Applications of Highly Nonlinear Dispersion Tailored Lead Silicate Fibres for High Speed Optical Communications

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ABSTRACT

Recent advances in optical fibre technology, most notably in the area of microstructured optical fibres (MOFs), offer a host of new opportunities within future high speed communication systems. Herein we review how our recent progress on the implementation of lead silicate fibre designs, allowing both flexible dispersion control and a high effective nonlinearity, can be integrated into various all-optical signal processing devices for high speed optical communication systems. Highly nonlinear lead silicate fibres have already proven to be well suited for achieving efficient four-wave mixing (FWM) due to their high effective nonlinear coefficient, low dispersion profile and short length.

Keywords: All-optical signal processing, nonlinear optics, optical communications, four-wave mixing.

1. INTRODUCTION

The ability to fabricate small core soft-glass holey fibres (HFs) with tailored dispersion properties (in particular with flattened and near-zero values) and 2-3 orders of magnitude higher effective nonlinearity than silica fibres opens new prospects in the implementation of compact, all-optical nonlinear devices [1], such as wavelength conversion, signal regeneration and the like, which can radically transform future optical networks. Four-wave-mixing (FWM)-based switches are particularly attractive, since they offer transparency both in terms of modulation formats and repetition rates. Key fibre parameters for achieving broadband, highly efficient FWM processes are: (i) a highly nonlinear medium, (ii) low dispersion values over a broad wavelength range and (iii) short lengths in order to enhance the phase matching process. While several high-nonlinearity and dispersion-flattened *air/glass* HFs have been demonstrated using either silica [2] or non-silica [1] glass as the host material, the precise control of their corresponding dispersion is extremely hard to achieve. This is because precise dispersion control requires extreme precision in the dimensions and spacing of the µm-scale holes of the microstructure. The complex interdependence between temperature, surface tension and internal pressure within the holes, however, causes small-scale longitudinal cross sectional variations, which are very difficult to control in practice. To solve this issue we have proposed in [3] a new *all-solid* fibre concept based on the use of three commercial lead silicate glasses (Schott SF57, LLF1, SF6) arranged in a W-type index profile. The fabricated fibre presents a flattened and near-zero dispersion profile and a high nonlinearity of 820W^{-1}km^{-1} at the telecom wavelengths. Accurate polishing of the glass preform before the fibre drawing has allowed us to reduce the propagation losses from an initial value of ~5dB/m [3] down to ~2dB/m [4] in the 1.55µm region.

In this talk we will review some examples of successful applications of the fabricated single-mode, highly nonlinear dispersion tailored lead silicate glass fibre for high speed optical communication.

2. EXAMPLES OF OPTICAL PROCESSING USING W-FIBRE

2.1 Parametric wavelength conversion

The inset of Fig.1 shows the SEM images of the fabricated W-type fibre [4]. As previously discussed, optical quality polishing at the perform level of the glass rod used to make the core of the fibre led to a greatly improved value of propagation loss of 2.1±0.2dB/m at 1550nm, (see inset of Fig.1), measured using the cut-back technique. In the inset of the same figure we also report good agreement between the simulated and measured fibre dispersion profiles from 1300 to 1680 nm. The measurement was carried out using a low-coherence Mach-Zehnder interferometric set-up and a supercontinuum source. A flattened profile at telecom wavelengths is shown with a dispersion slope of 0 ps/nm^2/km and dispersion of 2.6 ps/nm/km at 1525nm.

We tested the performance of the fabricated fibre for the realization of an all-optical efficient broadband wavelength converter [4]. The experimental set-up used a 2.2m sample of the W-type fibre, as shown in Fig. 1. The pump wave was a continuous wave (CW) laser, which was gated down by a Mach-Zehnder modulator to produce 100ps rectangular pulses with a duty cycle of 1:64. The pump was amplified and then combined in a 90/10 coupler with a CW signal, which was independently amplified to avoid any undesired nonlinear effects in the amplifier. Optical bandpass filters (BPFs) were used for both pump and signal to remove any undesired out-of-band amplified spontaneous emission (ASE) noise. Polarization controllers (PCs) were used to control the state of polarization of the two beams and to align them to the principal axis of the fibre. The combined beam was free-space launched into a 2.2m length of fibre with a coupling efficiency of ~25%. The average power of

