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Efficient Four-Wave-Mixing at 1.55 µm in a Short-Length Dispersion Shifted Lead Silicate Holey Fibre

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Abstract *We demonstrate four-wave-mixing in a 2.2m-long dispersion-tailored lead-silicate holey fibre with a conversion efficiency of -6dB and a bandwidth of ~30nm. The potential of dispersion-optimised soft-glass holey fibres for such applications is also discussed.*

Introduction

The ability to fabricate small core soft-glass holey fibres (HFs) with tailored dispersion properties 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]. Among the many all-optical nonlinear signal processing functions, wavelength conversion alone is of fundamental importance for the realisation of λ-switched wavelength-division-multiplexing systems. Four-wave-mixing (FWM)-based wavelength conversion is considered particularly attractive, since it offers transparency both in terms of modulation format and bit rate. Key parameters for achieving a broadband, highly efficient FWM process are a high pump power, a highly nonlinear medium and a low group velocity dispersion (GVD) in order to enhance the phase-matching process [2].

We have recently reported the fabrication of a highly nonlinear HF with a zero GVD wavelength around 1.55 µm, based on a commercially available, lead-silicate glass (SF57) [1]. In this paper we demonstrate the benefits of the combination of the tailored dispersion profile and the high nonlinearity of this SF57-HF for the implementation of a compact FWM-based wavelength converter operating at 1.55 µm. We support our experimental findings with theoretical simulations, and discuss the potential that an optimised SF57-HF based on similar design and fabrication rules would have for FWM applications.

Experimental Set-up and Results

The experimental setup for the wavelength converter based on the SF57-HF is shown in Fig. 1. Two tuneable continuous-wave (CW) lasers operating in the C-band were used as the pump and signal sources respectively. To achieve a high peak pump power with a moderate average-power fibre amplifier, we intensity-modulated the CW pump with 100 ps rectangular pulses at a duty cycle of 1:64, using a $LiNbO_3$ modulator. The pulsed pump beam was amplified by an Erbium-Ytterbium fibre amplifier and combined with the pure CW signal through a 50:50 coupler. At the output of the coupler, the average pump and signal powers were 25.4 dBm and 9.3 dBm respectively. The combined beam was free-space coupled into the 2.2 m-long SF57-HF with a coupling efficiency of ~28%. Therefore, the peak pump power into the fibre was ~6.2 W, while the CW signal input power was ~2.4 mW. Care was taken to ensure that both the signal and the pump beams were aligned to the primary polarization axis of the fibre through proper adjustment of the polarization controllers.

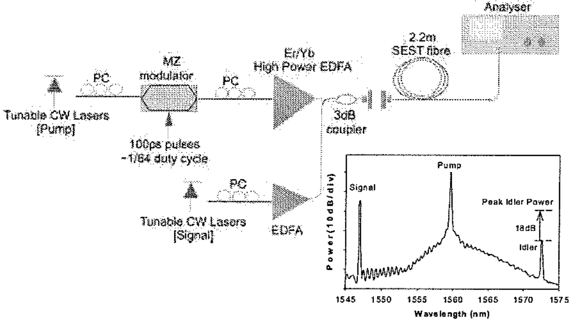


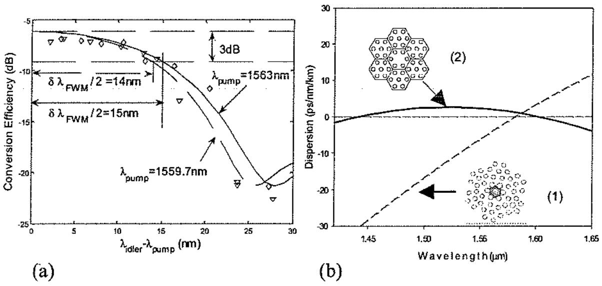
Fig.1 Experimental setup of the SF57-HF based FWM wavelength converter and a typical spectral trace measured at the output of the system.

The SF57-HF used in this experiment was fabricated using the structured-element-stacking (SEST) technique, which is an alternative to pure extrusion and provides the necessary structural freedom to allow for greater dispersion control. The fibre had a core diameter of ~4.3 µm and a design similar to that reported in [1] (see fibre profile in Fig. 2b). Numerical simulations conducted using a full vector model, have revealed that the particular fibre design resulted in a dispersion slope of 0.2 ps/nm^2·km within the C-band, which, unlike the exact zero-GVD wavelength, was largely insensitive to small structural non-uniformities. Hence, a slight uncertainty in the estimation of the size of the core and holes of the fibre from SEM images was expected to affect the precise position of the zero GVD wavelength, but not the dispersion slope.

