suitable wavelength for pumping erbium-doped fibre amplifiers.

It is concluded that high power output (over 100 mW) and efficient laser-to-fibre coupling can be achieved using multi-quantum well ridge waveguide laser structures.

Acknowledgments: We would like to thank D. J. Moule and J. A. Champelovier for the device processing, T. Bricheno, K. J. Warbrick and W. O. Bourne for the device packaging work and N. Taylor for his support and encouragement. The work in this letter was supported by STC Submarine Systems. The authors wish to thank STC Technology Ltd. for permission to present this letter.

28th August 1990

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TEMPERATURE DEPENDENT GAIN AND NOISE CHARACTERISTICS OF A 1480 nm-PUMPED ERBIUM-DOPED FIBRE AMPLIFIER

Indexing terms: Optical fibres, Amplifiers, Stability

The gain of a 1480 nm pumped erbium-doped fibre amplifier has been measured over the temperature range −40°C to 60°C. The characteristics can be modelled using emission and absorption cross-section data determined for this temperature range. The temperature dependence of the gain spectrum and noise figure are also predicted.

Introduction: The excellent performance of erbium-doped fibre amplifiers[1] (EDFA) for 1·5 μm communication systems has been confirmed by many recent experiments[2] and there is little doubt that EDFAs will soon be used in practical applications. An understanding of the amplifier temperature dependent characteristics is of great importance. Measurements using either the 0·6 or 0·98 μm pump band have reported no significant temperature dependence of either the gain or the amplified spontaneous emission (ASE) spectrum.[3,4] When resonantly pumped at the wavelength of 1·48 μm, the situation is different. In this case, temperature dependent gain and noise characteristics are expected because of a combination of the proximity of the pump and signal energies and the temperature-dependent distribution of ions within the metastable and the ground levels. Previous work[4] has shown a highly temperature sensitive gain for a 1·48 μm pumped amplifier.

We analyse the temperature dependent gain both theoretically and experimentally and show that the gain is not necessarily highly temperature sensitive.[5] We have measured both the amplifier gain and spectral absorption and emission cross-section data for temperatures in the range −40°C to 60°C, corresponding to the maximum likely temperature excursion of most systems. Within this range, the gain change was 1·5 dB, which is in good agreement with a prediction based on a two level model using the measured absorption and emission cross-sections. This confirms the practicality of the resonantly-pumped EDFA for field applications where significant variation in ambient temperature may be expected. The temperature dependence of the spectral gain and noise figure have also been predicted using this model.

Experiment: The erbium-doped fibre used in the experiment was germano-silicate fibre with an *NA* of 0·2, a cutoff wavelength of 1300 nm and erbium localised in the central region of the fibre core. The absorption and emission cross-sections at −40°C and 60°C were obtained based on those at room temperature[6] and the relative changes of absorption and fluorescence spectra at these temperatures. The unsaturated gain of a 16·3 m long EDFA, the whole of which was contained in an oven, was measured using the co-propagating pump scheme. The fibre length was optimised at room temperature. Two 1·48 μm high-power LDs were employed to give a launch power of 28 mW. The signal wavelength was 1·535 μm.

Theory: Since, for resonant pumping, both the pump and signal transitions are between the $^4I_{13/2}$ metastable and $^4I_{15/2}$ ground-levels, we have employed a two level model rather than a three level model.[7] The equations for the population inversion and the evolution of pump and signal power along the fibre are

$$dN_2/dt = (\beta W_p + \alpha W_s)(N_{tot} - N_2) - (W_p + W_s + 1/\tau_f)N_2 \tag{1}$$

$$dP_p/dz = \eta_p \sigma_E(\lambda_p) P_p [N_2 - \beta(N_{tot} - N_2)] \tag{2}$$

$$dP_s/dz = \eta_s \sigma_E(\lambda_s) P_s [N_2 - \alpha(N_{tot} - N_2)] \tag{3}$$

where N_2 is the population density of the metastable level, N_{tot} the total erbium concentration, W_p and W_s the pump and stimulated emission rates[7] and α is given by $\sigma_A(\lambda_s)/\sigma_E(\lambda_s)$ and β by $\sigma_A(\lambda_p)/\sigma_E(\lambda_p)$, where $\sigma_A(\lambda)$ and $\sigma_E(\lambda)$ are absorption and emission cross-sections at wavelengh λ. The parameter τ_f is the metastable lifetime and $\eta_{p(s)}$ is the overlap of the pump (signal) field with the erbium distribution.

The temperature-dependent characteristics of an EDFA results from the temperature dependence of σ_A and σ_E. It should be noted that the measured σ_A and σ_E reflect the distribution of ions in the ground and metastable levels at a given temperature. The gain and noise[7] characteristics were obtained from the above equations which were solved numerically taking account of ASE.

