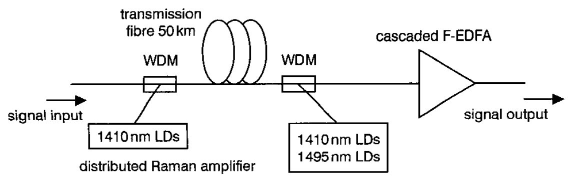

Fig. 5 *Configuration of hybrid amplifier*

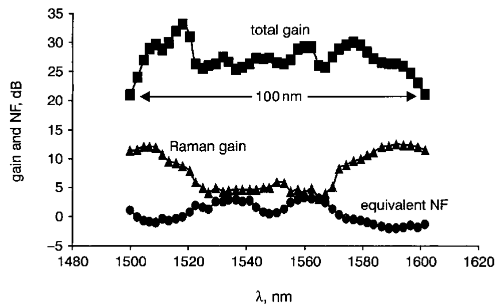

Fig. 6 *Total gain, Raman gain and equivalent NF of hybrid amplifier*

The Raman pumps consist of 90 mW backward-propagating 1495 nm polarisation multiplexed pumps for the longer wavelength region, along with forward and backward 1410 nm polarisation multiplexed pumps for the shorter wavelength region. The 1410 nm forward pump is 150 mW and the backward pump is 210 mW. 50 km of nonzero dispersion shifted fibre with roughly 14.3 dB attenuation is used for transmission fibre. Because bidirectional pumps are used, the maximum Raman pump power at any local position is 300 mW. Fig. 6 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. Compare this to the double-stage F-EDFA which has an NF distribution from 5.0 to 7.7 dB.

Conclusion: We have demonstrated a fluoride-based EDFA that has 20 dB gain over 65 nm. Combined with Raman amplification, the hybrid amplifier achieves 20 dB gain over 100 nm with an equivalent NF of less than 3.2 dB. This technology has previously been elusive because of the lack of a pump for fluoride-based EDFs, but the recent development of cerium-doped EDFs enables us to use 980 nm pumping. This amplification scheme is advantageous for future networks because it uses much safer levels of optical power than an all-Raman system, and it is much simpler than a banded EDFA system.

 11 April 2003
Electronics Letters Online No: 20030554
DOI: 10.1049/el:20030554

Y. Akasaka, I. White and J. Pan (*Advanced Technology Laboratory, Sprint, 30 Adrian Court, Burlingame, CA 94010, USA*)

Y. Kubota, and S. Sakaguchi (*Optical Device Development, Central Glass Co., 3-7-1 Kanda-Nishikicho, Chiyoda-ku, Tokyo, Japan*)

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Record performance of parametric amplifier constructed with highly nonlinear fibre

S. Radic, C.J. McKinstrie, R.M. Jopson, J.C. Centanni, Q. Lin and G.P. Agrawal

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 ($A_{eff} \sim 10\ \mu m^2$) is almost an order of magnitude smaller than that of a standard singlemode fibre (SMF) and the dispersion slope ($dD/d\lambda \sim 0.02\ ps/nm^2km$) 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 wideband, 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 ($1/A_{eff}$) with a small higher-order chromatic dispersion coefficient and low polarisation-mode dispersion (PMD). Typically, the small effective area and the high-index profile, which are required to achieve high optical confinement, lead to considerable dispersion fluctuations along the fibre length. This remains one of the most serious impairments inhibiting the design of wideband PAs.

Here, we report record CW parametric gain achieved using a HNLF having a high confinement factor ($A_{eff} = 11\ \mu m^2$), a mean PMD of $0.2\ ps/km^{-1/2}$, a zero-dispersion wavelength λ_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 ($\lambda_{1,2}$). The initially narrowband pump light was broadened using phase modulators (PM) driven by $2^{31} - 1$ pseudorandom 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 0.1 nm) prior to insertion into the HNLF. The pumps were combined in a 3 dB coupler (PC). An external-cavity laser (λ_3) 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 the HNLF. After traversing a polarisation controller (PC_7) and a variable attenuator (T_2), 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_6) was used to investigate polarisation-dependent loss in the HNLF by changing both 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_1). Another optical spectrum analyser (OSA_4) monitored the onset of the SBS threshold. Significant SBS was not observed for the maximal pump power (650 mW) used in the experiments described here.

