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Design and fabrication of high gain-efficiency erbium-doped fibre amplifiers.

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Abstract

The gain efficiency of a fully optimised EDFA is calculated as a function of the fibre NA and dopant confinement in the core and is shown to agree well with experimental data. A gain efficiency of 8.9dB/mW is demonstrated which is the best reported value to date for MCVD fibres. In addition, the detrimental effect of pump and signal background losses on the optimum gain efficiency is considered in detail.

Introduction: Erbium-doped fibre amplifiers (EDFAs) [1] are expected to play an important role in the implementation of high quality, reliable, fibre-optic communication systems as line-, power- and pre-amplifiers. The reliability of the EDFA is primarily determined by that of the pump diode and can be maximised by reducing the pump power requirements. A highly gain-efficient fibre allows the pump power to be reduced with consequent gains in amplifier longevity. The gain performance of the EDFA is determined by a number of factors including host glass composition, dopant confinement, pump and signal wavelengths, fibre loss, cut-off wavelength and numerical aperture (NA). A careful choice of these parameters is necessary for the design of a highly efficient EDFA [2,3] but, to date, the effect of the background signal and pump loss on the gain efficiency of the amplifier has not been fully addressed, despite the fact that in practice these effects dominate the search for higher pump efficiency.

The best gain efficiency reported to date is 11dB/mW obtained with a germano-silicate fibre having an NA of ~ 0.28 and fabricated using the VAD method [4]. With the MCVD fabrication method, on the other hand, the best reported gain efficiency is much lower (6.1dB/mW) [5].

In this letter, we report the design and fabrication of low-loss, efficient erbium-doped fibres for optical amplifiers and consider in detail the detrimental effect of the signal and pump background loss on the gain efficiency. A gain efficiency of 8.9dB/mW is obtained which, to our knowledge, is the best reported efficiency for fibres fabricated using the MCVD method.

Design criteria: The effect of the gain medium on the efficiency of the EDFA is determined by the macroscopic measurable parameters of absorption and emission cross-sections at the pump and signal wavelengths [6]. These variables depend on the host-glass composition and are highest in GeO_2-SiO_2 fibres [7] which are known to give the best reported efficiencies [4]. The most efficient pump wavelength is around 980nm, giving near-quantum-limited noise performance [8,9], a desirable feature for pre-amplifier applications. On the other hand, emission and absorption spectra peak near 1536nm, resulting in maximum gain efficiencies at this signal wavelength.

The geometric parameters of the fibre determine the pump and signal field distributions across the fibre cross-section and affect the gain efficiency of the EDFA. The cut-off wavelength is chosen so that the fibre is single-moded at both pump and signal wavelengths for maximum overlap. Pump threshold and gain efficiency are strongly affected by the field distribution (spot size) and relative intensity of the pump wavelength, both of which are highly dependent on the fibre cut-off wavelength [2]. In addition, the spot sizes and relative intensities at the pump and signal wavelengths are influenced by the numerical aperture (NA) of the fibre, which in turn dramatically affects the gain efficiency of the EDFA [3,10]. Confining the erbium ions close to the centre of the core so that a larger proportion of them are subjected to increased pump intensities results in an improved population inversion and increases the gain efficiency further [10].

For the purposes of our optimisation, the gain efficiency of an EDFA pumped at 980nm in a co-directional configuration was calculated under fully optimised conditions. A three-level model was employed which utilised the overlap-integral and equivalent ASE-bandwidth approximations [6]. For each fibre NA, the fibre length and the input pump power were optimised for maximum gain efficiency. Finally, a further optimisation was performed with respect to cut-off wavelength. The absorption and emission cross-sections and the other parameters used in the numerical calculations were determined experimentally from saturation measurements performed in our laboratories [7]. The absorption and emission cross-sections at the signal wavelength were $7.9\times10^{-25}m^2$ and $7.11\times10^{-25}m^2$, respectively. The absorption cross-section at the pump wavelength was $2.55\times10^{-25}m^2$. The equivalent ASE bandwidth was 4.5nm.

In Figure 1, the optimum gain efficiency is plotted against the fibre NA for an input signal power of -55dBm and wavelength of 1536nm, confinement factors (ratio of dopant to core radius) of 1, 0.7 and 0.5 and optimum cut-off wavelengths of 835nm, 855nm and 880nm. The background losses at the pump and signal wavelengths are considered to be zero. The optimum gain efficiency is shown to increase quasi-quadratically with the fibre NA. For ultra-high gain efficiencies, confinement of the dopant into the fibre core is needed. With a fibre NA of 0.4 and a confinement factor of 0.5, a gain efficiency in excess of 23dB/mW is predicted. Experimental data shown on the figure will be discussed below.

