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ERBIUM-DOPED FIBRE AMPLIFIERS OPERATING AT 1.5μm

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INTRODUCTION

The field of rare-earth-doped fibre lasers[1,2,3] and amplifiers has expanded rapidly in recent years and there are now several groups working actively in the area. A variety of glass hosts, dopants and pump sources have been used, with the goal of achieving low-threshold, diode-laser-pumped operation of fibre lasers and amplifiers, particularly those operating in either the second or third telecommunication windows.

The small core size of the single-mode fibre allows high pump intensities for modest (~mW) pump powers. Moreover, the intensity can be maintained over long lengths and this leads to ultra- low lasing thresholds[4] and even permits CW diode-laser-pumped operation of three-level lasers. In conjunction with the long fluorescent lifetime of rare-earths in glass, the high pump intensity allows high-gain (>30dB) operation of fibre amplifiers with excellent saturation properties[5]. In addition, compatibility with existing fibre components is excellent, allowing all-optical fibre circuitry to be assembled with both active and passive components. This is particularly beneficial for the fibre amplifier, where splicing of the active fibre into the telecommunication link virtually eliminates troublesome Fresnel-reflection feedback which normally limits the gain in semiconductor laser amplifiers[6].

The configuration of a rare-earth-doped fibre amplifier is shown in Fig. 1. Using Er^{3+} as a dopant, exceptionally high gains (26dB) have been obtained at a wavelength of 1.536μm, for modulation rates up to 400MHz[5]. The amplifier is optically pumped using any one of a variety of wavelengths. The input equivalent noise power has been measured at -42dBm at a bit rate of 140Mb/s which compares favourably with state-of-the-art APD detectors at 1.54μm. A maximum output power of +13dBm has been achieved before onset of saturation. These early results demonstrate that Er^{3+}-doped fibre amplifiers possess excellent gain and noise characteristics which make them attractive as wideband amplifiers and repeaters for multi-channel optical transmission systems.

PUMPING OF ERBIUM-DOPED FIBRE AMPLIFIERS

Although fibre amplifiers

show exceptional promise, their application in transmission systems will be limited unless solid-state pump sources can be found. To date best performance has been obtained using impractical dye-laser[5] and Ar^+-ion[7] pump sources at wavelengths of 660nm and 514nm. Similar performance has yet to be demonstrated with more realistic pump sources.

Reference to the absorption spectrum of an erbium-doped fibre (Fig. 2) shows that potential practical pump-bands exist at wavelengths of 532nm, 670nm, 807nm and 980nm. Of these, solid-state sources at 532nm (frequency-doubled mini-YAG lasers) and 807nm (multi-stripe laser diodes) are available today, while at 670nm and 980nm relatively low-power laser diodes have been reported. Also shown on the Figure are regions of pump excited-state absorption (ESA), a phenomenon which particularly plagues three-level, longitudinally-pumped optical amplifiers. The effect occurs when a further transition is present above the (highly-populated) upper laser level with an energy difference corresponding to that of the pump photons. In this case an additional absorption occurs at the pump wavelength which drains pump power and limits the available gain. It can be seen that whereas 532nm, 670nm and 980nm are relatively clear of ESA, the most practical pump band (807nm) is quite strongly affected. Thus pumping at 807nm requires high pump power to overcome the poor pump efficiency and an undesirably large NA fibre to increase the pump intensity before high gain can be achieved[8].

Recently it has been shown[9] that the 980nm pump band is entirely free of ESA (Fig. 2) and that, as a result, high gain is obtainable at exceptionally-low pump powers. The results for an erbium-doped fibre amplifier (0.1 wt % Er_2O_3, NA = 0.16, λ_{cutoff} = 975nm) pumped with a cw dye laser operating at 980nm are shown in Fig. 3. The pump light was 10.5mW and was co-propagated with the signal. The figure shows signal output power as a function of fibre length for signal input powers of 250nW, 1.6μW and 70μW. Pump throughput is also shown and it can be seen to decay approximately linearly along the fibre length, indicating bleaching of the ground-state absorption and minimal ESA (the presence of which gives an exponential pump decay with length).

The small-signal (250nW) gain peaks at 24dB for a fibre length of 9m. This value of gain per unit pump (2.2dB/mW) is by far the most efficient yet reported and is well within the reach of GaAsSb-AlGaAsSb laser diodes, even though the fibre has a relatively-standard NA. The maximum gain of 24dB was limited only by the pump power available and gains in excess of 30dB can be projected for around 15mW of pump. The large signal gain is seen to saturate at a value of 11.5dB where an output power of 0.2dBm is available.

