HIGHLY EFFICIENT 978 nm DIODE-PUMPED ERBIUM-DOPED FIBRE AMPLIFIER WITH 24 dB GAIN

Indexing terms: Optical fibres, Optical communications, Doping, Lasers and laser applications

We report an Er^{3+}-doped fibre amplifier pumped with a strained GaInAs/AlGaAs quantum-well diode laser operating at 978 nm. Efficient optical coupling of the diode laser pump was achieved with a wedge-tipped fibre. An optical gain of 24 dB at 1535 nm was obtained with only 6·2 mW of pump power, corresponding to a gain of 3·9 dB/mW of pump power. This is the highest efficiency for a fibre amplifier achieved thus far.

Introduction: Erbium-doped fibre amplifiers operating at around 1·53 μm are of particular interest for optical fibre communications because of their low insertion loss, lack of polarisation sensitivity, high fibre-to-fibre gain and broad bandwidth.[1,2] Previous reports have demonstrated that the 980 nm pump band allows efficient pumping because of the lack of excited state absorption, and a gain coefficient as high as 2·2 dB/mW has been obtained with a dye laser pump.[3] More recently, a similar performance (2·1 dB/mW) has been obtained employing a pump wavelength of 1490 nm, obtained from a colour centre laser.[4]

Practical erbium-doped fibre amplifiers must be pumped by diode lasers. It is not clear at present which diode pumping wavelength, 980 or 1490 nm, will be more suitable in terms of pump efficiency and reliability, and amplifier performance. In this letter we discuss the optimisation of an erbium-doped fibre amplifier for 980 nm pumping to obtain a high-gain, low-pump-power fibre amplifier. A 978 nm strained GaInAs/AlGaAs quantum-well laser coupled to a wedge-tipped fibre was used to optically pump the amplifier. The pump light and the signal light at 1535·3 nm were coupled to the Er-doped fibre using a dichroic fibre coupler. An optical gain of 24 dB was obtained with only 6·2 mW of pump power, corresponding to a record gain of 3·9 dB/mW of pump power.

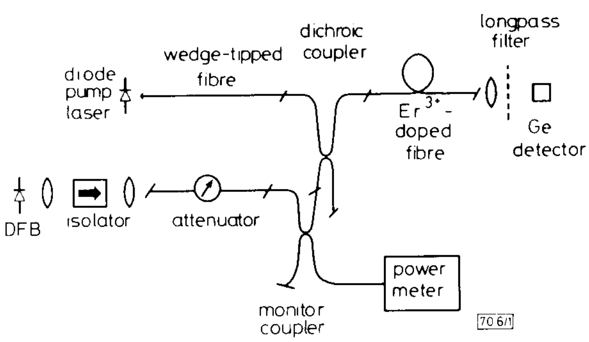

Fig. 1 *Experimental arrangement*

Experiment: The experimental arrangement is shown in Fig. 1. The strained $Ga_{0.75}In_{0.25}As$/AlGaAs quantum-well diode pump laser[5] had an oxide stripe width of 25 μm, a length of 600 μm, and the rear facet had a high-reflection coating to increase the power from the output facet. The lasing spectrum, shown in Fig. 2, was centred at 978 nm at an operating current of 250 mA. The majority of the diode's output power fell within the erbium 980 nm absorption band.

Efficient optical coupling of the diode pump laser was obtained using a wedge-tipped fibre. The fibre end was up-tapered to approximately twice its nominal diameter and subsequently polished to form a wedge tip which was aligned with the laser.[6] Up to 10 mW of pump power could be launched into the wedge-tipped fibre. This fibre was butt-coupled to the dichroic fibre coupler which had a loss of 0·2 dB at the pump wavelength. The other coupler input was used to add the signal from a 1535·3 nm DFB laser. The coupler's output port was spliced to the amplifier fibre, where splice losses of 0·3 dB at 1535 nm and 0·6 dB at 980 nm were obtained. Slightly reduced coupling into the wedge-tipped fibre and at the butt-coupled joint caused an additional 1·0 dB

