LOW-NOISE ERBIUM-DOPED FIBRE AMPLIFIER OPERATING AT 1·54 μm

Indexing terms: Optical fibres, Optical communications

High gain amplification of up to 28 dB has been observed in a 3 m-long erbium-doped fibre. The amplifier has a spectral bandwidth of greater than 300 GHz in the region of 1·536 μm and a measured sensitivity of −42 dBm at a bit rate of 140 Mbit/s.

Introduction: As optical communication systems improve, the requirement for high-bandwidth repeaters is becoming increasingly demanding. Optical amplifiers based on stimulated emission or nonlinear effects will probably play an important role in future systems because they eliminate the

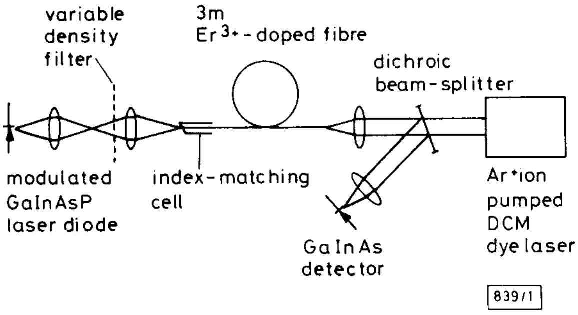

Fig. 1 *Experimental configuration for fibre amplifier*

need for electronic signal conversion, and have projected bandwidths of the order of 100 GHz or more. There are currently two competing technologies for optical repeaters, namely semiconductor laser amplifiers[1] and Raman amplifiers.[2] In this letter we demonstate a third approach, based on an optically pumped rare-earth-doped optical fibre.[3]

Experimental configuration: The experimental configuration for the fibre amplifier is shown in Fig. 1. A 3 m length of Er^{3+}-doped fibre[4] (NA = 0·2, λ_{cutoff} = 1·4 μm, dopant concentration $\simeq 10^{19}\,cm^{-3}$) was reverse-pumped longitudinally with light from a CW DCM-dye laser. The signal was provided by a 1·54 μm GaInAsP DCPBH laser. Thermoelectric cooling of the laser diode permitted temperature tuning of the wavelength from 1·532 to 1·540 μm. The mounting of the diode restricted the modulation frequency to a few hundred megahertz, and the majority of the measurements were taken at a signal bit rate of 140 Mbit/s

For experimental convenience, light from the diode was first launched into a single-mode fibre coupler which had a loss of 0·5 dB and a splitting ratio of 10 dB at 1·54 μm. The second output port provided a monitor for the signal power and wavelength. Light was launched into the doped fibre via an index-matched butt-splice, and the splice loss was measured to be less than 1 dB.

To prevent the onset of lasing, care must be taken to eliminate feedback into the amplifier from the fibre ends and from plane surfaces in collimated beam paths. Thus the signal input fibre endface was index-matched as shown, and index-matching oil was inserted at the butt-splice to reduce Fresnel reflection. In a practical fibre amplifier, fusion splicing of the active fibre in-line would be sufficient to reduce round-trip feedback to below −40 dB.

Output signal extraction was performed with a dichroic beam-splitter (90% *R* at 1·54 μm; 85% *T* at 670 nm) and detected with a biased GaInAs PIN diode. The load resistance was provided by the 50 Ω input impedance of either a Tektronix sampling head or a Marconi spectrum analyser. Although this detection scheme is simple and insensitive, it is adequate to detect signals of a few tens of nanowatts at the fibre input, thus demonstrating the potential of the fibre as a preamplifier.

Gain measurements: The same detection system was used alternatively to measure the input and output signals so that any losses in the detection were automatically compensated. The gain measurements presented here include the splice loss of ≃ 1 dB, and therefore represent a true fibre/fibre signal gain, as might be experienced in an in-line amplifier. The dependence of the amplifier gain on pump power is plotted in Fig. 2. The threshold power is a little over 10 mW, and a gain of 20 dB is available for approximately 20 mW absorbed in the doped fibre. Thereafter the gain saturates, indicating a high degree of inversion in the three-level Er^{3+} system. The maximum gain observed was 28 dB.

The power-transfer characteristic of the amplifier is given in Fig. 3. The measurement was made at an absorbed pump power of 60 mW. The gain begins to saturate at an input power grater than −20 dBm, when the output power is +5 dBm. A 3 dB compression from linear gain is observed for an output power of +7 dBm. For comparison, the 3 dB point in a typical semiconductor laser amplifier occurs at output powers between −18 dBm and −10 dBm.[5] The fibre amplifier can thus handle considerably more power, which is a distinct advantage if the amplifier is to be employed in a multichannel communication system.