These results have stimulated a number of diode laser manufacturers to commence development of 980nm pump sources.

The gain/pump power figures reported to date for erbium fibre amplifiers pumped at various wavelengths are shown in Table 1 where it can be seen that the 980nm pump wavelength is nearly an order of magnitude more efficient than wavelengths where ESA is present. The only comparable result is that obtained at 532nm where frequency-doubled mini-YAG lasers could be used.

Table 1 also gives an early result[10] for directly pumping into the gain band at 1.49μm. Diodes are available at this wavelength and it is thought that future results will significantly improve on ref. 10, making this a viable pump option.

NOISE IN ERBIUM-DOPED FIBRE AMPLIFIERS

Compared to a semiconductor injection amplifier, a fibre amplifier has the advantage that it can be spliced to standard telecommunications fibre with very low loss. This attribute also ensures low optical feedback and eliminates the partial resonances which plague semiconductor optical amplifiers. Thus quantum-noise limited operation of a fibre amplifier is more easily achievable.

In this section we quantify the various noise contributions in the erbium-doped fibre amplifier and predict its performance for different signal powers and optical bandwidths.

The output from an optical fibre amplifier is a combination of amplified signal and broad-spectrum amplified spontaneous emission (ASE). If the input signal is coherent its noise contribution is the usual shot noise associated with the amplified signal level. There is also a shot noise associated with the level of the ASE. Additional noise terms are introduced by the mixing on the detector of the amplified signal and the spectral components of the ASE to give signal-spontaneous beat noise and spontaneous-spontaneous beat noise[11,12].

The power spectral density of the signal-spontaneous beat noise is independent of the optical bandwidth, whereas spontaneous-spontaneous beat noise is a direct function of optical bandwidth. Thus reducing the optical bandwidth reduces the spontaneous-spontaneous beat noise contribution and at low signal input powers where this noise dominates, optical filtering can be an advantage.

The amplifier noise can therefore be expressed as the sum of 3 components, signal + ASE shot noise, signal-spontaneous beat noise and spontaneous-spontaneous beat noise[12]. When operating at signal input levels of interest to optical communications (i.e. $>10^{-9}$ BER), it transpires that the noise is dominated by signal-spontaneous beat noise. Under these conditions the parameter 2μ represents the amplifier noise figure, where μ is the amplifier inversion $n_2/(n_2-n_1)$ n_1 and n_2 being the population densities of the ground and metastable states. The parameter μ can be found accurately by integration of the spontaneous emission along the fibre length. When the medium is fully inverted, μ has a maximum value of unity and the best possible amplifier noise figure is 3dB.

An experiment[13] was conducted on a fibre (NA = 0.21, λ_{cutoff} = 1050nm) doped with 150ppm Er^{3+}. Using 100mW of pump light at 665nm, the small-signal (-40dBm) gain was measured at 28dB, falling to 16dB at large (-10dBm) signal inputs. The measured noise current normalised to a 1Hz bandwidth is shown in Fig. 4 (points) as a function of signal input level. Also shown is the calculated noise current (solid line), together with its constituent beat and shot noise components (dashed lines). The calculation assumes an ASE bandwidth of 2nm, an inversion parameter μ of unity and a detector quantum efficiency of 90%. The excellent agreement between experiment and theory indicates that a high inversion has been obtained at this pump level (i.e. $\mu \sim 1$).

It can be seen from Fig. 4 that at high input signals (>30dBm) the dominant noise source is signal-spontaneous beat noise. Here, as predicted, the erbium fibre amplifier is quantum limited and has a noise figure of 3dB. At lower input signal levels, however, spontaneous-spontaneous beat noise becomes the dominant noise source and the noise figure increases. Under these circumstances, optical filtering to reduce the spontaneous emission bandwidth is beneficial.

From the above results we can calculate that if used as a power amplifier to boost signal levels into the fibre to approximately +13dBm[13] at the input of a transmission link, the erbium fibre amplifier will produce an insignificant decrement in signal to noise ratio. Incorporated as a pre-amplifier prior to a 1GHz receiver, a maximum sensitivity of -41.5dBm (peak-to-peak) for a BER of 10^{-9} is obtainable, improving to -45dBm if the amplifier output is filtered to 0.1nm. This compares very favourably with the maximum sensitivity of -33dBm for a typical 1GHz Ge APD receiver.

CONCLUSIONS

Erbium-doped fibre amplifiers are poised to become a standard component in telecommunications systems. They exhibit excellent gain (>30dB) and noise characteristics and can be readily spliced into networks. Moreover, unlike diode optical amplifiers, they are polarisation insensitive.

