Wavelength Conversion in a Short Length of a Solid Lead-Silicate Fibre

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Abstract— We experimentally demonstrate a four-wave mixing-based wavelength conversion scheme at 1.55μm using a 1.1m length of highly nonlinear, dispersion tailored W-type lead-silicate optical fibre.

***Index Terms*—Four Wave Mixing, Nonlinear optics, Non-silica fibre, Optical fibre dispersion.**

I. Introduction

THE use of compound glasses for the fabrication of microstructured optical fibres (MOFs) and the ability to tailor their dispersion profile have opened up new possibilities towards the realization of compact nonlinear devices. Among the various nonlinear processes, four-wave-mixing (FWM) represents a key effect for the implementation of several devices, including all-optical wavelength converters [1]. In general, the most important fibre parameters that contribute towards achieving efficient and broadband FWM are a high nonlinear coefficient, a low and flat dispersion profile and a short fibre length [2]. Soft-glass holey fibres (HFs) have already been demonstrated to be good candidates for FWM processes. In ref. [3] a lead-silicate HF with a zero dispersion wavelength (ZDW) of 1582nm and a nonlinear coefficient of 164 $W^{-1}km^{-1}$ was used to demonstrate FWM over a bandwidth of 30nm, whereas a Bi-HF with a ZDW around 1550nm and a nonlinear coefficient of 580 $W^{-1}km^{-1}$ was used to achieve a bandwidth of 35nm in [4]. However, the optical parameters of a HF are quite sensitive to structural variations that might occur during the fibre drawing, making the fabrication of a complex HF a challenging task. One way to solve this problem is presented by the use of all-solid MOFs where the structure defined in the preform can be preserved with good accuracy during the fibre drawing. We have previously reported the benefits of the use of an all-solid MOF in a wavelength conversion process, even though the dispersion profile of the fibre was not optimised [5]. In attempting to optimise the structure we identified that far simpler structures incorporating multiple high-index soft-glasses, such as the W-type structure shown here, can provide fibres with highly desirable characteristics for FWM based devices.

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The use of highly nonlinear glasses allows the achievement of a high nonlinearity per unit length while the incorporation of a low index glass between two high index glasses provides great scope for tailoring the dispersion profile of the final fibre.

In this work we report on a highly nonlinear W-type fibre made of three lead silicate commercial glasses (Schott SF57, LLF1 and SF6) which exhibits a high nonlinear coefficient and low dispersion values at telecommunication wavelengths. We show that this fibre can be a suitable candidate for the realisation of a compact (~1m long) FWM-based wavelength converter operating at 1.55 μm. Eye-diagrams and bit-error rate (BER) curves confirm the high signal quality achieved in the conversion process. We support our experimental results with numerical simulations.

II. Experimental Set-up and Results

The experimental setup for the FWM-based wavelength converter is shown in Fig. 1. The converter was based on a

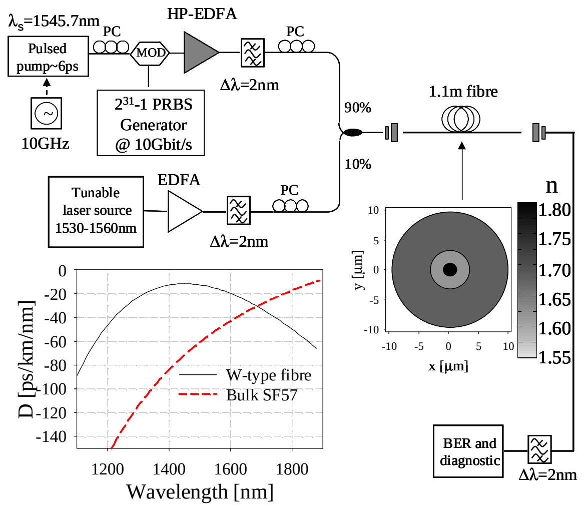

Fig.1: Experimental setup of the FWM-based wavelength converter. Insets: Image of the W-type fibre; numerical simulation of the fibre dispersion as a function of wavelength.