The detrimental effect of the signal and pump background-loss on the amplifier gain efficiency was considered next. Normalised optimum gain efficiency is calculated for a range of fibre NAs (0.1 to 0.4) as a function of normalised pump background loss for zero signal loss (Fig. 2a) and vice versa (Fig. 2b). The gain efficiency is normalised to the optimum value without background losses, shown in Figure 1, whilst signal and pump background-losses are normalised to the maximum unpumped signal absorption, i.e, $10\log[\exp(-N_T\sigma_{AS}\Gamma_S)]$ (dB/m), where N_T is the total number of erbium ions per unit volume, σ_{AS} is the absorption cross-section at the signal wavelength and Γ_S is the signal overlap integral [6].

From Figures 2(a) and (b), it is readily deduced that the background-loss at the pump wavelength has a much more pronounced effect on the deterioration of the gain efficiency than that at the signal wavelength. It is also evident that the gain-efficiency degradation with pump background-loss is strongly affected by the fibre NA. On the other hand, the NA has no effect on the gain-efficiency degradation with signal background-loss. All these effects are due to the fact that in the unsaturated, low input-signal power regime, the population inversion of the medium and, therefore, the gain efficiency of the EDFA is almost exclusively determined by the pump-power distribution along the fibre length.

From Figures 1, 2(a) and (b) it is clearly seen that increasing the fibre NA not only increases the gain efficiency of the amplifier but also renders it more tolerant to the pump background loss. The theoretical curves in Figures 2(a) and (b) correspond to the cases with zero background loss for the signal and pump, respectively, and constitute the upper limits of the expected optimum gain efficiencies. When, as in reality, the signal and pump background losses are simultaneously present the maximum efficiencies are expected to be lower. Examination of Figure 2(a) confirms that for a low excess loss (less than ~1% normalised loss), gain efficiencies in excess of 95% of the optimum values are achieved. Again, experimental data shown on Figure 2(a) will be discussed below.

Fabrication: Given the design criteria of a GeO_2-SiO_2 host, high NA, low Er^{3+} concentration, low excess loss and short cut-off wavelengths, additional constraints are placed on fibre manufacturing via the solution doping process [11]. Around 20% GeO_2 is incorporated in the silica-based core to achieve a NA of about 0.3. However, owing to the low viscosity of this composition, the deposition temperature is critical to form a frit suitable for doping. The deposition temperature must be sufficiently high to ensure complete oxidation and good adhesion to the substrate. However, the soot must also be of high porosity to allow incorporation of dopant from solution and outdiffusion of gasses during the subsequent fusion.

The low solubility of Er^{3+} in germanosilicates places an upper limit on the dopant concentration (less than ~ 100ppm) to prevent concentration quenching with reduced emission quantum efficiency. Given this limit, dopant is added uniformly across the core material to allow high absorption with little background loss. The doping levels are determined from the solution strength of $ErCl_3.6H_2O$ in H_2O.

O_2, N_2 and He gases heated to ~ 600°C are employed to remove residual solvent after doping. Cl_2 is not used as this can contribute to increased scatter loss. The drying temperature is chosen to ensure efficient removal of OH^- absorbed onto the frit without evaporation of dopant material. O_2 is employed throughout the dehydration and in all subsequent stages to ensure GeO_2 is not reduced to GeO with associated generation of defects or loss of material. He aids out-diffusion of trapped gasses during drying, sintering and preform collapse to ensure low background losses.

Minimal thermal processing is applied throughout the preform collapse and fibre drawing processes to reduce dopant diffusion and hence clustering which arises from the low solubility of Er^{3+} in the tetrahedral germanosilicate lattice. In addition, it is essential to minimise drawing-induced losses by employing high draw tensions at low temperature.

Experimental results - Discussion: A range of fibres having varying NAs, dopant concentrations and background losses were produced and tested. The parameters of some representative samples whose gain efficiencies appear in Figures 1 and 2(a) are summarised in Table I. Data referring to fibres #4 and #5 were provided by Pirelli Cables [12].

Optimum experimental data obtained in our and other laboratories are plotted in Figure 1 and, with the exception of the 11dB/mW [4], are in very good agreement with the theoretical predictions. This justifies the use in the modelling of the emission and absorption cross-sections obtained from saturation measurements and further strengthens the arguments put forward in Ref. [7]. According to our model, in order to achieve a gain efficiency of 11dB/mW with a fibre NA of 0.28, a confinement factor of about 0.7 is required. Our value of 8.9dB/mW was obtained with a fibre of 0.29 NA and, to the best of our knowledge, it is the highest gain efficiency reported in a MCVD fibre using an input signal level of -45dBm.