At present, extensive application of Er^{3+} amplifiers is limited only by the lack of suitable pump diodes. We have shown the advantage of using pump bands where no ESA is present, the 980nm band being ideal. A gain of 24dB was obtained for only 10.5mW of pump, a power well within the reach of semiconductor diodes. A further advantage of the long pump wavelength is that it ensures greater pump energy-efficiency, as well as allowing good overlap between pump and signal, since the fibre can be single-mode at both.

Measurements of noise in erbium fibre amplifiers show that under normal signal conditions they behave as ideal quantum amplifiers with a noise figure of 3dB. These results make fibre amplifiers an attractive proposition for practical in-line repeaters, power and pre-amplifiers.

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FIBRE TYPE	NA	λ_{pump}	P_{pump}	GAIN	GAIN/P_{pump}	REF.
SiO_2/GeO_2	0.16	532nm	25mW	34dB	1.35dB/mW	9
SiO_2/GeO_2	0.16	980nm	10.5mW	24dB	2.2dB/mW	9
SiO_2/Al_2O_3	0.18	514nm	100mW	22dB	0.22dB/mW	7
SiO_2/Al_2O_3	0.14	514nm	100mW	16dB	0.16dB/mW	9
SiO_2/Al_2O_3	0.14	528nm	100mW	31dB	0.31dB/mW	9
SiO_2/GeO_2	0.2	665nm	100mW	26dB	0.26dB/mW	5
SiO_2/GeO_2	0.3	807nm	20mW	8dB	0.46dB/mW	8
SiO_2/Al_2O_3	0.12	1.49μm	14mW	2dB	0.14dB/mW	10

Table 1 Published gain and pump requirements for erbium amplifiers pumped at various wavelengths