W-type fibre that exhibited a high refractive index core surrounded by first a low and then a high index ring of differing thicknesses. The fibre core (1.6μm in diameter) was made of a high index glass, Schott SF57 (n=1.82 @ 1550 nm) and was surrounded by a first cladding (6.7μm in diameter) made of a low index glass, Schott LLF1 (n=1.53 @

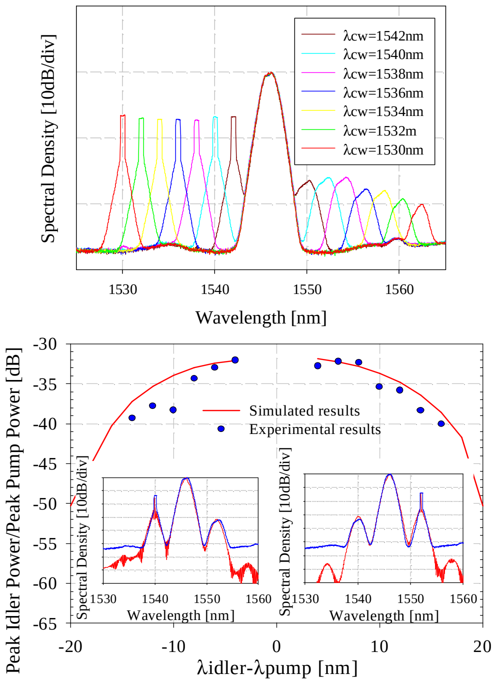

Fig. 2: (Top) Spectral traces of the converter output for various input CW signal wavelengths ranging from 1530nm to 1542nm (resolution =0.5nm). (Bottom) Simulated and measured Idler/Pump ratio when the CW wavelength is tuned from 1530nm to 1570nm and corresponding spectral traces of two CW wavelength settings.

1550 nm). The outer cladding is made of a different glass with a higher refractive index, Schott SF6, (n=1.76 @ 1550nm). The insertion of the ring of the LLF glass and the small core size allow the dispersion of bulk SF57 to be engineered so as to achieve a flat dispersion profile and low dispersion values around 1550 nm, as shown in the inset to Fig.1. The choice of SF6 as the outer cladding allows attenuating the higher order modes in order for the fibre to be effectively single mode. The fibre showed indeed effective single mode guidance at 1.55 µm and its propagation loss was measured to be 4.8±0.2 dB/m using the cut-back method. The high propagation losses of the fibre are believed to be due to the surface roughness of the various glass elements used to construct the fibre preform. Polishing the glasses would allow us to reduce the losses down to the material losses (~1 dB/m) [6]. By measuring the self-phase-modulation (SPM) response of the fibre, the nonlinear coefficient was found to be ~ 820 $W^{-1}km^{-1}$. Numerical simulations on the dispersion profile of the fabricated fibre showed a dispersion slope of -0.3 $ps/nm^2/km$ at 1.55 µm; this value is relatively insensitive to small structural variations. The dispersion of the fibre was evaluated to be about -12ps/nm/km at 1.55 µm through FWM measurements.

The pump signal of the FWM-based wavelength converter was generated by a 10GHz mode locked laser, which produced ~6ps full-width-at-half-maximum pulses at 1545.7nm. The pulses were amplitude modulated by a 2^{31}-1 pseudorandom bit sequence (PRBS) using a lithium niobate Mach-Zehnder modulator (MOD) and amplified using an erbium-doped fibre amplifier (EDFA). A second signal was generated by an amplified continuous wave (CW) tuneable laser. In order to control the relative power levels of the two signals and avoid any nonlinear interaction in the EDFA, two amplifiers were used. Bandpass filters (BPF) were employed at the output of the two amplifiers to reject any undesired out-of-band amplified spontaneous emission (ASE) noise. The states of polarisation of the two beams were controlled by two polarization controllers (PCs) and were aligned to a common polarization axis of the fibre. The pump pulses and the CW signal were then combined in a 90/10 coupler and free-space launched into the fibre. The coupling efficiency was estimated to be ~25% and the average powers of the pulsed pump and the CW signal at the very input of the fibre were 23dBm and 2.1dBm, respectively.