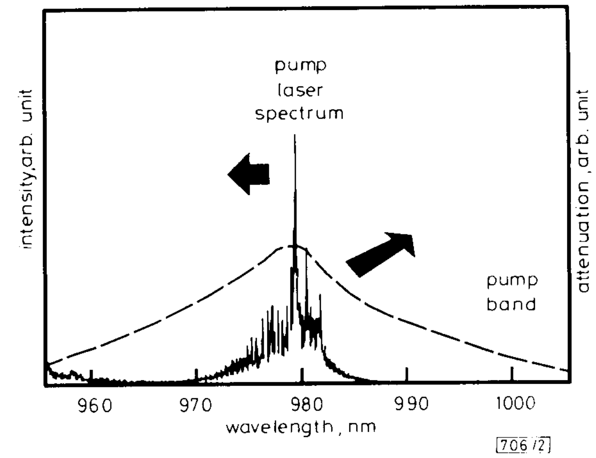

Fig. 2 *Spectra of strained GaInAs/AlGaAs quantum-well laser output and erbium pump band*

loss of pump power, resulting in 6·2 mW of pump power launched into the amplifier fibre.

The germano-silicate erbium-doped fibre amplifier was characterised by a relative index difference of 0·01, λ_{cutoff} at 955 nm, and a measured mode field diameter of 7·3 μm at 1555 nm. The splice loss to a commercial dispersion-shifted fibre was 0·2 dB at 1535 nm. For maximum pump/dopant overlap and best pump efficiency, the fibre was designed with the erbium localised in the central region of the core.[7] This localisation of the erbium doping, together with the increase in the fibre relative index difference compared with previous fibres, are the major reasons for more efficient pumping than previous 980 nm results,[3] where the measured fibre mode field diameter was 8·3 μm.

Results: An amplifier length of 11·5 m was chosen to maximise the gain. Figs. 3*a* and *b* show the amplifier gain plotted against input and output signal power, respectively. A gain of 24 dB was obtained for a launched pump power of 6·2 mW. A 3 dB gain compression occurred for input signals of −27 dBm, corresponding to an output signal of −6 dBm. These are excellent characteristics for use as an optical preamplifier. In addition, since the fibre design optimises the pump/dopant overlap and thus the gain medium inversion, the amplifier noise figure is expected[8] to be very close to the theoretical minimum value of 3 dB.

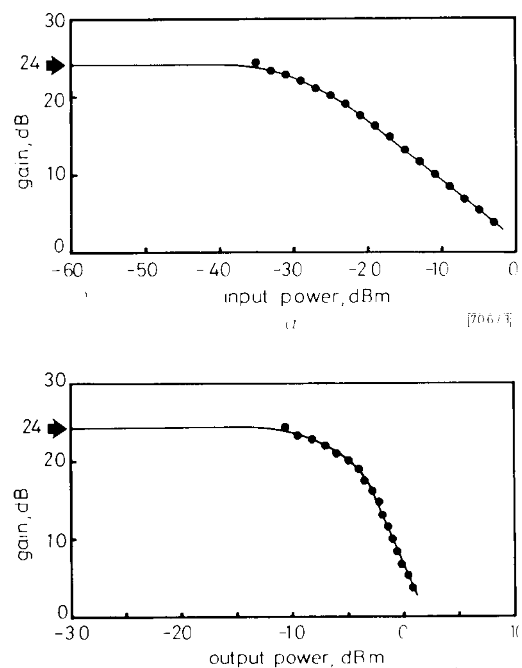

Fig. 3 *Gain against (a) input and (b) output signal powers, respectively, for 978 nm diode-pumped amplifier*

