transmission fibre. Because bidirectional pumps are used, the maximum Raman pump power at any local position is 300 mW. Fig. 1 shows total gain, Raman gain and equivalent NF (equivalent NF is defined as measured NF minus fibre attenuation). In addition to 100 nm 20 dB gain bandwidth, this amplifier also has the effect of flattening the noise figure with bidirectional pumping on the shorter wavelength region, thus keeping the equivalent NF less than 3.2 dB over 100 nm. This technology has previously been elusive because it uses much safer levels of optical power than an all-Raman EDFA. Proc. Optical Fiber Communication Conf., Dallas, TX, USA, pp. 6&69 Proc. European Conf. on Optical Communication, Brighton, UK, 1988 pp. 217-224

Recent advances in the fabrication of high confinement optical fibres have increased the prospects for the construction of practical parametric devices. Recent experiments have reported the use of high confinement fibre in amplification [1, 2] and processing [3] applications. This optical fibre is called highly nonlinear fibre (HNLF), a somewhat misleading appellation since the waveguide only provides high confinement with little enhancement of the material nonlinearity. For typical HNLFs the effective area (A_{eff} \approx 10 \mu m^2) is almost an order of magnitude smaller that of a standard singlemode fibre (SMF) and the dispersion slope (d\beta/dA \approx 0.02 ps/nm^2/km) is considerably lower. An efficient parametric amplifier (PA) can be constructed using less than 1 km of HNLF. A PA potentially offers wideband amplification anywhere within the optical transmission window and also provides the means for highly-efficient wavelength conversion and optical regeneration. A small-signal gain of 49 dB over less than 10 nm was recently observed within the optical transmission window and also provides the means for highly-efficient wavelength conversion and optical regeneration. A small-signal gain of 49 dB over less than 10 nm was recently observed in a single-pump PA operating in the continuous-wave (CW) regime [1]. The introduction of two-pump PAs offers the possibility of wide-band, equalised, polarisation-independent gain. CW operation of a two-pump PA recently provided [2] a 22 nm bandwidth of equalised gain using a combined pump power of 600 mW. Both one- and two-pump PA bandwidths are critically limited by the HNLF properties. An ideal HNLF combines a high confinement factor (A_{eff} = \text{1.1 \mu m}^2), a mean PMD of 0.2 \text{ps/nm/km} and a zero-dispersion wavelength :delta_0 of 1583.5 nm and a total loss of 0.9 dB for a length of 1 km. The HNLF was produced by Sumitomo Electric of Yokohama, Japan. The two-pump PA was constructed using C-band (1559 nm) and L-band (1610 nm) pumps, as shown in Fig. 1, originating in tunable external-cavity lasers (A_{1,2}). The initially narrowband pump light was broadened using phase modulators (PM) driven by 231 baseband bit sequences (PRBS) at 10 Gbit/s to suppress stimulated Brillouin scattering (SBS) in the high-power optical amplifiers (A_{1,2} and the HNLF). Optical filters (F_{1,2}) having a 0.6 nm bandwidth were used to reject amplified spontaneous emission (ASE) generated by A_{1,2} and provide a pump/ASE spectral contrast of 80 dB (measured within 3.8 km and 0.1 nm) prior to insertion into the HNLF. The pumps were combined

Record performance from a two-pump parametric amplifier constructed with highly nonlinear fibre is reported. Equalised continuous-wave parametric gain of 40 dB was achieved over 33.8 nm without any gain-flattening elements. Maximal difference between signal and idler powers was measured to be 1 dB within the equalised gain band.