Under phase matching conditions, the gain and the pulse shape of the signal and the generated idler depend on the pump shape and instantaneous power as well as the fibre parameters [2]. Despite the high losses exhibited by the fibre, the short length of the sample used, the low dispersion and the high nonlinearity per unit length allowed us to observe the generation of a strong idler signal over a range of wavelengths that cover both sides of the C-band symmetrically about the 1545.7nm pulsed pump signal. Fig. 2(top) illustrates the spectral traces at the output of the system when the CW wavelength was tuned from 1530nm to 1542nm and shows that an optical signal to noise ratio (OSNR) in the range of ~ 12-24 dB was achieved at the output of the system. The measurement of the signal OSNR is believed to be mainly limited by the ASE floor of the high power amplifier. The figure also shows clear sidebands around the CW wavelengths, which are the results of the combined effects of cross-phase modulation and parametric amplification. Fig. 2(bottom) shows the ratio between the idler and the pump peak powers when the CW signal is tuned across the available wavelength range of the tunable laser (from 1530nm to 1560nm). This ratio varies by ~8 dB across the whole tuning range of ~30nm, while the -3dB bandwidth is ~20nm. A good agreement can be seen with the corresponding simulated values. Two examples of measured and simulated spectra are compared in the insets of Fig.2 (bottom) for λ_{CW}=1540nm, left, and λ_{CW}=1552nm, right and again good agreement is observed (the additional higher order FWM components predicted were not observable due to the limited dynamic range of our OSA).

The wavelength converted pulses were then filtered and characterised in terms of pulse width and noise properties. We measured the autocorrelation traces of the output signals and compared them with those of the input pulses; a similar pulse width reduction for all the output signals from ~6ps to ~4ps was observed (as discussed in [7]), see Fig. 3(right). An example of the measured input/output autocorrelation traces for λ_{idler}=1540nm is shown in Fig. 3(left). These values of pulse width reduction have also been predicted by numerical

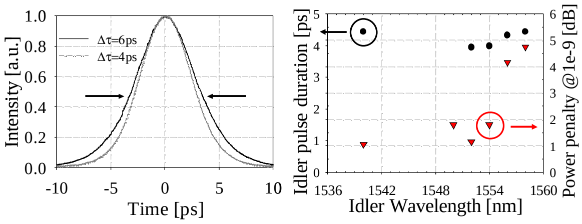

Fig. 3 (Left): Autocorrelation traces of the input pump (solid line) and output idler (dashed line) pulses obtained for λ_{idler}=1540m; (Right): Measurements of the pulse duration (dots) and power penalties (triangles) of the filtered idlers as a function of the CW wavelength.

simulations of the wavelength converter, where it was confirmed that the reduction was caused purely by the parametric amplification in the fibre. The performance of the FWM-based wavelength converter was assessed both in terms of eye-diagrams and BER measurements. The triangles in Fig. 3(left) represent the power penalty at error free operation (BER = 10^{-9}) for the various new generated idler wavelengths. A minimum power penalty of ~1dB can be found for the idler wavelengths relatively close to the pump, while the values increase up to ~5dB for a wavelength detuning of ~13nm, due to the OSNR degradation as previously discussed, see Fig. 2(top). The full BER characterisations of two wavelengths, λ_{idler}=1552nm and λ_{idler}=1540nm, are reported in Fig. 4 as examples, together with the corresponding eye diagrams which confirm their good quality. The BER of the input (pump) signal (B2B) is also reported for reference.

The performance of the wavelength converter in terms of bandwidth is closely related to the dispersion characteristics of the fibre. The dispersion curve for the fibre employed in our experiment is shown inset in Fig.1. We have found that this curve is not very tolerant in terms of variations in the core diameter of the fibre, and therefore only small variations in this parameter could allow for significant improvements in the wavelength converter performance. This is illustrated in Fig. 5 where it is shown that a radical change in the conversion bandwidth is predicted when the core diameter is changed from just 1.60µm to 1.68µm. The inset in Fig.5 shows the corresponding dispersion curves. We can see that there is a certain value of diameter for which the dispersion values are very close to zero for a large range of wavelengths, implying that a bandwidth covering at least the whole C-band with a fairly constant gain can be obtained through precise control of the core diameter. Work in this direction is under progress.