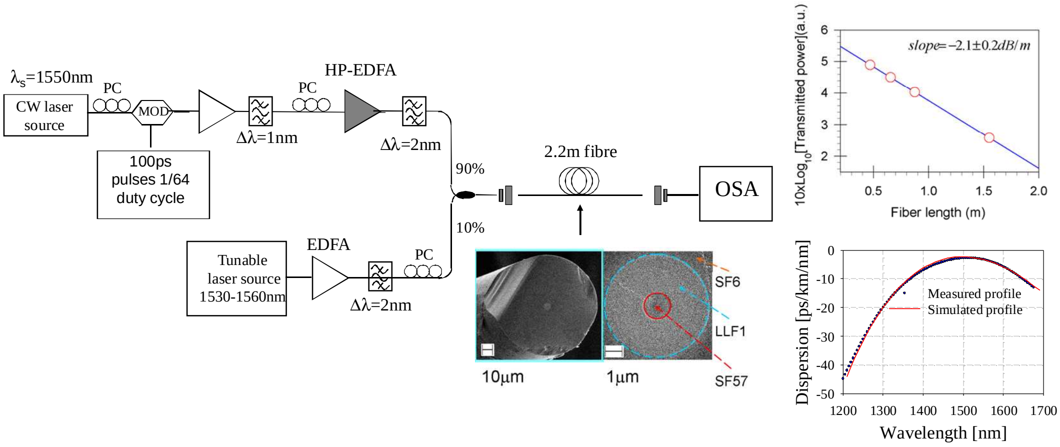

Fig. 1. Experimental setup of FWM-based wavelength conversion scheme. High power erbium-doped fibre amplifier: HP-EDFA. Insets: SEM photos of the W-fibre, linear fitting of the transmitted power (on a log scale) and simulated (red trace) and measured (black dotted curve) fibre dispersion profile.

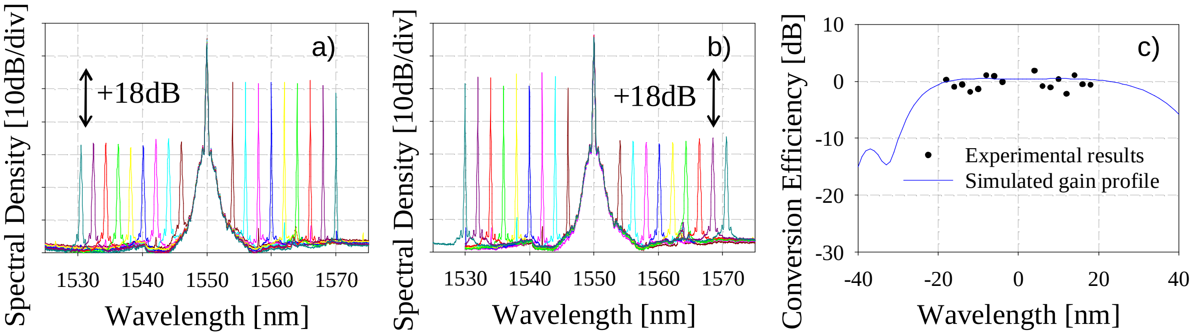

Fig.2 (a), (b): Measured spectral traces of FWM-based wavelength converter in 2.2m-length of W-type fibre using a quasi-CW pump and tunable CW signal; (c) Simulated (solid blue line) and measured (black symbols) curves for the FWM conversion efficiency in the fabricated W-type fibre.

the pump and the signal launched into the fibre were 17dBm and 2dBm, respectively. Fig.2(a) and Fig.2(b) show the corresponding measured spectral traces recorded at the output of the fibre when the CW signal wave was tuned across the C-band: from 1554nm to 1570nm (Fig.2a) and from 1546nm down to 1530nm (Fig.2b), respectively. The low loss, low dispersion and high nonlinearity per unit length of the fibre across the entire C-band used in this experiment have allowed us to observe uniform idlers for all the wavelength range considered. Note that the CW signal tuning is limited by the availability of the lasers used in the experiment. Because the pump (and therefore the new generated idlers) was gated with a duty cycle of 1:64, the corresponding idler peak powers are 18dB greater than the signal recorded by the optical spectrum analyser (OSA). Fig. 2(c) shows the calculated and measured values of conversion efficiency of the system (defined as the ratio of the power of the converted idler to the signal power, on a dB scale). An almost flat gain is observed showing an impressive value of ~0dB for the whole C-band in very good agreement with the simulated gain profile for the fabricated fibre.