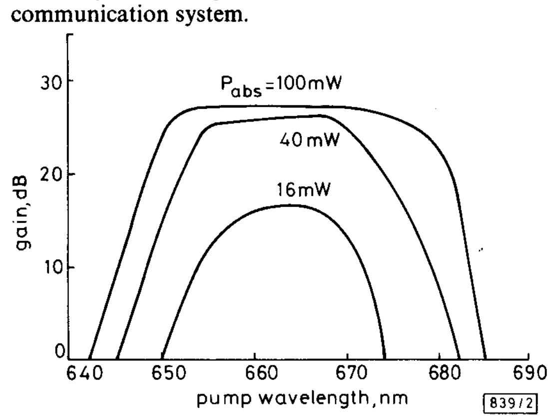

Fig. 2 *Amplifier gain against pump power and wavelength*

The spectral dependence of the gain is an important consideration if an amplifier is to be incorporated in broadband wavelength-multiplexed systems. In Fig. 4 the measured spectral dependence of the amplifier gain bears a close resemblance to the fluorescence spectrum, as demonstrated by the broken line superimposed on the Figure. The highest gains are available in a 300 GHz bandwidth centred on 1·536 μm.

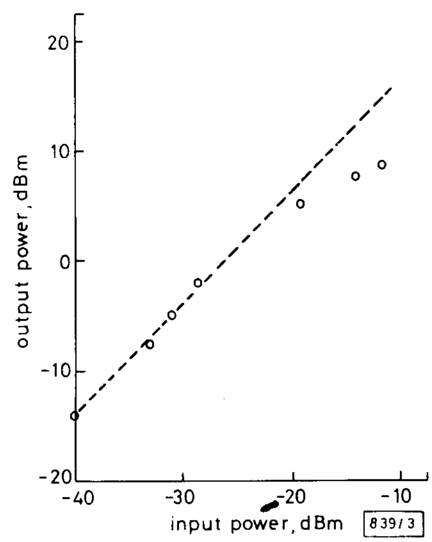

Fig. 3 *Power transfer characteristic*

Moreover, the broad fluorescence spectrum suggests that gains in excess of 10 dB should be available over a bandwidth as large as 4 THz (30 nm).

Measurements of the dependence of the gain on the pump wavelength (Fig. 2) indicate that the fibre gain is unimpaired for pump wavelengths between 655 nm and 675 nm. It is thus likely that more practical sources, such as the 670 nm laser diodes currently under development, might be used to pump the amplifier. Further possibilities for diode pumping are the use of the weak 800 nm pump band or codoping of the fibre with an Er/Yb mixture to create a large absorption band at

930 nm, from which resonant energy transfer occurs to the Er ions.[6]

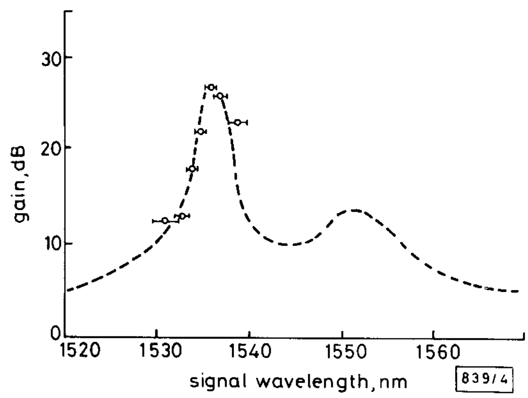

Fig. 4 *Gain spectrum and spontaneous emission*

Points represent experimental measurements and error bars indicate spectral width of diode laser spectrum
Curve represents fluoresence curve

Noise measurements: The noise performance determines the usefulness of the amplifier both as a repeater and as a receiver preamplifier. The amplifier noise in the region of 100 MHz was measured on a Marconi spectrum analyser to be $200\,pA/\sqrt{(Hz)}$, corresponding to a sensitivity of -42 dBm at 140 Mbit/s for a 10^{-9} bit error rate. This value compares favourably with state-of-the-art APD detectors at $1{\cdot}54\,\mu m$, and further illustrates the potential of the doped fibre as a preamplifier. Calculation of the shot noise associated with the measured amplified spontaneous emission power ($50\,\mu W$) suggests that an even greater sensitivity (-62 dBm at 140 Mbit/s) may be attainable. The reason for the discrepancy is not clear at present.

Conclusion: We have demonstrated a new technique of optical amplification using an erbium-doped optical fibre. Gains of up to 28 dB have been attained in the important wavelength region of $1{\cdot}54\,\mu m$. The amplifier has a spectral bandwidth in excess of 300 GHz. Although it has only been tested up to a few hundred megahertz, there is no reason to expect its performance to be impaired up to and beyond 100 GHz. Moreover, the excellent power handling characteristics make the amplifier well suited to high-bandwidth multichannel optical communication. A sensitivity of -42 dBm has been measured directly without spectral filtering, and potentially -62 dBm appears possible. If coherent techniques are used it should be relatively easy to reach the shot-noise limit. The fibre amplifier is expected to make an important impact both on long-distance telecommunications and in local networks, where gain can be used to increase the maximum number of subscribers.

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