23 cm long Bi_2O_3-based EDFA for picosecond pulse amplification with 80 nm gain bandwidth

H. Sotobayashi, J.T. Gopinath and E.P. Ippen

Amplification of a 1 ps pulse train in a 22.7 cm Bismuth oxide (Bi_2O_3)-based erbium doped fibre amplifier (EDFA) is reported. An amplification bandwidth of 80 nm, from 1520 to 1600 nm is demonstrated. Because of the short length, amplification of picosecond pulses is achieved without pulse broadening over a wide wavelength range.

Introduction: To achieve an ultrahigh capacity in photonic networks, it is important to expand the wavelength bands available for wavelength division multiplexing (WDM) signals. Multi-terabit/s transmission experiments usually utilise multiple wavelength bands both in the C- and L-band regions. However, in most cases, separate C-band and L-band erbium doped fibre amplifiers (EDFAs) are used as 1R repeaters [1]. In this configuration, some amount of bandwidth is wasted and the system setup can be complex. To overcome this inefficient usage of spectral resources, several novel amplifiers with continuous C- and L-band capabilities have been demonstrated. These include Raman amplifiers [2] and tellurite-based EDFAs [3, 4]. Bi_2O_3-based EDFAs (Bi-EDFAs) are other promising devices for broadband signal amplification [5–7]. Amplification that covers both the C- and L-bands has been demonstrated in 22 cm and 26 cm long Bi-EDF using a tunable CW light source [5, 6]. At 1530 nm, 250 fs pulse has been amplified in a 12 cm Bi-EDFA [7]. In this Letter, an amplification of picosecond pulses in a 22.7 cm Bi-EDF has been studied. Gains greater than 12 dB are achieved without pulse broadening over an 80 nm wavelength range, from 1520 to 1600 nm.

Experiments and discussions: Fig. 1 shows the experimental setup for investigating the amplification properties of a 22.7 cm Bi-EDF. The erbium concentration of the Bi-EDF was 6500 wt.ppm, the mode-field diameter at 1550 nm was 6.0 μm, and the numerical aperture was 0.20. The refractive indexes of the core and cladding were 2.03 and 2.02, respectively. Both ends of Bi-EDF were fusion spliced to SiO_2 fibres, with a loss per splicing of less than 0.7 dB [6]. The Bi-EDF was bi-directionally pumped by 975 nm laser diodes through WDM couplers. The power of each pump laser was set to 24.1 dBm. The signal source is an optical parametric oscillator (OPO), synchronously pumped by a Ti:sapphire laser. The OPO produces 150 fs pulses at a repetition rate of 82 MHz tunable between 1400–1600 nm. By spectrally slicing the OPO pulse, using a wavelength tunable 4.5 nm optical filter, we produce 1.0–1.3 ps pulses with a wavelength tuning range of 1520–1600 nm. The amplified signal was characterised using an optical spectrum analyser, an autocorrelator, and an optical power meter. The pulse widths were estimated by assuming a Gaussian pulse shape.

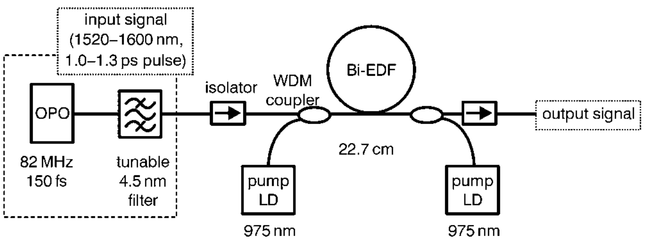

Fig. 1 *Experimental setup for picosecond pulse train amplification in 22.7 cm Bi-EDF*

