Microstructure-fibre-based optical parametric amplifier with gain slope of ~200 dB/W/km in the telecom range

R. Tang, J. Lasri, P. Devgan, J. E. Sharping and P. Kumar

A microstructure-fibre-based optical parametric amplifier with a gain slope of ~200 dB/W/km in the 1550 nm range is demonstrated, for the first time to the authors' knowledge. By using only 12.5 m-long fibre, gains were obtained of >20 dB over a bandwidth of approximately 30 nm, achieving a peak net gain of 25.4 dB.

Introduction: Microstructure fibres (MFs) have received a lot of attention owing to their high nonlinearity per unit length. In fact, all of the nonlinear effects that are present in standard optical fibres are expected to be observed in MFs with reduced length and pump-power requirements. A number of MF-based telecommunication applications have already been demonstrated, including Raman amplification [1], 2R regeneration [2], wavelength conversion [3], and optical switching [4].

In recent years, experiments with fibre optical parametric amplifiers (FOPAs) have demonstrated their unique features for many practical applications [5]. Previously, using nondegenerate four-wave mixing (FWM) in a 6 m-long MF having a zero-dispersion wavelength λ_0 near 750 nm, we demonstrated >13 dB gain using a pump peak power of only 6 W [6]. However, an MF-based FOPA for use in the telecom band has not been demonstrated. In this Letter we report a microstructure fibre optical parametric amplifier (MFOPA) operating in the 1550 nm region. The high nonlinear coefficient of the MF, $\gamma = 24\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$, allows us to obtain a parametric gain slope of ~200 dB/W/km, which is the highest value ever obtained from FOPAs in the telecom band. By using only 12.5 m of MF, we obtained >20 dB gain over a ~30 nm range, achieving a peak net gain of 25.4 dB with a peak pump power of 12.7 W.

Experiments: The experimental setup for the MFOPA is shown in Fig. 1. The 12.5 m-long piece of MF used in our experiments was fabricated at Crystal-Fibre A/S. The total loss through the fibre piece is 1.7 dB, including connector losses on each end of the fibre, and $\lambda_0 = 1544$ (+/−7) nm, as specified by the manufacturer. To achieve high peak pump power with use of a moderate average-power optical amplifier, we modulated the continuous-wave (CW) light from a distributed feedback (DFB) laser with an $\mathrm{LiNbO_3}$ Mach-Zehnder intensity modulator. The resulting pulses had a width of 100 ns and a repetition rate of 250 kHz. The duty cycle was 1:30, taking into account the extinction ratio of intensity modulation. The chopped light was further phase modulated using a 1.7 Gbit/s, $2^{31} - 1$ PRBS in order to minimise the pump-power back reflection owing to stimulated Brillouin scattering. The pulses were then amplified by an erbium-doped fibre amplifier (EDFA) to compensate for losses in the intensity and phase modulators and passed through a 1 nm optical bandpass filter (OBF) to suppress the amplified spontaneous emission (ASE) at the signal wavelengths. Finally, a second EDFA was used to boost the peak power of the pump pulses in order for the signal to see gain through the FWM process in the MF. A CW laser that is tunable from 1535 to 1565 nm was used as the signal source to probe the net gain of the MFOPA. An 80/20 coupler combined the pump with the signal into the MF.

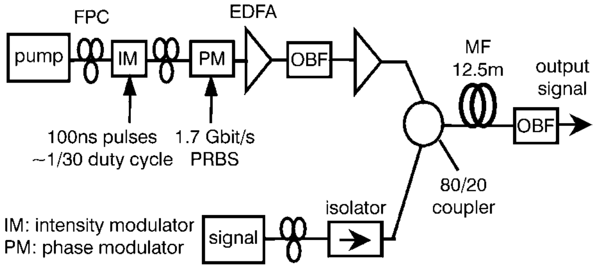

Fig. 1 *Experimental setup of MFOPA*

To find the region of optimum phase matching, our first step was to measure the λ_0 of the MF with as small an uncertainty as possible. We followed a procedure similar to that described in [6] and measured the FWM gains against peak pump power for various pump wavelengths ranging from 1535 to 1555 nm, while keeping the detuning between the pump and signal wavelengths constant at 8 nm. The measured gain values were then fitted with simulations of the FWM gain, treating the (GVD) coefficient, *D*, as a fitting parameter. The resulting best fits yielded values of *D* that are plotted in Fig. 2 against pump wavelength. As shown, we obtained a zero-dispersion wavelength of $\lambda_0 = 1544$ (+/−3) nm with a dispersion slope of −0.2 (+/−0.05) ps/nm^2/km. Next, we positioned the pump wavelength inside the anomalous dispersion regime at $\lambda_p = 1539$ nm (slightly shorter than λ_0) and measured the gain profile of the MFOPA. Fig. 3 shows the measured and the calculated gain spectra. The tuning range of our OBF allowed us to measure only one gain lobe of the two that surround λ_p (the calculated spectrum shows the two lobes). The close matching of the measured and calculated spectra in Fig. 3 clearly demonstrates the presence of net parametric gains of >20 dB over ~30 nm optical bandwidth, with a peak gain of 25.4 dB at the phase-matching wavelength (1558 nm). The inset in Fig. 3 shows an example of the optical spectrum measured at the output of the MFOPA with the OBF removed. Since the pump was chopped with a duty cycle of 1/30, only 1/30th of the CW input signal was amplified. Hence, the MFOPA gain $= 30*(P_{\mathrm{out}} - P_{ASE})/P_{\mathrm{in}}$, where P_{out} was the measured output signal power with the pump on, P_{ASE} was the leakage ASE power at the signal wavelength, and P_{in} was the signal power measured at the output with the pump off. Therefore, for the case shown in the inset, the MFOPA gain was ~24 dB.