Conclusions: The gain efficiencies of a fully-optimised EDFA have been calculated as a function of the fibre NA and dopant confinement and are shown to agree well with experimental data. A gain efficiency of 8.9dB/mW is reported, which is the best reported value to date for MCVD fibres. The detrimental effect of pump and signal background loss on the gain efficiency has also been considered in detail.

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FIGURE CAPTIONS

1. Calculated optimum gain efficiency as a function of the fibre NA for input signal power of -45dBm and confinement factors of 1, 0.7 and 0.5. The signal and pump background losses are zero. Experimental data are plotted for comparison.

2. Normalised optimum gain efficiency as a function of (*a*) normalised pump background-loss and (*b*) normalised signal background-loss. The fibres are with unconfined dopant and NA's of 0.1 to 0.4. The experimental data refer to fibres whose characteristics are summarised in Table I.

TABLE I

Performance characteristics of fibres used in this work.

Fibre No.	#1	#2	#3	#4	#5	#6	#7
Fibre NA	0.19	0.24	0.245	0.27	0.27	0.28	0.29
Gain Efficiency (dB/mW)	3.6	6.4	3.5	7.4	6.7	5.9	8.9
Signal absorption (dB/m)	5.5	0.95	1.2	0.33	0.33	1.6	1.2
Background loss @ 980nm (dB/km)	<5	<5	30	9	14	60	<13

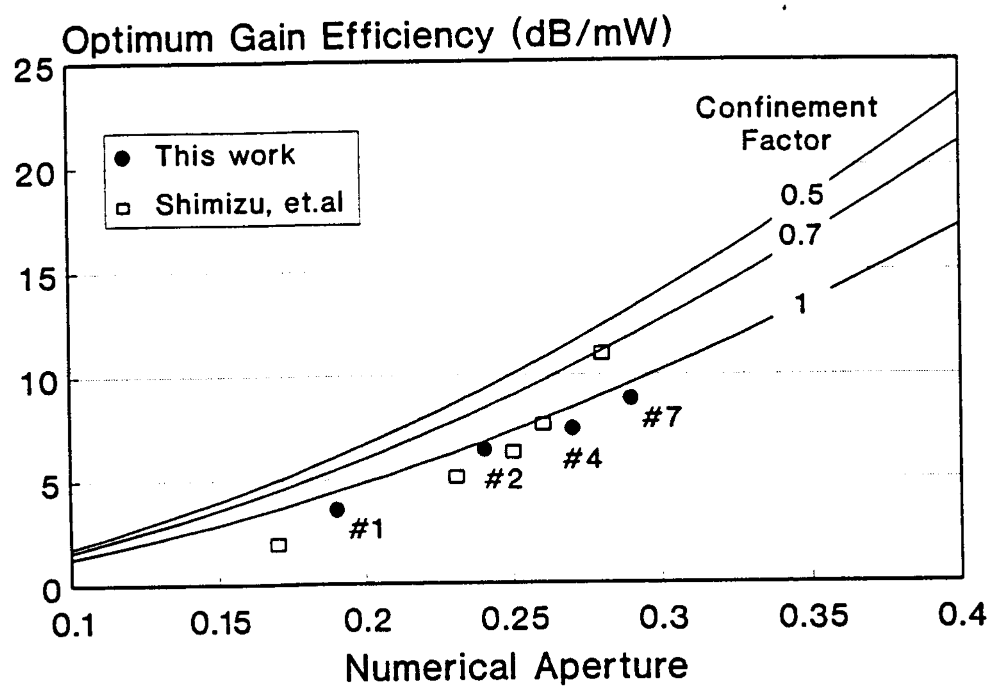

FIGURE 1. Calculated optimum gain efficiency as a function of the fibre NA for input signal power of -45dBm and confinement factors of 1, 0.7 and 0.5. The signal and pump background losses are zero. Experimental data are plotted for comparison.