The optical properties of the SF57-HF were measured at 1550 nm. The propagation loss was determined through the cutback approach and was found to be 3.2 dB/m. The effective nonlinear coefficient γ was obtained from a measurement of the self-phase-modulation induced phase shift on a dual-frequency, optical beat-signal propagating through the fibre. A γ

value of 164 $W^{-1}km^{-1}$ was measured.

The performance of the wavelength converter was tested for two pump wavelengths, namely 1559.7 and 1563 nm. A typical spectral trace at the output of the fibre is shown inset in Fig. 1, where a strong idler beam is observed alongside the pump and signal beams. It is worth noting that, since the pump was carved at a 1:64 duty cycle and the idler beam was generated only when the pump was present, the idler output peak power was 18 dB higher than its average power (as measured on the spectrum analyser). This is important for the calculation of the conversion efficiency (CE), which is defined as the ratio of the output idler peak power to the input signal power. A measurement of the CE as a function of the idler wavelength for the two pump wavelengths is shown in Fig. 2a. For an accurate estimation of the CE, the leakage amplified spontaneous emission (ASE) of the EDFA at the idler wavelength was subtracted. In our experiments we achieved a maximum CE of -6dB, and the 3dB operating bandwidth of the wavelength converter was ~30 nm (larger at the longer pump wavelength). A best fit of the experimental results to numerical simulations allowed us to estimate that the zero-GVD wavelength for this fibre was ~1582 nm (Fig. 2a).



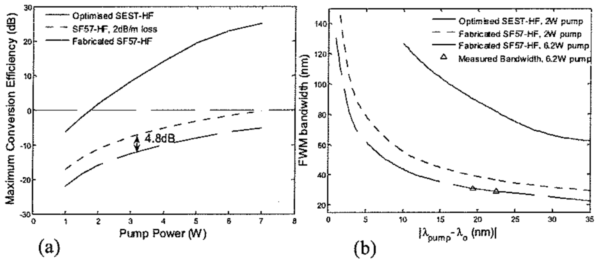
(a) (b)

Fig.2 (a) Measured and numerically fitted conversion efficiency curves for two different pump wavelengths; (b) Dispersion profiles of the SF57-HF used in the experiments (1) and that of the optimised SEST HF(2). The microstructure profiles of the two fibres are also shown in the figure.

Using the estimated dispersion profile of the fibre and its optical characteristics, we theoretically calculated the maximum CE for different input pump powers (Fig. 3a) and the 3dB bandwidth of the conversion process for different pump wavelengths at two different pump power levels (Fig. 3b). Fig. 3b in particular shows that conversion bandwidths in excess of 100 nm can be achieved with this fibre when the pump wavelength is suitably close to the zero-GVD wavelength. It should be appreciated however, that the fourth-order dispersion term, which has not been taken into account in this simulation, would eventually limit the broadening of the operating bandwidth when the pump wavelength is close to the zero-GVD wavelength.

We have previously demonstrated that it is possible to fabricate even smaller core SF57-HFs than the one used here, with losses as low as 2 dB/m [3]. It is hence reasonable to expect that improvements in the fabrication process can result in similar loss performance for the SF57-HFs fabricated with the SEST approach. If the fibre loss was reduced to 2.0 dB/m, then for a similar device length of 2.2 m, the CE would be improved by 4.8 dB relative to our experimental results (Fig. 3a). (Note that for our experimental conditions, the 3dB-CE bandwidth was only modestly affected by a fibre loss reduction, e.g. for a 1560 nm pump it was reduced by ~2 nm).

We have next studied theoretically the performance of an optimised SEST design that exhibits flat and low GVD across the C-band. This design would require only a small modification of the structural parameters Λ and d of the fibre microstructure relative to the fabricated SF57-HF, and identical procedures could be applied for its fabrication [1]. The optimised SEST HF has a smaller core of 2 µm and hence a higher nonlinearity of γ=526 $W^{-1}km^{-1}$. Using again 2.2 m of this fibre and assuming propagation losses of 2 dB/m, a CE of +1.6 dB could be achieved for a pump power of just 2 W (Fig. 3a). Operating bandwidths in excess of 50 nm are possible when pumping in the C-band (Fig. 3b).



(a) (b)

Fig.3 (a) Maximum conversion efficiency as a function of input pump power for the three HFs considered herein; (b) 3dB conversion bandwidth as a function of the pump wavelength.

Conclusions

We have demonstrated a FWM-based wavelength converter using a 2.2 m-long dispersion-tailored SF57-HF which was fabricated using the SEST technique. A maximum conversion efficiency of -6dB was obtained with a 3dB bandwidth of ~30nm. Numerical simulations have revealed that the FWM process can greatly benefit from further improvements in dispersion flatness, fibre loss and nonlinearity, which would establish such fibres as ideal candidates for compact parametric devices.

References

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