Fig. 2 shows the gain against input signal power at 1530 nm. The output power was 10.7 dBm and the gain was 17.1 dB for an input power of −6.46 dBm. Fig. 3 shows the autocorrelation traces measured before and after amplification at the signal wavelength of 1550 nm. The input signal powers were varied over an order of magnitude from −12.6 dBm to −2.50 dBm. The pulse width of the input signal was 1.06 ps and the amplified output pulse widths were 1.05 ps in both cases. The pulse widths did not change significantly in either the small signal or saturated amplification case. Because of the short length of the Bi-EDF, the total group velocity dispersion of the Bi-EDF did not affect the pulse width of the picosecond pulses in this experiment. Fig. 4*a* shows the gain against centre wavelength of the input signal for an input power of −11.5 dBm. Gain larger than 20 dB was observed between 1530 and 1555 nm and net gain larger than 11.8 dB was observed over a bandwidth of 80 nm (1520–1600 nm). The gain peak occurred at 1530 nm. Fig. 4*b* shows the pulse widths and spectral widths before and after amplification against the centre wavelength of the input signal. The output pulse widths appeared unchanged and are essentially the same as the input pulse widths over the measured wavelength range of 80 nm. There was not much change in spectral widths except at 1530 and 1535 nm. At these wavelengths, the changes in spectral width were caused by the self phase modulation. The peak power of the amplified pulse was above 100 W, therefore, the nonlinear length was about 30 cm because of the high nonlinear refractive index of Bi-EDF [8, 9]. These nonlinear effects can be avoided by using a high repetition rate pulse train.

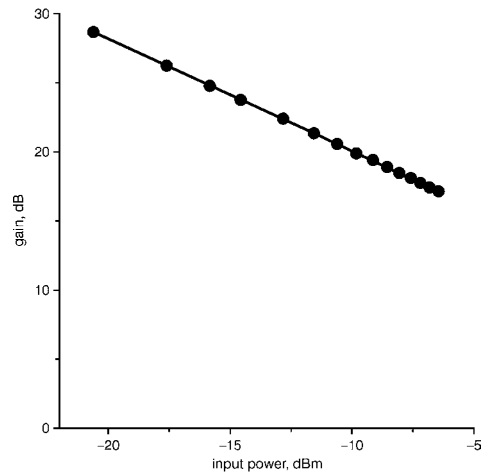

Fig. 2 *Gain against input signal power at 1530 nm*

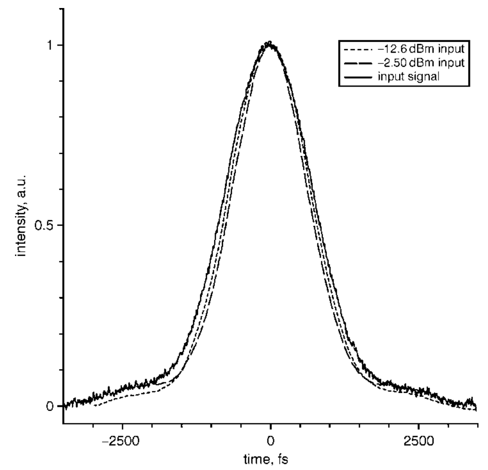

Fig. 3 *Autocorrelation traces of input and output pulses at 1550 nm*

In conventional EDFAs, picosecond pulse amplification without dispersion compensation is difficult. Because of low gain per unit length, conventional EDFAs are usually tens of metres long. This means that the total group velocity dispersion becomes high. However, because a Bi-EDF can amplify signals in a few tens of cm with larger than 10 dB gain, picosecond pulses can be amplified without pulse distortion over a broad wavelength range.