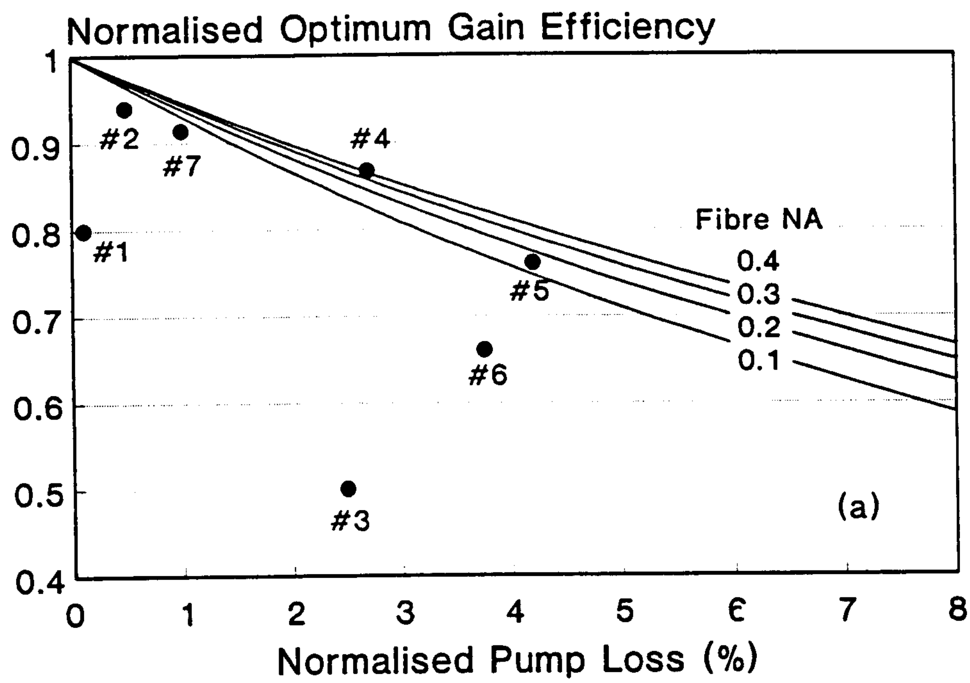

FIGURE 2(a). Normalised optimum gain efficiency as a function of normalised pump background-loss. The fibres are with unconfined dopant and NA's of 0.1 to 0.4. The experimental data refer to fibres whose characteristics are summarised in Table I.

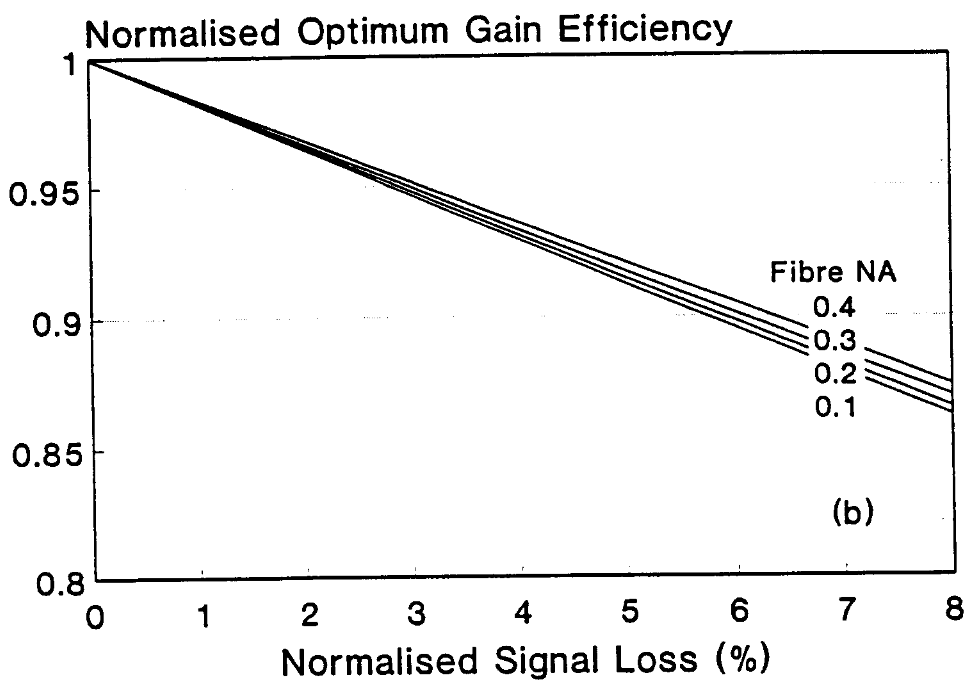

FIGURE 2(b). Normalised optimum gain efficiency as a function of normalised signal background-loss. The fibres are with unconfined dopant and NA's of 0.1 to 0.4. The experimental data refer to fibres whose characteristics are summarised in Table I.