Results and discussion: Figs. 1 and 2 show the temperature dependence of σ_A and σ_E, respectively. At the signal wavelength (1·535 μm), σ_A and σ_E decrease with temperature. At the pump wavelength (~1·48 μm), σ_A is found to decrease and σ_E increase. As a result, the amplifier gain was found to decrease from 21·6 dB to 20·1 dB on increasing the temperature from −40°C to 60°C, as shown in Fig. 3. These results are theoretically confirmed. The lower solid line in Fig. 3 is the numerical solution of eqns. 1–3, where the erbium distribution is approximated by a top-hat profile occupying 50% of the core area and having a local concentration $N_{tot} = 1{\cdot}7 \times 10^{18}\,\mathrm{cm}^{-3}$. This gives $\eta_p = \eta_s = 0{\cdot}48$.[8] The measured values of σ_A and σ_E from Figs. 1 and 2 and the previously determined value,[7] τ_f = 12 ms (assumed temperature independent) are also employed. For simplicity, the change in cross-section at each wavelength was assumed to be a linear function of temperature, with coefficients determined by cross-sections at −40°C, 20°C and 60°C.

This small change of gain with temperature can be readily compensated with AGC confirming the practicality of the EDFA. Recent work[9] has shown that the temperature dependence of amplifier gain can also be reduced by choosing a fibre length greater than the optimum value. However, in this case, the amplifier gain is significantly reduced, and thus AGC is preferred.

The upper solid line in Fig. 3 is a temperature dependence of the noise figure, which was calculated according to Reference 6 with the above parameters. The small variation in both gain and noise figure suggests a low temperature dependent population inversion even for 1·48 μm in-band pumping. The temperature dependence of the gain spectrum was also calculated (Fig. 4). Although the gain is higher at the low temperature, its profile remains similar, which agrees well with the measured ASE spectrum shown in the inset of Fig. 4.

