapter 7: Pulse compression in a step-index Bi-HNLF

Figure 7.7: (a) Compressed pulse intensity (solid lines) and instantaneous frequency profile (dotted lines) comparison between numerical simulations (red lines) and retrieved pulses (blue lines) using MZM-based L-FROG for an average input power to the Bi-HNLF of 23.80 dBm (SMF length: 31.5 m, pulse central wavelength: 1548.6 nm, repetition rate: 10 GHz, input pulse profile as shown in Fig. 7.5) (b) Comparison of the retrieved, measured and simulated spectra of the compressed pulses.

The good agreement observed between the simulations and the retrieved L-FROG data in both cases validates the parameters used for the numerical simulations. It should, however, be noted that the retrieved pulses exhibited a lower pedestal than expected by numerical simulations. To explain this discrepancy, the reason for the formation of pedestals has to be considered. In particular, for the pulse compression technique employed, the pedestal formation is attributed to the residual nonlinear chirp appearing at the sharp edges of the broadened by normal dispersion and SPM pulse [20]. This
nonlinear chirp, which occurs as an oscillatory structure far from the pulse centre, is shown in Fig. 7.8, where the simulated pulse shape after propagation through the Bi-HNLF in the case of an input average power of 24.45 dBm is presented (the input pulse shown in Fig. 7.5 was used in the numerical simulations). Since this nonlinear chirp is mainly generated at both sides of the spectrum, its effect in the formation of pedestals can be suppressed by filtering the spectral components at the edge of the spectrum [20]. It can be seen in Figs 7.6b and Fig. 7.7b that there was a small discrepancy between the retrieved spectrum and the measured by the OSA spectrum for wavelength components beyond ~1557 nm. Therefore, this underestimation of the intensity of the longer wavelength components could result in an underestimation of the formed sidelobes in the compressed pulse.

![Figure 7.8](image)

**Figure 7.8:** Simulated intensity (blue line) and instantaneous frequency (cyan) profile of the pulses after propagating through the 2 m-long Bi-HNLF. The input pulse characteristics shown in Fig. 7.5 (pulse central wavelength: 1548.6 nm, repetition rate: 10 GHz) were considered, while the input average power was set to 24.45 dBm. The nonlinear chirp at the pulse edges is clearly observed.

As mentioned above, the formation of the sidelobes observed in the compressed pulses could be suppressed by applying suitable spectral filtering. Numerical simulations were performed to study this improvement. For an input pulse profile similar to that shown in Fig. 7.5, the intensity profile of the compressed pulses for an average input power of 24.45 dBm and 28 dBm, after propagation through a 31.5 m-long and 32 m-long SMF respectively, was simulated (Fig. 7.9). By considering Gaussian spectral
filtering at the output of the SMF, pulses of improved quality in terms of sidelobe generation were obtained, albeit at the expense of slightly wider output pulses.

![Simulation of spectral filtering on the intensity profile of compressed pulses](image)

**Figure 7.9:** Simulated effect of spectral filtering on the intensity profile of the compressed pulses, for an average input power of (a) 24.45 dBm (31.5 m-long SMF) and (b) 28 dBm (32 m-long SMF). The input pulse profile shown in Fig. 7.5 (pulse central wavelength: 1548.6 nm, repetition rate: 10 GHz) was considered.

