Accurate Modeling and Experimental Validation of a Singlemode 4 W Output Power Double Cladding Erbium Ytterbium Fibre Amplifier

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ABSTRACT

We developed a model that accurately predicts the performances of high power double cladding erbium ytterbium fibre amplifiers. We experimentally validate the model in co- and counter-propagation configuration for different pump wavelengths and fibre lengths. By adjusting the ytterbium to erbium cross-relaxation rate with a simple amplifier experiment, we obtained a complete agreement between the model predictions and the experimental data regarding the output signal. We measured that the McCumber relationship considerably overestimates the ytterbium emission cross-section; with a correction of this parameter, we obtained an excellent prediction of the ytterbium spontaneous emission at 1.0 µm. The model is valid for high power singlemode amplifiers as we obtained a full agreement for a 4W output power amplifier from a seed signal of 8 mW at 1556nm. The output was diffraction limited with a measured M^2 parameter of 1.03 without doing any mode selection from a slightly multimode fibre with a core diameter of 10 µm and a numerical aperture of 0.18.

Keywords: high power amplifier, erbium ytterbium, modeling, double cladding fibre, energy transfer, cross-relaxation, cross-section, McCumber

1. INTRODUCTION

Singlemode pump diodes of few hundred milliwatts have been extensively used to pump erbium doped fibre amplifiers. However these singlemode fibre pigtailed pumps represent a mature technology and are limited to power levels of less than 1 W. Double-cladding optical fibres have been developed to overcome this limitation. An inner cladding has been added around the core such that a large amount of multimode pump power can be launched in this large cladding while preserving singlemode operation in the fibre core. However, this improvement in power scaling with double-cladding fibre decreases the pump absorption as the overlap between the pump power and the core is significantly reduced. Thus, co-doping erbium with ytterbium becomes essential to increase the pump absorption. Ytterbium ions, which have a high absorption at wavelengths between 900 nm and 1000 nm, absorb pump light and transfer their energy to erbium ions through a non-radiative cross-relaxation effect. Therefore, double-cladding erbium ytterbium amplifiers are very attractive for power scaling of standard erbium doped fibre amplifiers.

To optimize the performances of any fibre amplifier, a theoretical model is necessary to predict fibre length, pump power, signal wavelength, etc., for optimal operation conditions. However, when erbium is codoped with ytterbium, modeling becomes more difficult because unknown parameters are added to the problem such as the non-radiative cross-relaxation transfer rate (K_{tr}) between erbium and ytterbium ions. Even if this parameter is critical to good simulation results, its value is often guessed since a direct experimental measurement is difficult to achieve[1,2]. Furthermore, this transfer rate is dependent on the host glass composition and the dopant concentrations[3] and cannot be extrapolated from one fibre to another. Another unknown parameter in erbium ytterbium system is the non-radiative transition time (τ_{32}) between the $^4I_{11/2}$ and the $^4I_{9/2}$ level of the erbium ions. This parameter is often neglected with erbium alone, but becomes important in erbium ytterbium systems since it determines the amount of back energy transfer from erbium to ytterbium. Nevertheless, this parameter is also difficult to quantify exactly[4] and its value is most often guessed.

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In this paper, we adequately address the issue of determining K_{tr} and τ_{32} to develop a model that accurately predicts the performance of erbium ytterbium amplifiers. We first describe a simple but sufficient electronic structure to represent the electronic population of erbium and ytterbium ions and we introduce the mathematical model used to simulate fibre amplifiers. The unknowns K_{tr} and τ_{32} are then determined from a simple erbium ytterbium amplifier experiment. We then verified that the knowledge of these parameters allows us to accurately predict the output signal power of amplifiers in any configuration. We also measured that the McCumber relationship tends to overestimate the emission cross-section of the ytterbium ions; thus, we adjusted this parameter such that the amplified spontaneous emission (ASE) emitted at 1.0 µm is also accurately predicted by the theory.

2. MATHEMATICAL MODEL

We developed a general theoretical model that can predict the behaviour of any fibre laser or amplifier. The model is based on standard rate equations that can be found in many textbooks and papers[5,6]. In this paper, we present a version that specifically addresses erbium ytterbium amplifiers. The model uses the electronic level diagram shown in Figure 1. As we demonstrate subsequently, this simplified structure happens to adequately model the system without the need to take into consideration secondary energy transfer phenomena such as upconversion or quenching phenomena[7]; we consider that the energy transfer between erbium and ytterbium ions mainly governs the system. Stimulated transitions between levels i and j are represented by W_{ij}, spontaneous transitions by τ_{ij}, electronic populations by N_i, and the transfer rate between ytterbium and erbium by K_{tr}.