III. Conclusions

We have fabricated a W-type soft glass fibre exhibiting a high nonlinearity coefficient of $820W^{-1}km^{-1}$ and a low dispersion of -12ps/nm/km at telecom wavelengths. We have successfully demonstrated a FWM-based wavelength converter over the full C-band utilising only 1.1m of this fibre. The combination of a short fibre length and a low

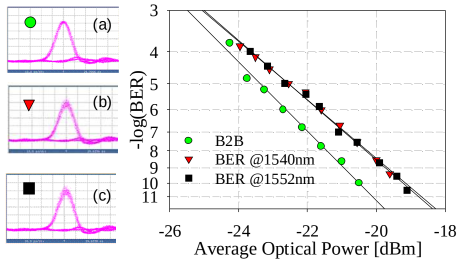

Fig. 4 (Left): Eye diagrams of (a) input (back2back), (b) λ_{cw}=1540nm and (c) λ_{cw}=1552nm; (Right): Corresponding BER measurements at the input (B2B) and output of the system for λ_{cw}=1540nm and λ_{cw}=1552nm.

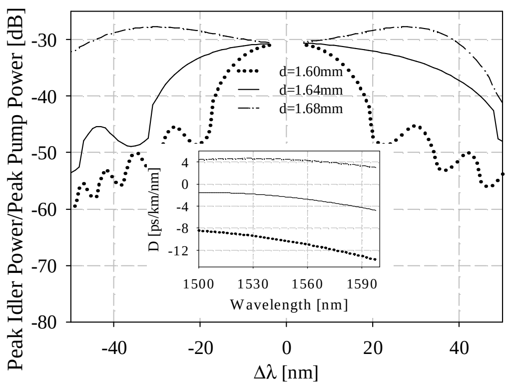

Fig. 5: Simulated gain profile for various values of core diameter. The inset shows the corresponding dispersion curves.

dispersion profile together with a high nonlinear coefficient allow us to achieve broadband wavelength conversion, despite the high losses exhibited by the current fibre. We believe that this experiment highlights the potential of soft-glass technology for the realization of compact and ultrafast nonlinear devices.

References

[1] M. N. Islam and Özdal Boyraz , “Fiber Parametric Amplifiers for Wavelength Band Conversion”, *IEEE J. Sel. Topics Quantum Electron*, vol. 8, no. 3, pp 527-573, Jun. 2002.

[2] J. Hansryd, P. A. Andrekson,, M. Westlund, J. Li and P. O. Hedekvist, “Fiber-Based Optical Parametric Amplifiers and Their Applications”, *IEEE J. Sel. Topics Quantum Electron*, vol. 8, no. 3, pp 506-520, Jun. 2002.

[3] S. Asimakis, P. Petropoulos, F. Poletti, J. Y. Y. Leong, R. C. Moore, K. E. Frampton, X. Feng, W. H. Loh and D. J. Richardson, “Towards efficient and broadband four-wave-mixing using short-length dispersion tailored lead silicate holey fibres”, *Opt. Exp*., vol. 15, no. 2, pp 596-601, 2007.

[4] K. K. Chow, K. Kikuchi, T. Nagashima, T. Hasegawa, S. Ohara, and N. Sugimoto, “Four-wave-mixing based widely tunable wavelength conversion using 1-m dispersion-shifted bismuth-oxide photonic crystal fibre”, *Opt. Exp.*, vol. 15, no. 23, pp 15418-15423, 2007.

[5] A. Camerlingo, F. Parmigiani, X. Feng, F. Poletti, P. Horak, W. H. Loh, D. J. Richardson and P. Petropoulos, “Four wave mixing based wavelength conversion in a short length of a solid 1D microstructured fibre”, ECOC Vienna, 2009.

[6] X. Feng, F. Poletti, A. Camerlingo, F. Parmigiani, P. Horak, P. Petropoulos, W. H. Loh and D. J. Richardson, “Dispersion-shifted all-solid high index-contrast microstructured optical fiber for nonlinear applications at 1.55µm”, *Opt. Exp.*, vol. 17, no. 22, pp 20249-20255, 2009.

[7] T. Yamamoto and M. Nakazawa, “Active optical pulse compression with a gain of 19.0 dB by using four-wave-mixing in an optical fibre”, *IEEE Photon. Technol. Lett*., vol. 9, no12, 1595-1597, Dec. 2007.