It should be noted that the 2-m long pigtailed Bi-HNLF employed in the pulse compression experiment was the only available piece of bismuth-based step-index fibre at the time, therefore no optimization of its length was possible. Numerical simulations were carried out to predict the performance of the Bi-HNLF for different fibre lengths. The simulations revealed that the performance of the fibre would be greatly enhanced if a shorter fibre piece was employed. This behaviour can be attributed to the effect of the large GVD that the Bi-HNLF exhibits. The large dispersion of the fibre leads to rapid pulse spreading, which in turn affects the spectral broadening and limits the induced chirp [18]. Therefore, a longer fibre piece does not
necessarily lead to a greater spectral broadening, since the pulse evolution is governed by the interplay of both the GVD and the fibre nonlinearity. This can be seen in Fig. 7.10, which presents the numerically calculated pulse and instantaneous frequency profile at the output of different lengths of Bi-HNLF, considering an input pulse with a profile similar to that shown in Fig. 7.5 and an average input power of 28 dBm. It can be seen that for a Bi-HNLF of 0.5 m (Fig. 7.10a), an almost rectangular pulse is obtained, with a large positive chirp throughout its duration (~4.25 ps). For a 1 m-long Bi-HNLF (Fig. 7.10b), the output pulse has a FWHM of ~6.5 ps and exhibits a slight oscillatory behaviour near the pulse edges, i.e. optical wave breaking is taking place. The quality of the pulse is greatly degraded for a fibre length of 2 m (Fig. 7.10c), in which case a strong oscillating behaviour stemming from wave-breaking appears at both the leading and trailing edges of the pulse and a reduction of the gradient of the linear instantaneous frequency profile is observed. In Fig. 7.11, the optimum compressed pulse, obtained after propagation through the Bi-HNLF and a suitable length of SMF, is examined for the different lengths of Bi-HNLF. It can be seen that a similar compressed pulse of ~290 fs is obtained for a Bi-HNLF length of 0.5 m and 1 m. However, the use of a 0.5 m-long piece is advantageous, both in terms of compactness of the pulse compressor and pulse quality in terms of sidelobes suppression. On the contrary, using a 2 m-long Bi-HNLF, yields a slightly broader pulse with more pronounced sidelobes.
Figure 7.10: Simulated intensity and instantaneous frequency profile of the pulses at the output of a (a) 0.5 m-long, (b) 1 m-long, and (c) 2 m-long Bi-HNLF. The input pulse profile shown in Fig. 7.5 (pulse central wavelength: 1548.6 nm, repetition rate: 10 GHz) was considered. The average pump power was set to 28 dBm.
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7.4 Dependence of the L-FROG performance on the optical bandwidth of the gating device

L-FROG has the advantage of a higher sensitivity as compared to the more conventional SHG-FROG, however the pulse widths that can be reliably characterised are typically limited by the duration of the optical gate, or more crucially by the optical bandwidth of the gating devices. In order to study this dependence, the same setup as shown in Fig. 7.4 was employed. The compressed pulses were characterised using L-FROG and the gating was performed either in an electro-absorption modulator (EAM) or in a LiNbO$_3$ MZM.

In this experiment, the central wavelength of the pulses was 1548.8 nm. The pulse train was amplified up to an average power of 25.8 dBm and was launched into the Bi-HNLF. The FWHM duration of the input pulses was measured both by EAM and a MZM-based L-FROG and was found to be $\sim 1.85$ ps (Fig. 7.12a). At the output of the Bi-HNLF, the pulses were broadened up to $\sim 9$ ps FWHM with a fairly linear instantaneous frequency profile throughout the pulse duration, as shown in Fig. 7.12b.
It should be noted that the L-FROG measurement setup employed the use of a 3 m-long SMF, which was taken into account in the numerical simulations shown in the same figure. The difference between the retrieved temporal pulse intensity and that predicted by numerical simulations pulse intensity is attributed to random polarization instabilities during the L-FROG measurement.

Figure 7.12: Temporal intensity (blue and red lines) and instantaneous frequency profile (cyan and magenta lines) of (a) the input pulses and (b) the pulses after propagation through the 2 m-long Bi-HNLF (pulse central wavelength: 1548.8 nm, repetition rate: 10 GHz, average input power 25.8 dBm). The blue and cyan lines correspond to the retrieved pulse characteristics, while the red and magenta lines were obtained from numerical simulations.

The broadened, chirped pulses obtained at the output of the Bi-HNLF were compressed by propagating through a 32 m-long SMF. In Fig. 7.13, the directly
measured spectrum of the compressed pulses on an OSA is compared to the retrieved spectrum obtained both with EAM- and MZM-based L-FROG.