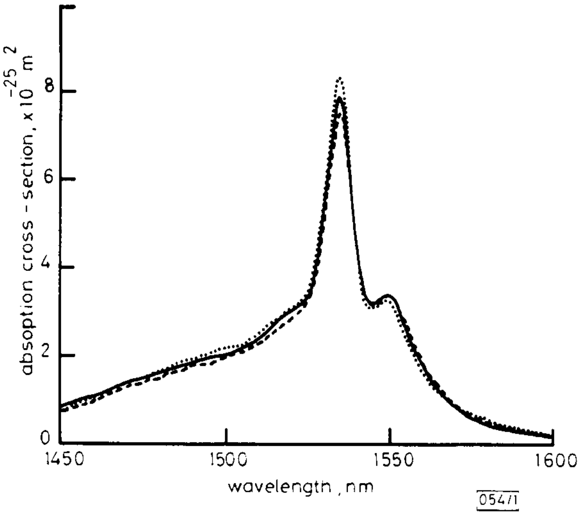

Fig. 1 *Absorption cross-section data*

······· −40°C
——— 20°C
- - - - 60°C

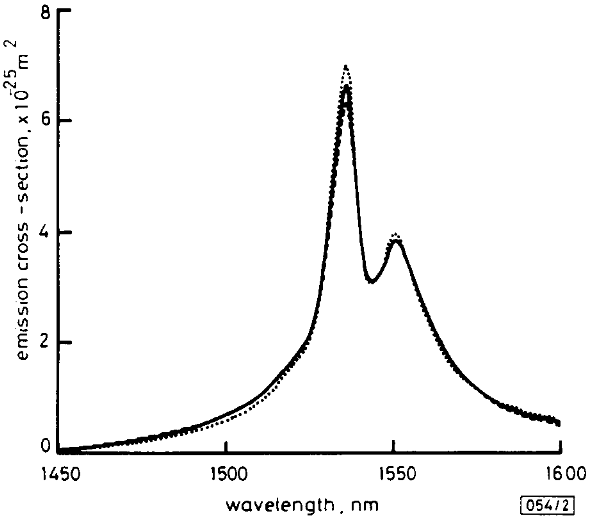

Fig. 2 *Emission cross-section data*

······· −40°C
——— 20°C
- - - - 60°C

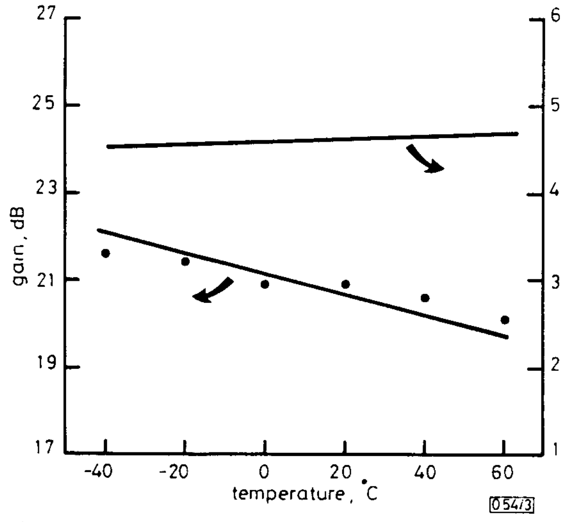

Fig. 3 *Temperature dependence of gain and noise figure*

——— calculated values

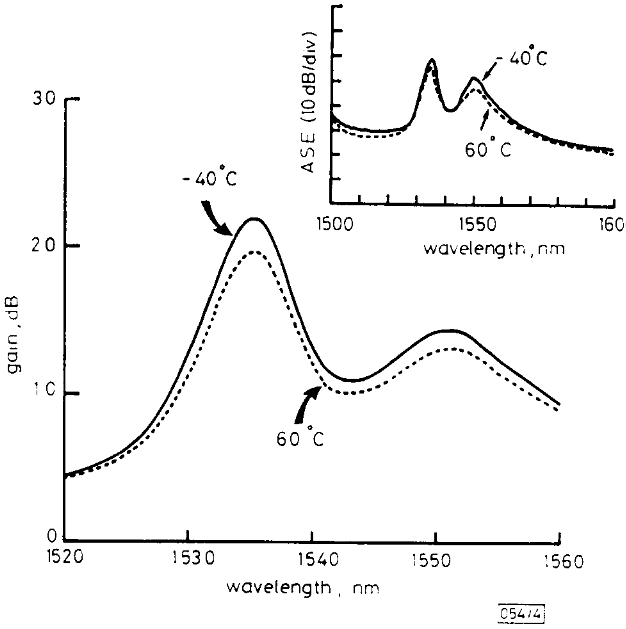

Fig. 4 *Calculated gain spectra*

Inset: measured ASE spectra

Conclusion: We have measured the change in gain with temperature for a resonantly-pumped EDFA and temperatures in the range −40 to 60°C. The gain change in this temperature range was from 21·6 to 20·1 dB. We have also measured emission and absorption cross-section data for the same temperature range. A theoretical model of the amplifier employing these data predicts a similar gain dependence on temperature. Temperature dependence of the noise figure and the gain spectrum were calculated using this model. We envisage that these results will be invaluable in the design of multiple amplifier chains involving AGC.

Acknowledgments: This work was supported by Pirelli General Plc. We wish to thank P. R. Morkel for useful discussions, N. Chinone of Hitachi for providing the signal LD and J. D. Minelly for the fibre coupler. M. Suyama is on leave from Fujitsu Laboratories, 1015 Kamikodanaka, Nakahara, Kawasaki, 211, Japan.

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HIGHLY EFFICIENT OPTICAL FIBRE AMPLIFIER PUMPED BY A 0·8μm BAND LASER DIODE

Indexing terms: Optical fibres, Amplifiers

A highly efficient Er-doped fibre amplifier pumped by GaAlAs laser diodes is reported. Using a low Er-cluster content fibre with a high numerical aperture, the EDFA attains 39 dB signal gain for double LD pumping and 30 dB for single LD pumping at 1·536 μm. A maximum gain coefficient of 1·3 dB/mW was achieved at the 0·827 μm pump band.

Erbium-doped fibre amplifiers (EDFA) pumped by laser diodes (LD) are attractive optical devices for 1·5 μm optical communication systems because of their low-insertion loss, high gain and low noise. Large signal pass gains of more than 30 dB have been obtained with laser diode pumping sources of 0·98 and 1·48 μm.[1,2] A semiconductor–laser diode (LD) pumping into the 0·8 μm absorption band[3–5] is a more practical pump source because this LD has many advantages such as high reliability, high power and low cost. The disadvantages of 0·8 μm band pumping is that at this wavelength, efficient pumping is severely impeded by pump excited-state absorption (ESA). Improvement of the gain coefficient of Er-doped optical fibres offers great potential for the EDFA to be pumped by GaAlAs laser diodes.

We report a highly efficient GaAlAs pumped by a 0·8 μm band laser diode. The key feature of the EDFA is the application an erbium-doped fibre with a low-Er cluster content and high numerical aperture, so highly efficient pumping is achieved.

