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MODELLING ERBIUM/YTTERBIUM-DOPED FIBRE AMPLIFIERS

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ABSTRACT

A rate equation analysis of Er/Yb-doped fibre amplifiers has been performed. It is expected that the analysis will enable optimisation of co-doped fibre designs for particular pump wavelengths.

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Introduction

Erbium/Ytterbium-doped fibre amplifiers (EYDFAs) have been demonstrated to provide high gain and efficient power amplification around 1.54μm using diode-pumped miniature Nd:YAG laser pump sources operating at 1.064μm[1,2]. Such demonstrations are significant in that high power, TEM_{00} mini-Nd:YAG sources are highly developed, readily available and, crucially, utilise high reliability, low-brightness AlGaAs pump sources. The laser diode pump source is likely to be the limiting factor in the reliability of fibre amplifier systems and thus this facet is of substantial significance. The output power of these mini-Nd:YAG sources is expected to scale readily with additional pump power, particularly in side-pumped geometries. This may make the mini-Nd:YAG pumped EYDFA the preferred approach for use in a number of applications, particularly where high output powers are required in local area networks for example. The high efficiencies reported to date from these systems have been due to the use of specialised phospho-silica based fibre hosts[2]. These have given performance exceeding that even of fibres fabricated from commercial, highly-doped Er/Yb phosphate glasses.

So far no theoretical modelling of EYDFA devices has been performed. Modelling in this case provides an extra complication over the widely published EDFA models[3,4,5] in that an extra population (Yb^{3+}) and its coupling to the Er^{3+} population must be accounted for. In this paper we describe a model, based on rate equations, which shows the behaviour of co-doped fibre amplifier systems. The coupling of the two excited state populations has been described using the small signal transfer rate which can be conveniently determined experimentally from lifetime measurements. The approach uses an effective modal area for the fibre and a fixed amplified spontaneous emission (ASE) bandwidth[3]. This approach allows the general behaviour of the amplifier to be readily examined, without the computational resources required for extensive 3-dimensional modelling[5] and it is particularly suited to devices operating on the peak of the emission curve at around 1.54μm.

Theory

Fig. 1 shows an energy level diagram relating to the Er/Yb-doped system. Assuming the Yb concentration in the fibre is high enough (locally) to allow rapid cross relaxation of energy between Yb^{3+} ions, then we can analyze the situation using average populations. Additionally, for the erbium $^4I_{11/2}$ level lifetime which is negligible compared to the small-signal transfer rate then back transfer of energy can be ignored. In phosphate glasses the transfer rate is $\approx 10^4$ s^{-1} compared with the $^4I_{11/2}$ decay rate of $\approx 10^6$ s^{-1} and this assumption is justified[6]. Under these conditions the Yb^{3+} and Er^{3+} excited-state populations can be given in terms of the small signal transfer rate, determined from measurements of the Yb^{3+} lifetime in an Er/Yb fibre. Pump light is absorbed by the Yb^{3+} ions

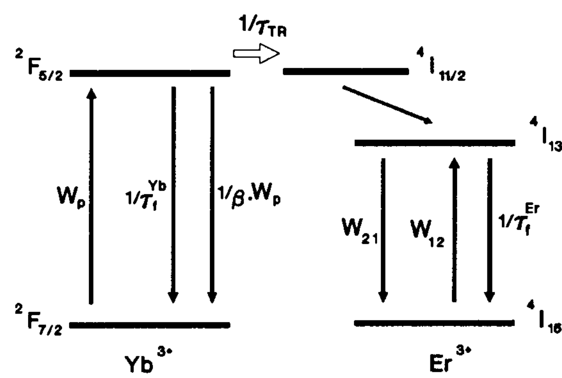

Fig. 1 Erbium-ytterbium energy level diagram.

and establishes a local excited population given by:

$$N_2^{Yb}(z) = N_T^{Yb}\left[\frac{W_p(z)}{W_p(z)\left(1+\frac{1}{\beta}\right)+\frac{1}{\tau_f^{Yb}}+\frac{(N_T^{Er}-N_2^{Er}(z))}{N_T^{Er}\tau_{tr}}}\right] \tag{1}$$

where: $N_2^{Yb}(z)$ = Yb^{3+} excited state population (ions/cm^3)
N_T^{Yb} = Total Yb^{3+} concentration (ions/cm^3)
τ_f^{Yb} = Yb^{3+} natural lifetime with no Er^{3+} present (s)
β = Yb^{3+} pump absorption/emission cross section ratio
$W_p(z)$ = Pump rate (s^{-1})
N_T^{Er} = Total Er^{3+} concentration (cm^{-3})
$N_2^{Er}(z)$ = Er^{3+} excited state population (cm^{-3})
τ_{tr}^{-1} = Small signal Yb^{3+}-Er^{3+} energy transfer rate (s^{-1})

Note that for pumping on the long wavelength wing of the Yb^{3+} absorption band at 1.064μm, the parameter β in eq. 1 must be substantially less than unity. This prevents the Yb^{3+} excited-state population rising above a small fraction of unity depending on its magnitude. This is the *opposite* case to direct EDFA pumping where the pump absorption/emission cross section ratio must be greater than unity to allow gain to be obtained.