![Graph showing spectra comparison](image)

**Figure 7.13:** Directly measured, retrieved and predicted by numerical simulations spectra of the compressed pulses (pulse central wavelength: 1548.8 nm, repetition rate: 10 GHz, average input power: 25.8 dBm, SMF length: 32 m).

It can be seen that the frequency cut-off of the semiconductor in the EAM is unable to capture wavelength components below \(\sim 1540\) nm, thus making this device inadequate for characterizing broadband pulses. On the other hand, the retrieved spectrum obtained from the MZM-based L-FROG measurement matches well with the directly measured spectrum, owing to the much broader optical bandwidth of this modulator.

The retrieved temporal pulse shape and instantaneous frequency profile obtained from the EAM and MZM-based L-FROG measurements were compared to numerical simulations. The simulations, which were based on the SSF method, considered the effects of dispersion up to the third order term and Kerr nonlinearity. A good agreement was observed in the case of the MZM-based L-FROG, which yielded a compressed pulse of \(\sim 405\) fs FWHM as compared to the theoretically calculated FWHM duration of \(\sim 395\) fs (Fig. 7.14a). On the contrary, the EAM-based FROG yielded a central compressed pulse with a FWHM duration of \(\sim 385\) fs, but with a very
different instantaneous frequency profile and sidelobes intensity profile than the numerically predicted (Fig. 7.14b).

**Figure 7.14:** Compressed pulse shape (solid lines) and instantaneous frequency profile (dotted lines) comparison between numerical simulations (red lines) and retrieved pulses (blue lines) using (a) MZM-based L-FROG and (b) EAM-based L-FROG for an average input power of 25.8 dBm and the input pulse characteristics shown in Fig. 7.12a.
7.5 Conclusions

In this Chapter, the use of a Bi-HNLF with a high normal dispersion throughout the C-band was presented in a simple external pulse compression experiment. The experiment was conducted for RZ pulse trains at a repetition rate of 10 GHz, and demonstrated the potential of Bi-HNLF technology in high-speed applications. The high nonlinearity per unit length of the Bi-HNLF, in combination with its high normal dispersion, enabled the employment of a 2 m-long fibre length in the experiments, thus revealing the improvement in terms of compactness that compound-glass technology can yield. In particular, the nonlinear propagation of RZ picosecond pulses in the normally dispersive and highly nonlinear bismuth fibre led to the formation of rectangular-like pulses with a large linear instantaneous frequency profile, which were linearly compressed in a suitable length of anomalously dispersive SMF.

Starting from pulses of the order of two picoseconds, pulses with a width of a few hundred femtoseconds were received at the output of the implemented compressor for average input powers as low as ~24.5 dBm. The compressed pulses were characterized using the FROG technique and a good agreement between the obtained experimental results and numerical simulations was verified. It was confirmed that for the chosen experimental conditions, the compressor was able to generate fairly good quality, slightly chirped sub-picosecond pulses. The quality of the obtained compressed pulses could possibly be improved by using a suitably designed FBG that could compensate for the chirp imposed by nonlinearity and dispersion on the phase characteristics of the pulse throughout its entire duration. The pedestal formation was attributed to the residual nonlinear chirp occurring as an oscillatory structure outside the pulse centre. Since this chirp was mainly generated at both sides of the spectrum, its effect in the formation of pedestals could be suppressed by suitable spectral filtering. Simulations showed that this could be done at the expense of a slightly longer pulse. Additional numerical simulations revealed that by employing a shorter fibre length as low as 0.5 m the compression factor and the quality of the compressed pulses could be potentially improved.

It is expected that further improvement in the splicing loss between Bi-HNLFs and SMFs would drastically decrease the required power requirements of Bi-HNLF based
compressors, thus enabling their use in practical applications. Moreover, by combining compound-glass technology with the flexibility of HF design, fibres with optimum nonlinearity-dispersion characteristics could be fabricated, which would result in significant enhancement of the quality of implemented external pulse compressors.