The pump source for gain measurement is a commercially available GaAlAs laser diode for a compact disc (CD) optical memory. Outputs from two 0·827 μm laser diodes used as pumping light sources are combined by a polarisation beamsplitter. To reduce the coupling loss between the LD and the fibre (fibre coupler), each output beam from the GaAlAs LD is collimated by using a LD collimating lens and an anamorphic prism pair. The lowest coupling loss is 2·8 dB. The signal light source is an external cavity type laser diode. The signal source can be tuned from 1·48 to 1·58 μm. The wavelengths for gain measurements are set at 1·536 and 1·553 μm. The pumping light and the signal light are multiplied by a dichroic fibre coupler, and are launched into an Er-doped fibre. The coupling efficiency at 0·827 μm is 95% and at 1·536 μm is 98%. Two polarisation-insensitive optical isolators are used to avoid laser oscillation. One is installed between the erbium-doped fibre and the EDFA output. The other is installed between the signal input and the fibre coupler.

The Er-doped fibre (EDF) was fabricated by the extended VAD method. This method has an advantage of providing low Er-cluster content optical fibres, since erbium is uniformly doped into silica soot preform in a vapour phase atmosphere. To attain highly efficient Er-doped optical fibres, two key features must be considered. The first is the erbium concentration in silica glass. Previously, we found for the first time that an increase in Er concentration caused deterioration of the amplification efficiency, which originated in the Er-cluster. This occurred even with a relatively low erbium concentration of less than 500 ppm.[6] On the basis of this result, we fabricated an EDF with an erbium content of 81 ppm for this experiment.

The second important feature is the fibre structural design to attain maximum pumping efficiency.[7] To maximise pump/dopant overlap and therefore maximum pump efficiency, the fibre structure was designed with a high numerical aperture (NA). A high NA Er-doped fibre was achieved using a glass system of a GeO$_2$-doped silica core and fluorine-doped silica cladding. The fibre has a relative refractive-index difference of 1·88%, which corresponds to a 0·28 numerical aperture.

The relationship between the fibre length and the signal gain at 1·536 μm is shown in Fig. 1. The coupled signal power was maintained at −43 dBm, and the incident coupling pump power was 25·4 mW for single LD pumping and 49·6 mW for double LD pumping. The two curves with open and closed circles correspond to double LD and single LD pumping, respectively. Optimum fibre length is around 85 m with a maximum gain of 30·1 dB for single LD pumping, and around 110 m with a maximum gain of 3·5 dB for double LD pumping.

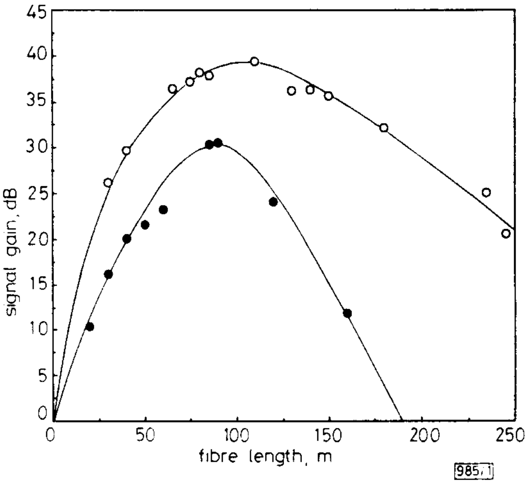

Fig. 1 *Fibre length dependent signal gain at 1·536 μm*

● single LD: 25 mW
○ double LD: 50 mW

The gain characteristics of EDFAs with optimum fibre lengths is shown in Fig. 2. Two curves with open and closed circles correspond to gains for double and single LD pumping, respectively, and two curves with open and closed squares correspond to gain coefficients for double and single LD pumping, respectively. The threshold pump power was 16 mW for double LD pumping and 10·5 mW for single LD pumping. A maximum gain coefficient of 1·31 dB/mW is achieved at a 18·8 mW pump power for single LD pumping. To the best of our knowledge, this efficiency is the highest value ever reported for an EDFA pumped at a 0·8 μm band.

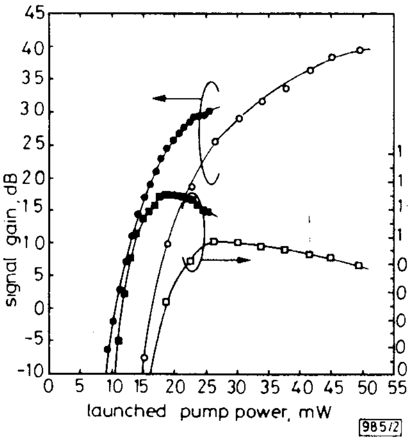

Fig. 2 *Gain characteristics of GaAlAs LD-pumped EDFAs*

●■ single LD (fibre length: 85 m)
○□ double LD (fibre length: 110 m)