The local excited state population for erbium can be written:

$$N_2^{Er}(z) = N_T^{Er}\left[\frac{\frac{N_2^{Yb}(z)}{\tau_{tr}N_T^{Er}}+\alpha W_{21}(z)}{\frac{1}{\tau_f^{Er}}+(1+\alpha)W_{21}(z)+\frac{N_2^{Yb}(z)}{\tau_{tr}N_T^{Er}}}\right] \tag{2}$$

where: α=Er^{3+} absorption/emission cross section ratio at 1.54μm ($\approx$1.25), $W_{21}(z)$=Er^{3+} stimulated emission rate.

Assuming negligible excited state absorption, the absorption of pump light can be written:

$$\frac{dP_p(z)}{dz} = -P_p(z)\sigma_p\eta_p\left(N_T^{Yb}-\left(1+\frac{1}{\beta}\right)N_2^{Yb}(z)\right) \tag{3}$$

where: σ_p=pump absorption cross section in ytterbium, η_p=pump mode overlap factor

The build up of ASE power in the amplifier fibre is described by:

$$dP_{ase}^{+,-}(z) = 2\mu(z)\gamma(z)h\nu\Delta\nu+P_{ase}^{+,-}(z)\gamma(z) \tag{4}$$

where: $\Delta\nu$=ASE spectral bandwidth, $\mu(z)$= local inversion parameter ($=N_2^{Er}(z)/((1+\alpha)N_2^{Er}(z)-\alpha N_T^{Er})$) and $\gamma(z)$ is the local gain given by:

$$\gamma(z) = \sigma_{21}\eta_s\left[(1+\alpha)N_2^{Er}(z)-\alpha N_T^{Er}\right] \tag{5}$$

where: σ_{21}=emission cross section at 1.54μm & η_s=signal overlap factor

Finally, the stimulated emission and pump rates are given by:

$$W_{21}(z) = \sigma_{21}\eta_s\left(\frac{P_s^{+,-}(z)+P_{ase}^{+,-}(z)}{h\nu_s A}\right) \qquad W_p(z) = \sigma_p\eta_p\left(\frac{P_p(z)}{h\nu_p A}\right) \tag{6}$$

where: A = fibre core area

Modelling

The above expressions can be simultaneously solved numerically. Co-propagating simulations were performed by considering a length of amplifier fibre divided into 200 axial sections. Parameters used throughout, corresponding to a typical fibre, were:
τ_f^{Yb} = 1.5ms, τ_f^{Er} = 10.7ms, σ_{21} = 7x10^{-21} cm^2, α = 1.25, λ_p = 1064nm, λ_s = 1540nm, A = 25μm^2, η_p = 0.8, η_s = 0.4 & $\Delta\nu$ = 4x10^{11} Hz ($\approx$2nm).

Comparisons were made in a number of simulations with a directly-pumped amplifier whereby the pump was considered to excite the erbium ions directly. The same pump wavelength (1064nm) was academically chosen for the sake of direct comparison and in fact this corresponds quite closely with direct 980nm pumping of erbium doped fibres. Particular aspects of the Er/Yb amplifier system which were considered were the effect of pump absorption cross section on the gain and the effect of the Yb/Er dopant concentration ratio. Additionally, the effect of varying pump power and transfer rate have been considered.

Fig. 2 shows the results of simulation of the variation of small signal (1μW) gain with pump absorption cross section for the Er/Yb system and a directly pumped Er^{3+} system. A pump power of 100mW was chosen and the gain refers to the optimum length in each case. The optimum length is also indicated, normalised to the emission scale. ie $(\eta_s\sigma_{21}N_T)^{-1}$=unity. A value of 0.1 was used for the pump absorption/emission cross section (β) for the Er/Yb (direct Er^{3+} pumping; $\beta=\infty$). Also experimental values of $\tau_{tr}\approx 20\mu s$ and Yb/Er ratio of 10 were used[2]. As can clearly be seen, an optimum absorption cross section exists for the Er/Yb system. For direct pumping, larger absorption cross sections are required to obtain appreciable gain and the characteristic in this case is monotonically increasing. A peak gain of $\approx$41dB is simulated for the Er/Yb compared with $\approx$44dB for direct pumping. The gain reduces for Er/Yb as the cross section increases as the Yb^{3+} population builds up too high in this case, so losing energy to Yb fluorescence. The rate at which the gain decreases for larger cross sections depends heavily on the parameter β. For larger values of β, the gain drops off more rapidly. Cross sections relating to 1.064μm absorption in Yb^{3+} [6] and 980nm absorption in Er^{3+} are indicated. For 1.064μm pumping, a peak gain of $\approx$40dB compares with published data of 38dB for 110mW pump power[2].