A comparison between the EAM and the MZM-based L-FROG techniques in terms of short pulse characterization was also attempted. Numerical simulations of pulse propagation in the Bi-HNLF revealed that the relatively narrow optical bandwidth of EAMs significantly limits the ability of the EAM-based FROG technique to adequately characterize sub-picosecond pulses. On the contrary, the much broader optical bandwidth of MZMs makes them suitable for the characterization of pulse widths as short as a few hundred femtoseconds.
References


Chapter 8

Conclusions

The objective of this thesis was to explore the feasibility of using highly nonlinear compound-glass fibres in nonlinear, all-optical applications. Two promising compound glasses have been employed for fibre fabrication: the commercially available lead-silicate Schott glass SF57 and a bismuth-oxide based glass. Bismuth glass offers the great advantage of being compatible with silica fibres for fusion splicing, while it does not contain any toxic elements. With regard to lead-silicate glass, its comparatively smooth temperature-viscosity-curve and its higher crystallization stability are major assets, since they allow for relatively easy fibre fabrication. Fibres of both a conventional step-index and a holey design, made from these compound glasses, have been characterized in terms of their optical properties and used in nonlinear applications.

With regard to compound-glass fibres of a step-index design, a small-core, highly nonlinear bismuth-oxide based fibre, fabricated from the Asahi Glass Company, has been explored. The fibre was single-mode in the C-band, while cladding modes were effectively eliminated [1]. It exhibited a very high nonlinearity of \( \sim 1100 \text{ W}^{-1}\text{km}^{-1} \) and a high normal dispersion in the C-band. Most importantly, it could be spliced to silica fibres, hence it was available in a fully-connectorized form.

The optical characteristics of this fibre were suitable for 2R regeneration applications, based on the SPM and offset optical filtering technique, as well for pulse compression applications, which exploit the linearly varying instantaneous frequency acquired by the nonlinear propagation of a pulse under normal dispersion conditions. Using a 2 m-long connectorized piece of bismuth fibre, 2R regeneration of RZ pulses modulated at 10 Gb/s and 40 Gb/s has been demonstrated, leading to an improvement in the receiver sensitivity of \( \sim 5 \text{ dB} \) and \( \sim 2 \text{ dB} \) respectively. An average input power of \( \sim 1 \text{ W} \) was adequate for the operation of the regenerator, leading to a \( \text{power \times length} \) product of just \( \sim 0.09 \text{ Wkm} \), much lower than any other 2R regeneration scheme reported to date.
With regard to pulse compression, the compression of \( \sim 2 \) ps pulses by a factor of \( \sim 5 \) has been demonstrated. It was shown that, even at low peak powers, a significant compression could be achieved in such a short fibre piece, revealing the potential of this fibre in pulse compression applications. The experiment also helped in highlighting the ability of the L-FROG technique to reliably characterise ultra-short pulses. It should be mentioned that other groups have examined different applications of this fibre, such as wavelength conversion, high-speed demultiplexing and FWM-based wavelength conversion [2, 3, 4].

All the above-mentioned applications support the prospect of employing compound glass fibres in all-optical applications. However, there are still issues that should be resolved in order for these fibres to achieve commercial, practical value. In particular, a limiting factor is the splicing loss to silica fibres. Currently, splicing losses of the order of \( \sim 2-3 \) dB have been achieved. It is expected that the use of a tapered waveguide structures could potentially decrease the splicing loss of small-core, bismuth fibres to SMFs even further. Fibre loss is another important issue. Currently, the loss of the bismuth fibre is \( \sim 0.9 \) dB/m, but it is anticipated that it can be reduced further by improvement in the fabrication process. Perhaps the most critical issue regarding step-index, compound-glass fibres is the non-optimised dispersion profile. When short pulses are considered, pulse dispersion and walk-off effects limit the performance of nonlinear devices based on this fibre. For example, in FWM applications, the fibre exhibits a narrow 3-dB bandwidth due its large dispersion slope [4], whereas when XPM effects are utilised, walk-off effects reduce the strength of the Kerr-effect between the interacting waves [5]. The large chromatic dispersion of bulk bismuth glass cannot be easily overcome using the generally low waveguide dispersion of step-index designs, and therefore has to be tolerated in nonlinear devices that employ such fibres (see, for example, Refs. 5, 6). The farther increase in fibre nonlinearity, by fabrication of fibres with a smaller effective area, or the use of even more nonlinear glasses, might enable a reduction in the fibre length, hence correspondingly a reduction in the net amounts of dispersion and walk-off.