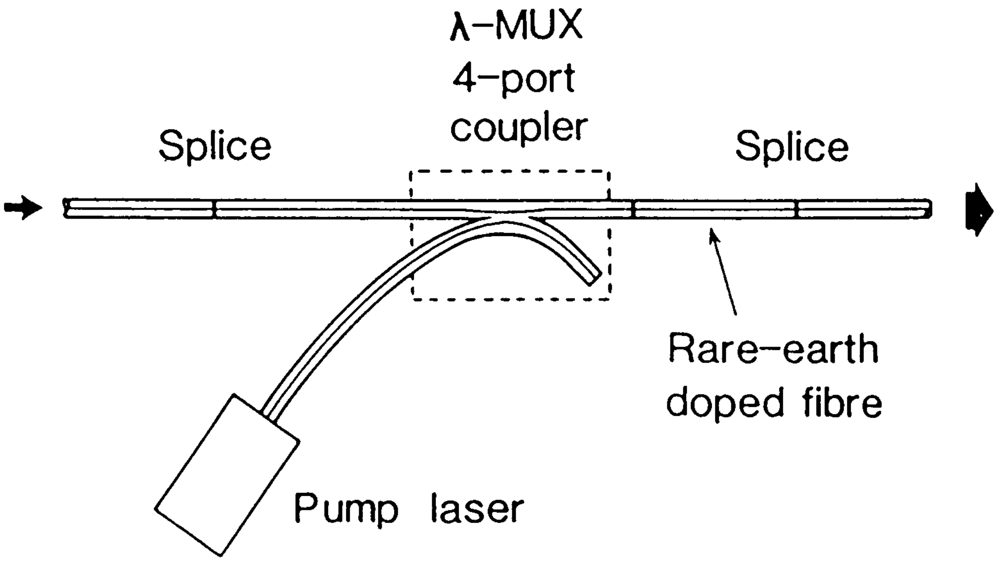

Fig. 1 Erbium-doped fibre amplifier configuration

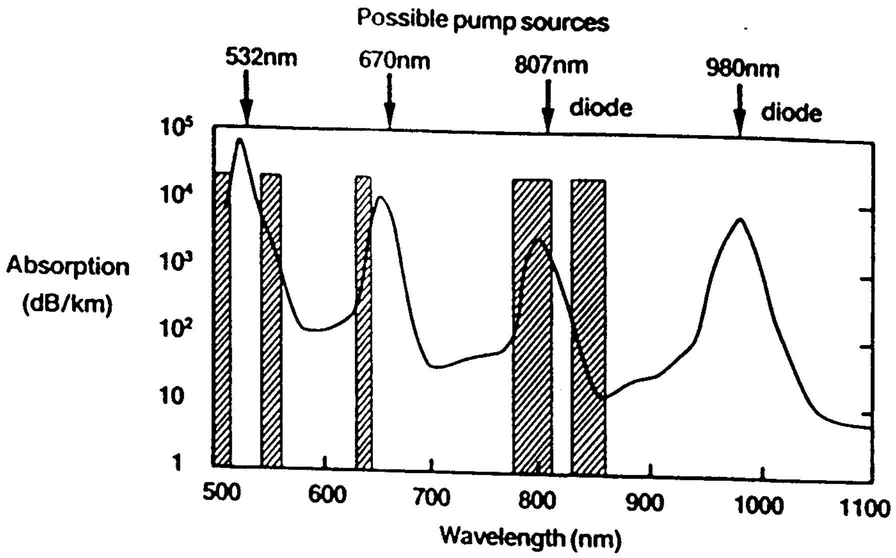

Fig. 2 Absorption spectrum of Er3+-doped fibre showing regions of excited-state absorption (shaded)

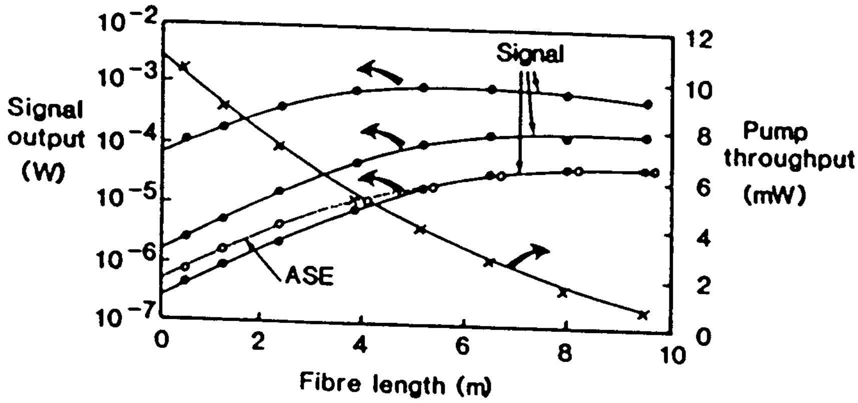

Fig. 3 Signal output and pump throughput for an Er^{3+}-doped fibre amplifier pumped at 980nm (10.5mW)

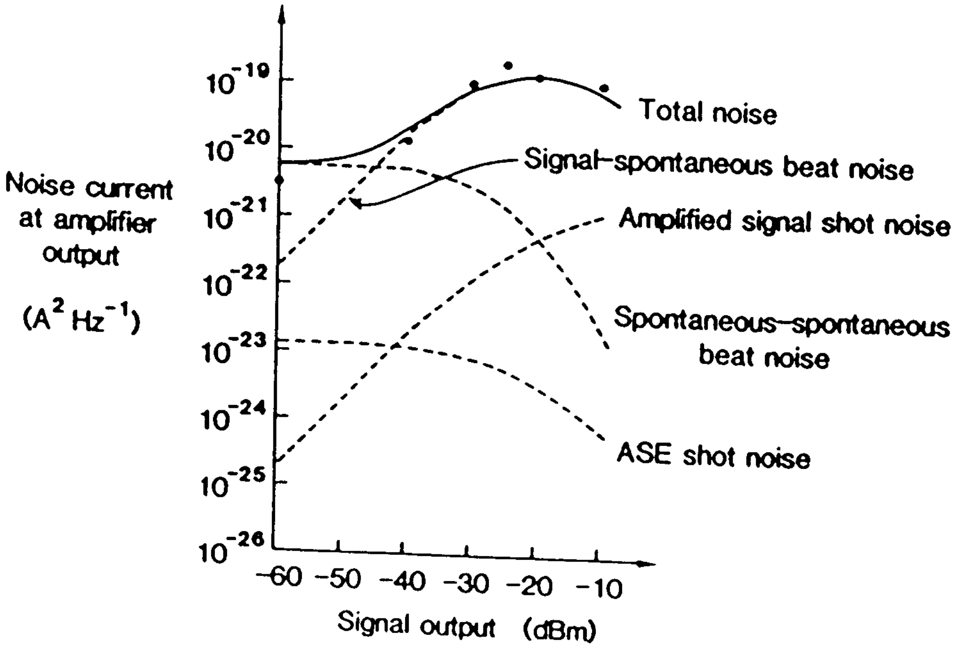

Fig. 4 Experimental (points) and theoretical (curves) noise performance of an Er^{3+}-amplifier.