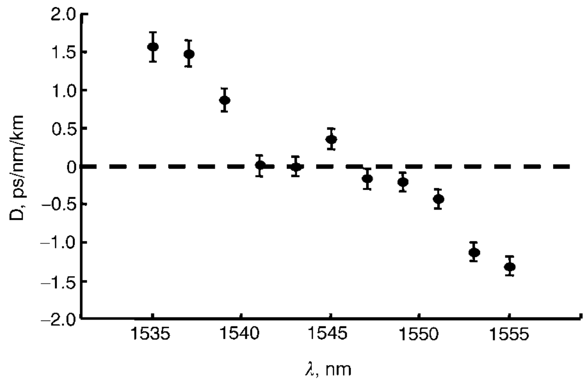

Fig. 2 *GVD coefficient, D, against pump wavelength*

Error bars represent 90% confidence interval for *D*

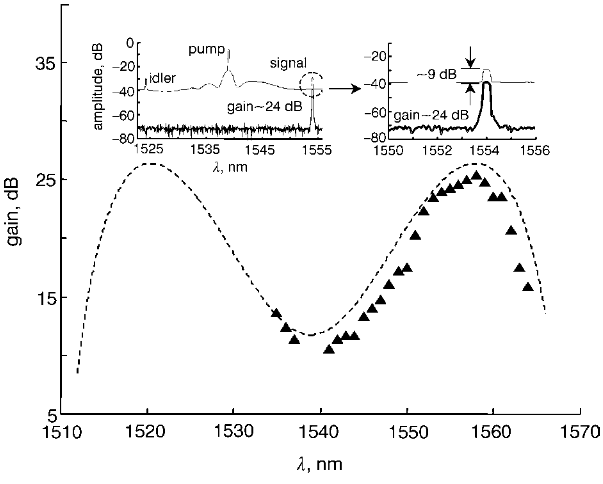

Fig. 3 *Measured and calculated gain spectra*

▲ measured

--- calculated

Inset: Example of optical spectrum measured at output of MFOPA with OBF removed

Fig. 4 shows the pump-power dependence of the measured parametric gain at the peak wavelength of $\lambda_s = 1558$ nm. The measured data is in good agreement with the theoretical prediction [5], which for the case of optimum phase matching implies that the parametric gain in dB units is approximately linearly proportional to the pump power and the gain slope is ~8.7γ dB/W/km. The experimental data in Fig. 4 gives the gain slope for our MFOPA to be 203 dB/W/km, which agrees with the theoretical prediction using $\gamma = 24\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$.

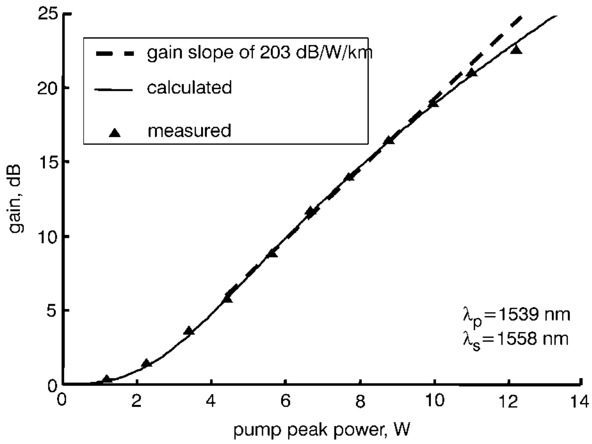

Fig. 4 *Measured and calculated MFOPA gain against peak pump power at phase-matching wavelength*

Conclusions: We have demonstrated, for the first time, a microstructure-fibre-based optical parametric amplifier in the 1550 nm telecom band with a record gain slope of 203 dB/W/km. We obtained parametric gains of >20 dB over a bandwidth of ~30 nm, achieving a peak net gain of 25.4 dB in the region of perfect phase matching.

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References

1 YUSOFF, Z., LEE, J.H., BELARDI, W., MONRO, T.M., TEH, P.C., and RICHARDSON, D.J.: 'Raman effects in a highly nonlinear holey fiber: amplification and modulation', *Opt. Lett.*, 2002, **27**, p. 424

2 PETROPOULOS, P., MONRO, T.M., BELARDI, W., FURUSAWA, K., LEE, J.H., and RICHARDSON, D.J.: '2R-regenerative all-optical switch based on a highly nonlinear holey fiber', *Opt. Lett.*, 2001, **26**, p. 1233

3 BELARDI, W., LEE, J.H., FURUSAWA, K., YUSOFF, A., PETROPOULOS, P., IBSEN, M., MONRO, T.M., and RICHARDSON, D.J.: 'A 10 Gbit/s tunable wavelength converter based on four-wave-mixing in highly nonlinear holey fibre'. ECOC 2002, Copenhagen, Denmark, 2002, post-deadline paper 1.2

4 SHARPING, J.E., FIORENTINO, M., KUMAR, P., and WINDELER, R.S.: 'All-optical switching based on cross-phase modulation in microstructure fiber', *IEEE Photonics Technol. Lett.*, 2002, **14**, p. 77

5 HANSRYD, J., ANDREKSON, P.A., WESTLUND, M., LI, J., and HEDEKVIST, P.O.: 'Fiber-based optical parametric amplifiers and their applications', *IEEE J. Select. Top. Quantum Electron.*, 2002, **8**, p. 506

6 SHARPING, J.E., FIORENTINO, M., COKER, A., KUMAR, P., and WINDELER, R.S.: 'Four-wave mixing in microstructure fiber', *Opt. Lett.*, 2001, **26**, p. 1048