Recent advances in the fabrication of high confinement optical fibres have increased the prospects for the construction of practical parametric devices. Recent experiments have reported the use of high confinement fibre in amplification [1, 2] and processing [3] applications. This optical fibre is called highly nonlinear fibre (HNLF), a somewhat misleading appellation since the waveguide only provides high confinement with little enhancement of the material nonlinearity. For typical HNLFs the effective area (A_{eff} \approx 10 \mu m^2) is almost an order of magnitude smaller than that of a standard singlemode fibre (SMF) and the dispersion slope (d\beta/dA \approx 0.02 ps/nm^2/km) is considerably lower. An efficient parametric amplifier (PA) can be constructed using less than 1 km of HNLF. A PA potentially offers wideband amplification anywhere within the optical transmission window and also provides the means for highly-efficient wavelength conversion and optical regeneration. A small-signal gain of 49 dB over less than 10 nm was recently observed in a single-pump PA operating in the continuous-wave (CW) regime [1]. The introduction of two-pump PAs offers the possibility of wide-band, equalised, polarisation-independent gain. CW operation of a two-pump PA recently provided [2] a 22 nm bandwidth of equalised gain using a combined pump power of 600 mW. Both one- and two-pump PA bandwidths are critically limited by the HNLF properties. An ideal HNLF combines a high confinement factor (A_{eff} = \text{1.1 \mu m}^2), a mean PMD of 0.2 \text{ps/nm/km} and a zero-dispersion wavelength :delta_0 of 1583.5 nm and a total loss of 0.9 dB for a length of 1 km. The HNLF was produced by Sumitomo Electric of Yokohama, Japan. The two-pump PA was constructed using C-band (1559 nm) and L-band (1610 nm) pumps, as shown in Fig. 1, originating in tunable external-cavity lasers (A_{1,2}). The initially narrowband pump light was broadened using phase modulators (PM) driven by 231 baseband bit sequences (PRBS) at 10 Gbit/s to suppress stimulated Brillouin scattering (SBS) in the high-power optical amplifiers (A_{1,2} and the HNLF). Optical filters (F_{1,2}) having a 0.6 nm bandwidth were used to reject amplified spontaneous emission (ASE) generated by A_{1,2} and provide a pump/ASE spectral contrast of 80 dB (measured within 3.8 km and 0.1 nm) prior to insertion into the HNLF. The pumps were combined

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in a 3 dB coupler (PC). An external-cavity laser ($\lambda_2$) provided a tunable signal, which traversed a power adjusting variable attenuator (T$_1$) prior to combining with the pumps through the higher-loss input of a 10/90 coupler. Polarisation controllers (PC$_2$,4) were used to adjust the pump-polarisation states at the input of the HNLF. The polarisation of the pumps was monitored by tapping off 10% of the light prior to entry into a 3 dB coupler (PC). After traversing a polarisation controller (PC$_6$) and a variable attenuator (T$_3$), the light passed to a polarisation beam splitter (PBS) and two optical spectrum analysers (OSA$_2$,3) to monitor the relative pump-polarisation states. A polarisation controller (PC$_1$) was used to combine with the pumps through the higher-loss input of a 10190 polarisation controller (PC). A polarisation controller (PC$_2$,4) was used to adjust the pump-polarisation states simultaneously, while maintaining their relative polarisation. The output of the PA was attenuated (T$_3$) and monitored using an optical spectrum analyser (OSA$_4$) monitored the onset of the SBS threshold.

Significant SBS was not observed for the maximal pump power ($\approx 600$ mW and $\approx 200$ mW) provided a CW gain of 40 dB. The solid curve in Fig. 3 shows a theoretical fit to the data obtained from a set of coupled-wave equations that include both parametric and Raman interactions [4, 5]. The parameters used in this calculation include $\gamma = 1.7 \text{ W}^{-1} \text{km}^{-1}$ (measured) and pump powers identical to those used in the experiment. A fit was obtained using the dispersion coefficients $\beta_2 = 0.055 \text{ ps}^2/\text{km}$ and $\beta_4 = 2.35 \times 10^{-7} \text{ ps}^4/\text{km}$, and an effective interaction length of 600 m. The polarisation dependence of the small-signal gain ($P_{in} = -25$ dBm) at 1578 nm is 4.6 dB for the cross-polarised pump configuration. This observation supports the assumption about pump-polarisation walkoff: relative pump-polarisation states are changed while propagating along the HNLF and do not retain their initial orthogonality. The latter argument further justifies the use of an effective interaction length that is shorter than the HNLF physical length.

Conclusion: We have demonstrated record fibre PA performance characterised by 40 dB of CW gain and wavelength-conversion efficiency with a 3 dB bandwidth of 33.8 nm. The bandwidth was limited not by the HNLF, but by the power available at pump wavelengths longer than 1610 nm. Therefore, we believe that HNLF offers the promise of even wider parametric gain, provided the necessary pump power at longer wavelengths can be obtained.

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S. Radic, C.J. McKindrie, R.M. Jopson and J.C. Centanni (Bell Laboratories, Lucent Technologies, 791 Holmdel-Keyport Road R-231, Holmdel, NJ 07733, USA)
E-mail: radic@lucent.com
Q. Lin and G.P. Agrawal (The Institute of Optics, University of Rochester, Rochester, NY 14627, USA)

References

Fig. 1 Experimental setup
Notation described in text

Fig. 2 ASE generation for co- and cross-polarised pump launch states
Pump wavelengths 1559 and 1610 nm for co-polarised states, 1559.0 and 1610.7 nm for cross-polarised states

Fig. 3 Measured and theoretical gain profiles for co-polarised pump-signal launch states

The measured idler powers in the corresponding bandwidth found to be high as 40 dB.