TRADE-OFF AND DESIGN CONSIDERATIONS OF THE ERBIUM-DOPED FIBRE AMPLIFIER

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ABSTRACT: The trade-off between gain efficiency and noise figure is evaluated for an optimised EDFA pumped at 980nm. It is shown that operating at maximum gain efficiency always results in an increased noise figure well above the 3dB quantum limit and that any attempt to reduce the amplifier noise figure results in a decrease in gain efficiency. Alternatively, for a fixed amplifier gain and pump power, increasing the fibre NA and the dopant confinement in the core reduces the amplifier NF. Finally, the input pump power required to achieve a target NF is calculated as a function of the amplifier gain, fibre NA and dopant confinement.

INTRODUCTION.

Erbium-doped fibre amplifiers (EDFAs) [1] will play an important role in the implementation of high quality, reliable, fibre-optic communication systems as line-, power- and pre-amplifiers. Gain efficiency and noise figure (NF) are among the most important figures of merit in describing and comparing the various EDFA configurations. It is well known that a combination of erbium-doped germano-silicate-based fibre and a 980nm pump-wavelength results in amplifiers with the highest gain-efficiency. In addition, the co-propagating pump and signal configuration gives a reduced NF [2,3]. The performance of the EDFA is also influenced by a number of additional factors including the fibre NA, cut-off wavelength and dopant confinement. An optimisation of the fibre design is, therefore, required to maximise gain efficiency and minimise simultaneously NF.

THEORETICAL MODEL.

A 3-level theoretical model was employed in which the overlap-integral and equivalent ASE-bandwidth approximations were used [4]. A co-propagating pump (980nm) and signal (1536nm) configuration was considered. The forward- and backward-propagating ASE were considered as quasi-monochromatic waves of equivalent bandwidth $\Delta v = 600GHz$ ($\approx$4.5nm), centered at the signal wavelength. The pump absorption, signal absorption and emission cross-sections were determined experimentally by power saturation measurements to be $2.55 \times 10^{-25} m^2$, $7.9 \times 10^{-25} m^2$ and $6.7 \times 10^{-25} m^2$, respectively [5]. The metastable lifetime was determined to be 12.1ms. The signal input power was always -45dBm.

EDFA OPTIMISATION.

For each fibre NA and confinement factor (dopant/core-radius ratio), the fibre length, input pump power and cut-off wavelength were optimised to give maximum gain efficiency. In Figures 1(a) and (b), the optimum gain efficiency and the accompanying NF are plotted against the fibre NA for confinement factors of 1, 0.7 and 0.5. The optimum cut-off wavelength depends only on the dopant confinement and it was found to be 833nm, 850nm and 880nm for confinement factors of 1, 0.7 and 0.5, respectively. The optimum gain efficiency is shown to increase quasi-quadratically with the fibre NA. For ultra-high gain efficiencies, confinement of the dopant inside the fibre core is needed. In Figure 1(a), some of the best reported gain efficiencies [6], as well as, results obtained in our laboratories are plotted showing a very good agreement with the theoretical predictions.

From Figure 1(b), it is deduced that, under fully optimised conditions, the amplifier NF increases with the fibre NA. It should also be noted that the amplifier NF is always well above the 3dB quantum limit. The amplifier NF deviates from the quantum limit since under fully-optimised conditions the backward-travelling ASE attains high levels and severely depopulates the metastable level, particularly close to the input end, thus, deteriorating the population inversion. This occurs even for the moderate gains (~25dB) obtained at the maximum-gain-efficiency.

From Figures 1, it is concluded that optimum (maximum) gain efficiency and near-quantumlimited NF cannot be simultaneously achieved in an EDFA. The dopant confinement has a small effect on the amplifier NF.

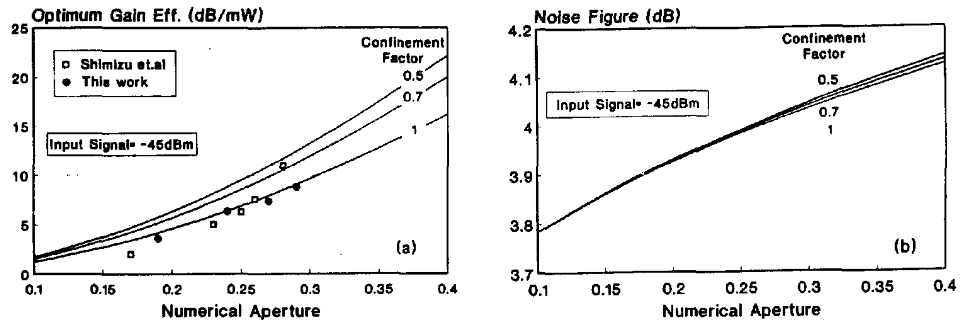
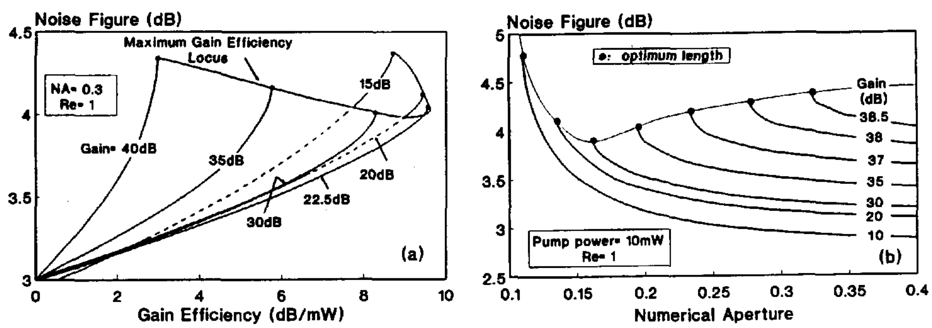


Figure 1: *(a)* Gain Efficiency and *(b)* Noise Figure against the fibre NA under fully optimised conditions.