2.2 Multichannel wavelength conversion of 40Gbit/s NRZ DPSK signals

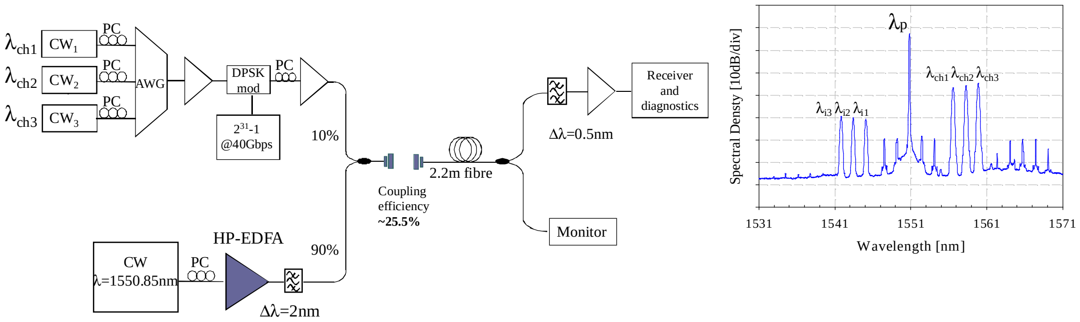

Fig.3: Experimental setup of the FWM-based wavelength converter. Inset: optical spectrum obtained at the output of the W-type fibre.

The experimental set-up was then modified to demonstrate simultaneous FWM-based wavelength conversion of three WDM 40 Gbit/s non-return to zero (NRZ) differential phase shift keyed (DPSK) signals in the same fibre sample, see Fig.3 [5]. The outputs of three CW lasers (λ_{ch1}=1556.86nm, λ_{ch2}=1558.58nm, λ_{ch3}=1560.20nm) were multiplexed together using an arrayed waveguide grating (AWG) and modulated with a 2^{31}-1 pseudorandom bit sequence (PRBS) at 40Gbit/s. The pump signal was generated by CW laser, amplified and filtered before being combined in a 90/10 coupler and free-space launched into the fibre with a coupling efficiency of ~25.5%. The average powers of the CW pump and the three DPSK signals at the very input of the fibre were 23dBm and 8.7dBm, respectively.

The inset to Fig.3 shows the measured optical spectrum at the output of the system. The new generated idlers exhibited an optical signal to noise ratio (OSNR) greater than 25 dB and a uniform conversion efficiency of -12dB. The output spectrum also indicates the generation of some low-power spurious frequency components, which were mixed FWM products between the various WDM channels and the pump. However, these components were clearly at different wavelengths to the WDM channels, or their idlers, and did not affect the performance of the system. This negligible nonlinear cross-talk was also confirmed by the corresponding eye diagrams and bit error ratio (BER) measurements of each idler, after being carefully filtered. Following demodulation in a 1-bit delay line interferometer (DLI) and balanced detection using a dual port photo-detector, the DPSK demodulated eye diagrams of each channel at the system input and the corresponding generated idlers at the output of the system are shown in Fig. 4 (left). The good quality of the conversion process was reflected in the BER measurements (Fig. 4 (right)), which showed a power penalty between 0.5dB and 2dB for the three converted channels.

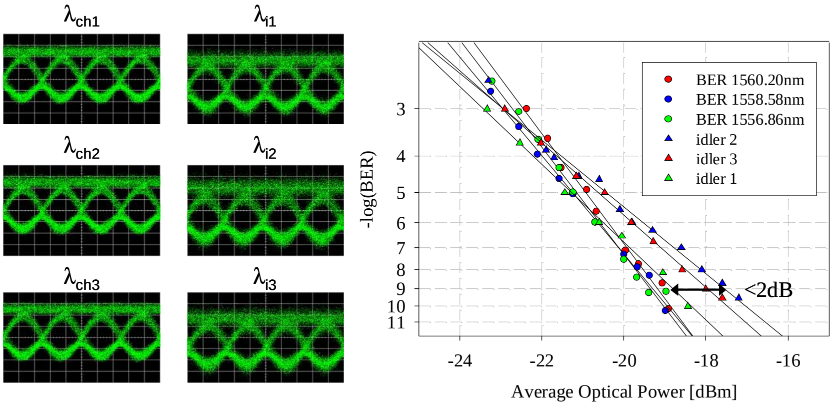

Fig 4 (Left): DPSK demodulated eye diagrams of each channel and of the corresponding generated idlers. (Right): Corresponding BER curves using balanced detection.