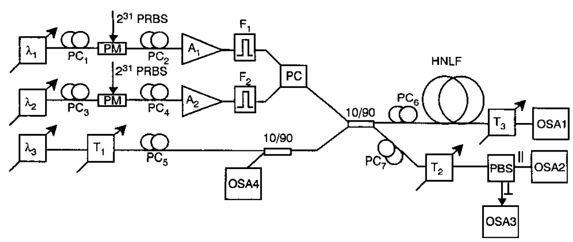

Fig. 1 *Experimental setup*
Notation described in text

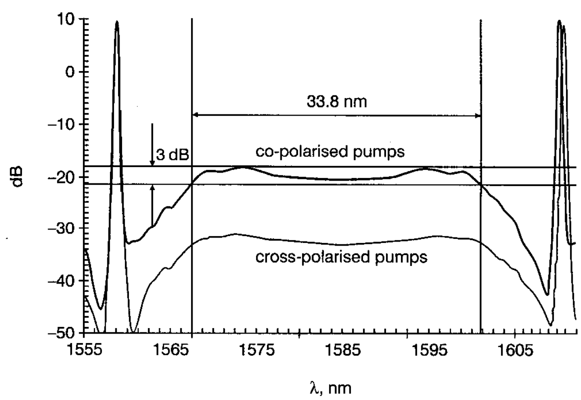

Fig. 2 *ASE generation for co- and cross-polarised pump launch states*
Pump wavelengths 1559 and 1610 nm for co-polarised states, 1559.0 and 1610.7 nm for cross-polarised states

Fig. 2 shows parametric ASE in the absence of an input signal for co-polarised and cross-polarised (orthogonal) pump launch states. The two cases have similar equalised noise spectra with the spectral density generated by the cross-polarised launch state approximately 10 dB lower than that of the co-polarised launch state. The PA gain was measured for a low-power input signal ($P_{in} = -27$ dBm) over the spectral band lying between the pumps (1565–1605 nm). A polarisation controller (PC_5) was used to adjust the signal-polarisation state with respect to the pump states. Fig. 3 shows the gain spectrum for co-polarised signal and pump launch states. Pump powers of $P_{1559} = 600$ mW and $P_{1610} = 200$ mW provided a CW gain of 40 dB with a 3 dB bandwidth of 33.8 nm. Note that the apparatus shown in Fig. 1 provides knowledge of the *launched* polarisation states only; the relative pump-signal polarisation within the PA depends on PMD in the HNLF. The PA exhibits a high wavelength-conversion efficiency, with the measured idler powers in the corresponding bandwidth found to be within 1 dB of the amplified signal powers. This is the first measurement of flat CW parametric gain exceeding the bandwidth of a conventional EDFA (~31 nm) and possessing a small-signal gain as high as 40 dB.

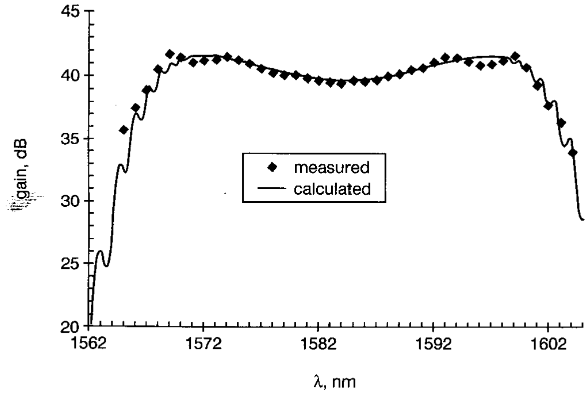

Fig. 3 *Measured and theoretical gain profiles for co-polarised pump-signal launch states*

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 $\gamma = 17\ W^{-1}\ km^{-1}$ (measured) and pump powers identical to those used in the experiment. A fit was obtained using the dispersion coefficients $\beta_3 = 0.055\ ps^3/km$ and $\beta_4 = 2.35 \times 10^{-4}\ ps^4/km$, 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.

17 February 2003
Electronics Letters Online No: 20030544
DOI: 10.1049/el:20030544

S. Radic, C.J. McKinstrie, 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*)

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