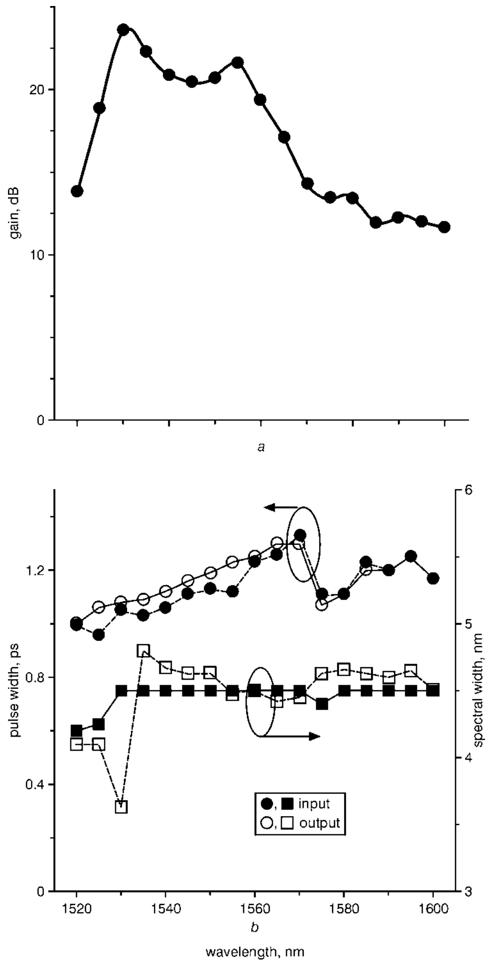

Fig. 4 *Gain against signal wavelength and pulse width and spectral width against signal wavelength*

Input power was set to −11.5 dBm. Step in pulse width at 1575 nm is due to filter change
a Gain against signal wavelength
b Pulse width and spectral width against signal wavelength

Conclusion: We have demonstrated 1 ps pulse amplification with a broad gain bandwidth over 80 nm (1520–1600 nm) in a 22.7 cm Bi_2O_3-based EDF. These characteristics of this amplifier are suitable for 160 Gbit/s based WDM systems covering both C- and L-bands.

Acknowledgments: The authors would like to thank F. Koizumi of Asahi Glass Company for his collaboration. This work was supported in part at MIT by Air Force Office of Scientific Research Contract F49620-01-1-0084.

26 June 2003
Electronics Letters Online No: 20030877
DOI: 10.1049/el:20030877

H. Sotobayashi, J.T. Gopinath and E.P. Ippen (*Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*)

References

1 ITO, T., FUKUCHI, K., and INADA, Y.: '3.2 Tbit/s-1500 km WDM transmission experiment using 64-nm hybrid repeater amplifiers'. Proc. 25th Optical Fiber Communications Conference (OFC2000), Baltimore, March 2000, Paper PD24

2 SHIMOJOH, N., *et al.*: '2.4-Tbit/s WDM transmission over 7400 km using all Raman amplifier repeaters with 74-nm continuous single band'. Proc. 27th European Conference on Optical Communication (ECOC 2001), Amsterdam, September 2001, Paper PD1

3 YAMADA, M., *et al.*: 'Gain-flattened Tellurite-based EDFA with a flat amplification bandwidth of 76 nm', *IEEE Photonics Technol. Lett.*, 1998, **10**, pp. 1244–1246

4 SOTOBAYASHI, H., *et al.*: 'Wavelength-band generation and transmission of 3.24-Tbit/s (81-channel WDM40-Gbit/s) carrier-suppressed return-to-zero format by use of a single super-continuum source for frequency standardization', *J. Opt. Soc. Am. B*, 2002, **19**, (11), pp. 2803–2809

5 SUGIMOTO, N.: 'Ultrafast optical switches and wavelength division multiplexing (WDM) amplifiers based on Bismuth oxide glasses', *J. Am. Ceram. Soc.*, 2002, **85**, pp. 1083–1088

6 KUROIWA, Y., *et al.*: 'Fusion spliceable and high efficient Bi_2O_3-based EDF for short length and broadband amplification pumped at 1480 nm'. Proc. 26th Optical Fiber Communication Conference (OFC 2001), Anaheim, March 2001, TuI5

7 TAIRA, K., KIKUCHI, K., and SUGIMOTO, N.: 'Dispersion and pulse amplification characteristics of Bismuth oxide-based Erbium doped fiber amplifiers'. Proc. Optical Amplifiers and Applications Conference (OAA 2002), Vancouver, July 2002, Paper OTuC2

8 KITANO, H., *et al.*: 'Measurements of the nonlinear refractive index of an Er^{3+}-doped Bi_2O_3-based glass fiber', *Jpn. J. Appl. Phys.*, 2001, **40**, (9A/B), pp. L955–L957

9 SET, S., *et al.*: 'Low nonlinearity Bismuth oxide-based Erbium-doped fiber amplifiers for short pulse amplification'. Optical Fiber Communication Conference (OFC2003), Atlanta, March 2003, Paper FB7