2.3 Generation of ultra-high repetition rate pulses

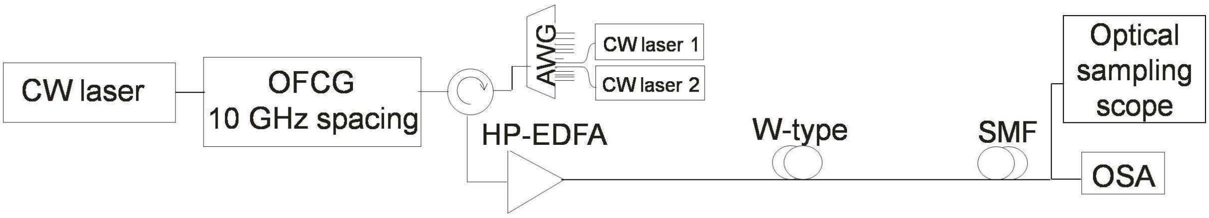

Fig 5: Experimental setup of the ultra-high repetition rate pulses scheme.

Finally, we used another sample (3m-long) of the same W-type fibre to experimentally demonstrate the generation of ultra-high repetition rate (200GHz) pulses through stable injection-locking of two semiconductor lasers [6].

The corresponding experimental setup is shown in Fig.5. A CW laser was fed into a 10GHz spaced optical frequency comb generator (OFCG) [7]. The output of the comb was demultiplexed using a 100GHz AWG and then coupled into two semiconductor lasers to induce phase locked operation. The combined phase-locked lasers were then amplified and free-space launched into the W-type fibre, followed by a few tens of meters of standard single mode fibre (SMF) to temporally compress the pulses. The frequency spacing between the two injection-locked lasers was chosen to be 200 GHz and could be controlled (in 10GHz steps) by changing the operational temperature of the two phase-locked lasers. The signal in the time and spectral domains at different points along the system are shown in Fig. 6, using an optical sampling oscilloscope (EXFO Inc.) electrically triggered by the OFCG and an OSA, respectively. The initially sinusoidal waves, not shown here, have full-width-at-half-maxima (FWHM) corresponding to a half of the signal period, i.e. 2.5ps (200GHz), a value which was quite comparable to the corresponding FWHM of the pulses at the output of the fibre, as shown in Fig.6 (b). After the SMF the

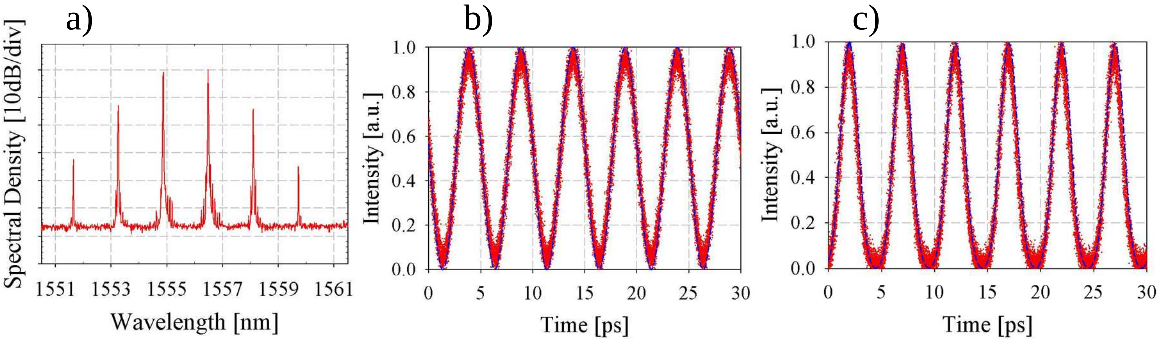

Fig 6: Output spectral trace (a) and temporal traces at the output of the W-type fibre (b) and after the SMF (c) at 200GHz.

pulses were compressed down to 1.5ps (200GHz), as shown in Fig. 6(c), corresponding to compression factors of 1.67.

3. CONCLUSIONS

We have reviewed several successful all-optical signal processing demonstrations for optical communication systems based on a few meters of a highly nonlinear, dispersion tailored compound glass W-type fibre. The low dispersion and dispersion slope of this fibre together with its high nonlinearity play a key role in the successful implementation of these processing applications.

4. ACKNOWLEDGEMENTS

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