A promising technology that has only recently emerged is compound-glass HF technology. The HF approach offers the prospects of single material fibres, hence eliminating the inherent problem of finding thermally and mechanically compatible
glasses, as required for the realization of step-index designs. Furthermore, fibres with a very high NA and a small effective area can be realized, thus leading to unprecedented values of fibre nonlinearity. Most importantly, HF technology offers the advantage of tailoring the fibre dispersion by realizing suitable fibre designs. In this thesis, fibres of two designs have been presented: a triangular-core design, which resembles the strand-on-air approach, and a design with a hexagonal hole arrangement. The optical properties of the fibres have been thoroughly studied by applying suitable measurement techniques. The conclusions drawn from the characterization process have been invaluable to the fibre fabrication group, since they revealed the dependency of the HF properties on parameters such as the fibre structure, the core dimensions and the fabrication conditions. The generally good agreement between theoretical predictions and experimental measurements has ensured the validity of the inverse design tools, which were used for identifying suitable fibre designs, and led to a gradual improvement in the HF fabrication process.

The performance of compound-glass HFs in real nonlinear applications has also been studied. It was shown that, by employing the triangular-core structure, it is possible to take advantage of the maximum nonlinearity offered by compound glasses, since their effective mode area can be reduced close to its optimum value. This approach led to the demonstration of nonlinearities as high as \( \sim 1125 \, \text{W}^{-1}\text{km}^{-1} \) for bismuth-oxide based fibres and \( 1860 \, \text{W}^{-1}\text{km}^{-1} \) for lead-silicate fibres. The major limitation of the triangular core design lies in its inability to lead to effective tailoring of the fibre dispersion properties. Nevertheless, it was shown that, for applications in the 1.06 µm region, where high power laser sources are available, lead-silicate triangular-core fibres with a core diameter of \( \sim 1.3 \, \mu\text{m} \), seem very promising, since they can simultaneously exhibit a very high nonlinearity and a ZDW close to 1.06 µm. This is particularly important in SC applications, where pumping close to the ZDW leads to optimization of the acquired output spectral bandwidth.

The recently adopted SEST approach, which simplifies the fibre fabrication process by combining the relative advantages of extrusion and stacking, has been successfully used for the fabrication of more complex fibre structures. In particular, compound-glass fibres with a hexagonal arrangement of holes were shown to be very promising for nonlinear applications, since they offer the necessary design flexibility to tailor
both the nonlinear and the dispersion fibre properties. Suitably designed lead-silicate fibres, fabricated using the SEST approach, were shown to exhibit a low dispersion in the C-band and a nonlinearity as high as $\sim 164 \text{ W}^{-1}\text{km}^{-1}$. Such a fibre piece has been successfully employed in both FWM and XPM-based applications. A conversion efficiency of -6 dB with a 3-dB bandwidth of 30 nm was demonstrated in a FWM-based experiment, while XPM-based wavelength conversion was demonstrated for both a KS and a co-polarized pump and probe configuration. These experiments have constituted some of the very first applications of compound-glass HF technology in optical communications systems. They were based on the use of very short fibre lengths, therefore demonstrating the advantage of compound-glass HF technology in terms of realizing short devices. The combination of a short fibre length, a high nonlinearity, a low dispersion and a relatively low dispersion slope enhanced the performance of the demonstrated applications, clearly revealing the potential of compound-glass HF technology. Numerical modelling has shown that potentially, SEST fibres with an even higher nonlinearity, a ZDW lying inside the C-band and a flatter dispersion profile can be realized by adopting a suitable HF design.