Pump power = 6·2 mW

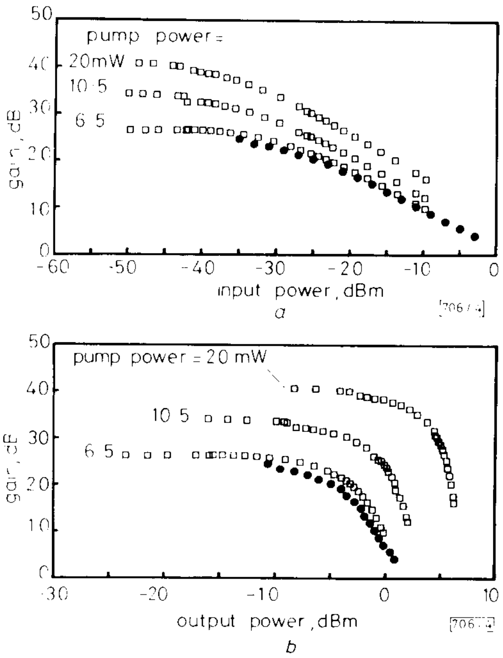

Fig. 4 *Gain against (a) input and (b) output signal powers, respectively, for different pump powers*

□ 980 nm dye laser pump ● 978 nm diode laser pump
Diode laser pump power = 6·2 mW

Under optimum operating conditions, the unabsorbed pump power emerging from the fibre amplifier was measured to be 1·5 mW. Of this, 0·75 mW was attributed to the spectrally broad fluorescence background emission from the diode pump laser which failed to overlap the erbium pump band at 980 nm. The effects of higher diode pump powers were simulated using a dye laser operating at 980 nm, and are compared with the actual diode pumping results in Figs. 4*a* and *b*. In each case the fibre length was optimised for maximum gain. The Figure shows gain as a function of input and output signal powers, and suggests that a gain in excess of 40 dB can be obtained in future diode-pumped amplifiers for only 20 mW of pump power at 980 nm, provided optical reflections do not limit the gain to lower values.

Conclusion: We have demonstrated an efficient, high-gain erbium fibre amplifier pumped with a 978 nm strained GaInAs/AlGaAs quantum-well diode laser. A gain of 24 dB was obtained with only 6·2 mW of pump power. It has also been shown that a gain of 40 dB can be obtained using 20 mW of pump power at 980 nm.

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References

1 MEARS, R. J., REEKIE, L., JAUNCEY, I. M., and PAYNE, D. N.: 'Low-noise erbium-doped fibre amplifier operating at 1·54 μm', *Electron. Lett.*, 1987, **23**, pp. 1026–1028

2 DESURVIRE, E., SIMPSON, J. R., and BECKER, P. C.: 'High-gain erbium-doped travelling-wave fibre amplifier', *Opt. Lett.*, 1987, **12**, pp. 888–890

3 LAMING, R. I., FARRIES, M. C., MORKEL, P. R., PAYNE, D. N., SCRIVENER, P. L., FONTANA, F., and RIGHETTI, A.: 'Efficient pump wavelengths of erbium-doped fibre optical amplifier', *Electron. Lett.*, 1989, **25**, pp. 12–14

4 DESURVIRE, E., GILES, C. R., SIMPSON, J. R., and ZYSKIND, J. L.: 'Efficient erbium-doped fibre amplifier at $\lambda = 1{\cdot}53\,\mu m$ with high output saturation power'. Proc. conf. on lasers and electro-optics, CLEO '89, Baltimore, 1989, PD-20

5 BOUR, D. P., EVANS, G. A., and GILBERT, D. B.: 'High power conversion efficiency in a strained InGaAs/AlGaAs quantum well laser', *J. Appl. Phys.*, 1989, **65**, pp. 3340–3343

6 SHAH, V., CURTIS, L., VODHANEL, R. S., BOUR, D. P., and YOUNG, W. C.: submitted to OFC '90

7 AINSLIE, B. J., ARMITAGE, J. R., CRAIG, S. P., and WAKEFIELD, B.: 'Fabrication and optimisation of the erbium distribution in silica based doped fibres'. Proc. 14th Europ. conf. on opt. commun., ECOC '88, Brighton, 1988; *IEE Conf. Publ. 292*, 1988, Pt. 1, pp. 62–65

8 OLSHANSKY, R.: 'Noise figure for erbium-doped optical fibre amplifiers', *Electron. Lett.*, 1988, **24**, pp. 1363–1365