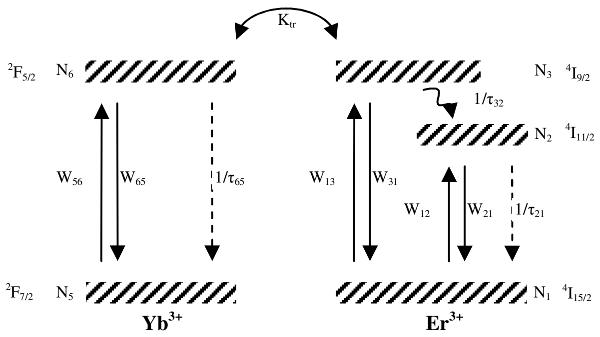

Fig. 1. Diagram of the electronic levels of the system erbium ytterbium used for the model

$$\frac{dN_2}{dt} = W_{12}N_1 - W_{21}N_2 - 1/\tau_{21}\,N_2 + 1/\tau_{32}\,N_3 \quad ; \quad \frac{dN_3}{dt} = W_{13}N_1 - W_{31}N_3 - 1/\tau_{32}\,N_3 + K_{tr}N_1N_6 - K_{tr}N_3N_5 \quad ; \quad \rho_{er} = N_1 + N_2 + N_3 \tag{1}$$

$$\frac{dN_5}{dt} = W_{65}N_6 - W_{56}N_5 + 1/\tau_{65}\,N_6 + K_{tr}N_1N_6 - K_{tr}N_3N_5 \quad ; \quad \rho_{yb} = N_5 + N_6 \tag{2}$$

$$W_{ij}(r) = \int \frac{\sigma_{ij}(\lambda)P_{in}^{+,-}(\lambda)\psi(r,\lambda)}{E_{ij}(\lambda)}d\lambda \quad ; \quad \frac{dP}{dz} = 2\pi\int_0^{r_o}\Big[\big(\sigma_{ji}N_j(r) - \sigma_{ij}N_i(r)\big)P_{in}\psi(r,\lambda)rdr + 2E\sigma_{ji}N_j\psi(r,\lambda)rdr\Big] \tag{3}$$

The rate equations for the electronic population ion are given by Equation (1) for erbium and by Equation (2) for ytterbium, where ρ_{er} and ρ_{yb} are the dopant concentrations of erbium and ytterbium. These two sets of equations can be solved analytically by putting the time derivatives equal to zero. Stimulated transitions between levels i and j and amplification of light of power P along the fibre coordinate z are given by Equation (3) knowing the cross-sections σ_{ij} of the transitions, the radius r_o of the cylindrical volume where the dopants are uniformly distributed, the energy separation of the electronic levels E, and the normalized mode profile ψ evolving into the fibre. The generation of amplified stimulated emission (ASE) is also included in the model. The pump mode profile is considered uniform in the inner cladding and a LP_{01} mode profile is used for the singlemode propagation in the core. The signs of Equation (3) for propagation are inverted for negative propagation. These equations are implemented numerically and solved using a Runge-Kutta routine for differentiation in the longitudinal propagation and a trapezoidal rule method for integration of the radial mode profile; a relaxation algorithm is used to reach convergence[7].

3. EXPERIMENTAL VALIDATION

3.1 Fibre characterization

Several parameters in the theoretical model need to be determined experimentally. These include the fibre geometry, the dopant concentrations, the fluorescence lifetimes, the absorption and emission cross-sections and the background losses. The dopant concentrations were measured with an electron-probe micro-analysis, the absorption cross-section was measured using the small signal absorption of the fibre, and the emission cross-section was derived from the absorption cross-section curve using the McCumber relationship[9]. As discussed below, the emission cross-section of ytterbium has been corrected. To conduct our investigation, we used CorActive Hpa-Ey-10-01 erbium ytterbium fibre and we thus characterized it completely. All of its parameters are summarized in Table 1. The theoretical model was designed for singlemode propagation in the core; therefore, we verified this feature by measuring the output beam quality under amplification in a co-propagation configuration. The fibre exhibits diffraction limited M^2 parameter of 1.03, as shown on Figure 2. We also measured a coupling efficiency to standard singlemode fibre larger than 96 %, which confirms the singlemode behaviour of the fibre.

Parameters	Symbol	Value		Unit
core diameter	a	10.0	± 0.1	μm
numerical aperture	NA	0.186	±0.010	-
cladding absorption at 915 nm	α(915 nm)	4.4	± 0.4	dB/m
core absorption at 1553 nm	α(1553nm)	28.7	± 0.7	dB/m
ytterbium fluorescence lifetime	τ_{yb}	835	± 95	μs
erbium fluorescence lifetime	τ_{er}	9.0	± 0.2	ms
inner cladding area	A	13532	± 20	μm^2
signal background loss (at 1200 nm)	α_p	595	± 68	dB/km
pump background loss	α_s	20	± 5	dB/km
dopant diameter	r_o	9.8	± 0.2	μm
splice loss to singlemode fibre	-	0.15	± 0.10	dB

Table 1. Key parameters of the erbium ytterbium fibre characterized experimentally.