GAIN EFFICIENCY AND NOISE FIGURE TRADE-OFF.

The NF requirements of an EDFA are quite stringent in pre- and line-amplifier applications and it will be shown that they can only be met by accepting a lower, i.e *sub-optimal*, gain efficiency. For a given amplifier gain, the NF is reduced by increasing the pump power and reducing the fibre length so that an increased population inversion is achieved over the entire fibre length (Fig. 2a). Alternatively, for a given input pump power and fixed amplifier gain, the NF can be reduced by increasing the fibre NA (Fig. 2b) and/or the dopant confinement (Fig. 2c). Increasing the fibre NA results in a pump spot-size decrease and, consequently, a pump-intensity increase inside the fibre core. By confining the dopant close to the core centre, effectively, a larger proportion of the dopant ions are subjected to the high pump intensity around the core centre. Both actions, result in an improved population inversion and NF decrease.



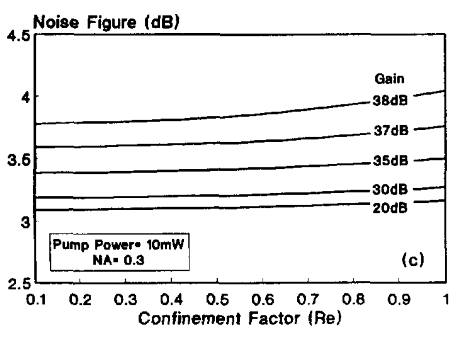
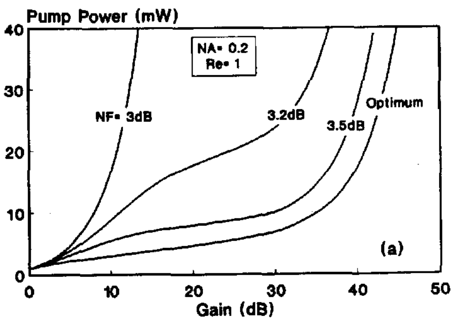


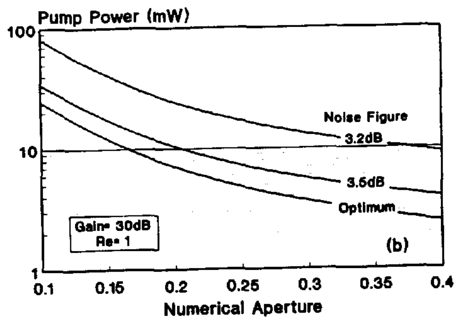
Figure 2: Amplifier NF plotted against *(a)* gain efficiency, *(b)* fibre NA and *(c)* dopant confinement for the shown conditions.

DESIGN CONSIDERATIONS.

Having discussed the gain and noise performance of an EDFA under fully optimised conditions and the inevitability of the gain-efficiency/NF trade-off, engineering curves are given which facilitate the EDFA design when certain system requirements are established.

In Figure 3(a), the pump power required to achieve a target amplifier-NF is plotted against the amplifier gain for a fibre NA of 0.2 and confinement factor of 1. It is clear that, for a given gain, considerably higher pump power is required as the target NF is reduced. In Figure 3(b), the input pump power required to achive a certain NF is plotted against the fibre NA for a fixed gain of 30dB and confinement factor of 1. For a given design, however, the pump requirements can be further relaxed by confining the dopant. In Figure 3(c), the pump power required to achieve an amplifier gain of 30dB and NF of 3.1, 3.2 and 3.5 are plotted versus the dopant confinement factor for a fibre NA of 0.2. In all figures, the curve designated as optimum corresponds to optimum pump power and fibre length.





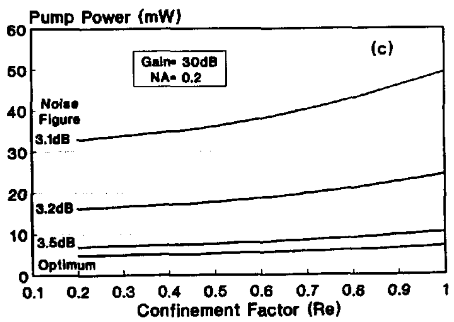


Figure 3: Pump power required to achieve the shown target-performances plotted against *(a)* amplifier gain, *(b)* fibre NA and *(c)* dopant confinement.

CONCLUSIONS.

We have shown that under fully optimised conditions, an EDFA always exhibits moderate gain and NF well above the 3dB quantum limit. Thus, in most system-applications, a trade-off between gain efficiency and NF is required resulting in sub-optimal operation of the EDFA. Engineering curves have been given which show the pump power requirements in order to meet certain system specifications.

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