Amongst the various compound-glass fibre designs considered, the HFs fabricated with the SEST approach represent the most promising candidates for fibre-based nonlinear applications. However, the characterization of their optical properties and the assessment of their use in practical all-optical applications presented in this thesis has revealed several issues regarding their performance. These issues can serve as fundamental objectives of future research and development efforts.

First of all, fibre propagation loss has been identified as a major limiting parameter in the performance of SEST HFs. The best fabrication approaches so far yielded a loss of 3.2 dB/m, which is too high for practical nonlinear applications. One of the major contributions to the loss in extruded HFs is the presence of defects, such as bubbles and scattering particles, in the fibre perform [7]. Further improvement in the preform surface quality through the optimization of extrusion parameters, such as temperatures, pressure and die design, is a promising route to decrease the losses of HFs down to the bare fibre losses. It is expected that improvements in the fabrication process, as well as the use of glasses with lower bulk loss, will lead to a drastic decrease in HF losses, to figures below 1 dB/m.
Moreover, splicing to SMFs is a critical issue. So far, free-space coupling has been applied in demonstrations involving compound-glass HFs, resulting in reduced coupling efficiencies, difficulties in coupling light into the fibre core and increased set-up dimensions. The use of compound glasses that are fusion-sliceable to silica and the realization of tapered structures would greatly benefit the applicability of compound-glass HF technology.

Moreover, even if splicing and propagation losses are reduced, a major setback regarding the use of compound-glass HFs in optical communication systems is the birefringence of small-core HFs. Although in some applications (for example, KS-based wavelength conversion) birefringent fibres are required, birefringence is normally considered to be detrimental in practical optical communications due to the associated PMD issue. The preform spinning technique that has been suggested for silica HFs might be applicable to compound-glass HFs as well, leading to the fabrication of low-birefringence, small-core, highly nonlinear compound-glass HFs [8].

Furthermore, inverse design procedures have revealed that ultra-high nonlinearity HF designs providing near-zero, flat dispersion at 1.55 µm or zero dispersion at 1.55 µm and a low dispersion slope throughout the C-band can be realized by application of the SEST approach. The use of such fibres would be ideal for a range of nonlinear applications where the elimination of walk-off and GVD effects is essential. However, these designs generally require a complex arrangements of air holes. At present, it is generally considered difficult to stack multi-ring elements, while at the same time ensuring that the holes are in their proper position [7]. It is anticipated that improvements in the fabrication of compound-glass HFs will enable the realization of even more complex fibre structures, resulting in an enhancement of the performance of compound-glass HFs.

Finally, it is also necessary to consider alternative glasses for the fabrication of compound-glass HFs. For example, the chalcogenide glasses possess advantages over the heavy metal oxide glass systems in terms of higher $n_2$ and longer wavelength multiphonon absorption edges [9], and applications involving step-index chalcogenide
glass fibres have recently been demonstrated [10, 11]. Thus, the combination of chalcogenide glasses and HF technology can be a very promising route for the development of extremely compact nonlinear devices, especially for broad-ranged, mid-IR SC generation.

In conclusion, this thesis has clearly revealed the potential of compound-glass fibres in future nonlinear device applications. In particular, compound-glass HFs have been identified as the ultimate candidate for future fibre-based nonlinear devices, since they can combine ultra-high nonlinearity with novel dispersion properties. At present, compound-glass fibres of conventional design and silica-based HNLFs clearly represent more mature technologies. Nevertheless, the field of compound-glass HFs is still at its infancy, and it is anticipated that further research would result in the realisation of fibres with extraordinary optical properties, suitable for the realization of extremely compact nonlinear devices with low power requirements.
Chapter 8: Conclusions

References


List of publications