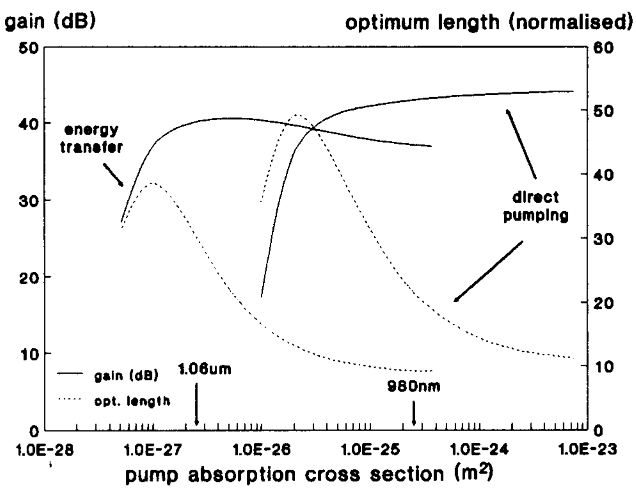

Fig. 2 Variation of gain at 1.54μm with pump absorption cross section for energy transfer and direct pumping. Optimum length normalised to emission scale.

Fig. 3 shows small signal gain vs pump cross section simulations for systems with varying Yb/Er ratio. As can be seen, the optimum absorption cross section (or pump wavelength) depends on the concentration ratio. From this data we believe that the Yb/Er concentration ratio can be optimised for a given pump wavelength.

Fig. 4 shows a gain vs pump cross section simulation for a typical power amplifier configuration. Compared with the small signal data, reduced sensitivity to variations in absorption cross section is observed in this case. Here the input signal was chosen as 1mW and the gain for 1.06μm pumping corresponds to $\approx$50% slope efficiency. This compares with $\approx$38% experimentally reported[2].

Summary
A theory describing gain in erbium-ytterbium-doped fibres has been described for the first time. Results from numerical simulations are in broad agreement with experimental data for 1.064μm pumping. Additionally the analysis shows that an optimum absorption cross section and hence pump wavelength exists for these fibres and that the Yb/Er concentration ratio can be used to specify this optimum. With optimised parameters efficiencies within a few dB of direct pumping can be expected. Further results showing the effects of pump power and transfer rate (including non-uniform transfer rates) and noise will be presented.

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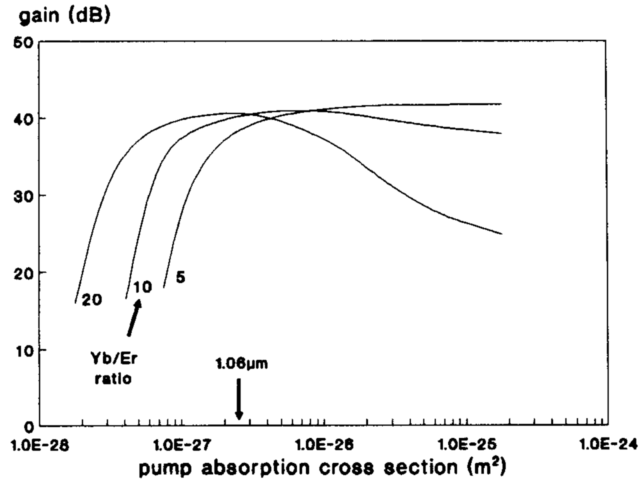

Fig. 3 Variation of small signal gain with pump absorption cross section for various dopant ratios. Pump=100mW.

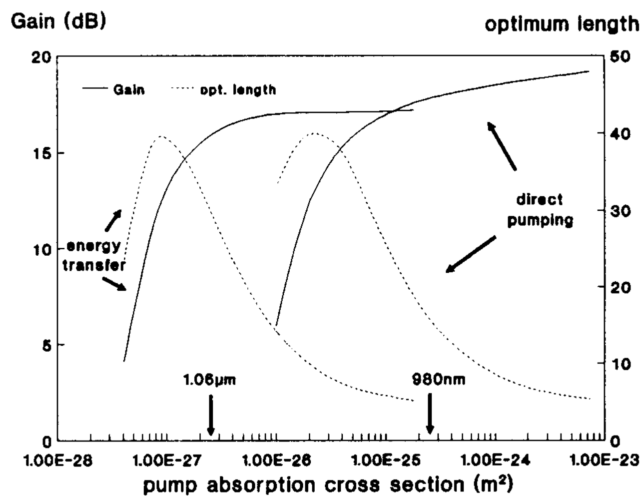

Fig. 4 Variation of large signal gain with absorption cross section. Pump=100mW, signal=1mW. Optimum length normalised to emission scale.

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