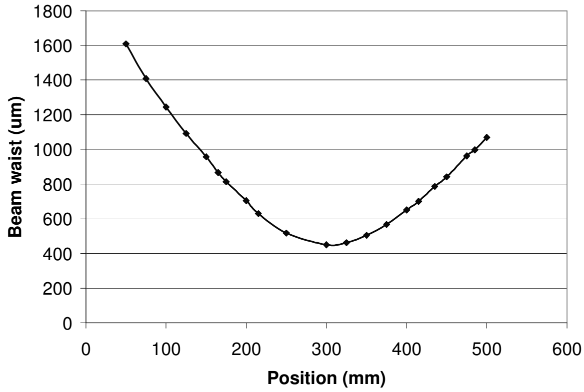

Figure 2. Measured beam waist exiting the erbium ytterbium fibre as a function of the propagation distance. It is consistent with a M^2 value of 1.03

3.2 Adjustment of theoretical parameters

The results from the theoretical model remain inaccurate as long as the transfer rate (K_{tr}) and the relaxation time (τ_{32}) are unknown for a given fibre. To measure these parameters, we built an amplifier with CorActive Hpa-Ey-10-01 erbium ytterbium fibre. An 8-mW signal at 1556 nm is amplified using 9 W of pump power at 915 nm in co-propagation. The signal and pump powers are injected through a multimode pump combiner with a signal feedthrough. The output power was measured as a function of fibre length with a power meter. The output spectrum was measured with an optical spectrum analyser (OSA). Backward amplified spontaneous emission (ASE) emitted from the ytterbium ions around 1.0 µm was also measured with a power meter. The experimental configuration is shown in Figure 3.

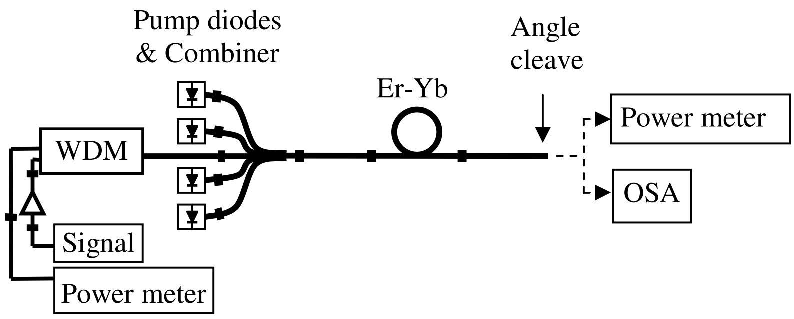

Figure 3. Experimental setup used to conduct the amplifier experiment.

The parameters K_{tr} and τ_{32} were adjusted to fit the simulation results with the experimental data as shown in Figure 4. We noted that K_{tr} and τ_{32} exhibit the same effects in the fit such that one parameter can be fixed and ignored while adjusting the other. An excellent correlation was obtained for $K_{tr} = 1.0 \times 10^{22}$ m^3/s and $\tau_{32} = 0.01$ µs.

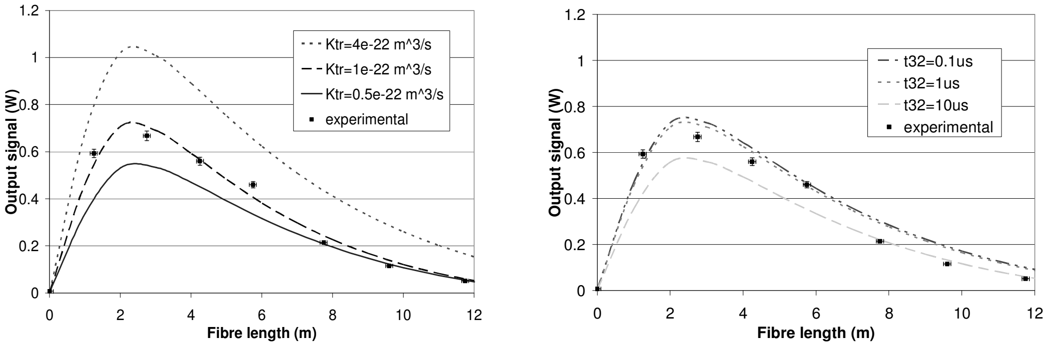

Fig. 4. Fit between simulated and experimental output signal to adjust the transfer rate between ytterbium and erbium K_{tr} and the non-radiative decay time of erbium τ_{32}

However, the ASE at 1.0 µm was strongly overestimated by the model by two orders of magnitude. Since the model predicts satisfactorily the output signal amplified by the erbium ions, we suspected that this divergence did not come from erbium parameters or from the transfer rate between erbium and ytterbium ions. We found that the ASE at 1.0 µm strongly depends on the emission cross-section of ytterbium alone, regardless of other parameters. We thus measured the fluorescence spectra of the fibre around 1.0 µm by totally inverting the ytterbium ions. Even if this cannot give quantitatively the emission cross-section of ytterbium, this can reveal the spectral shape of the emission cross-section. We achieved this measurement by pumping the fibre with 200 mW of pump power at 977 nm directly injected in the core of a 2 cm long sample. We collected spontaneous emission from the side of the fibre with an optical spectrum analyser. We noticed a significant difference between the emission cross-section predicted by the McCumber theory and the fluorescence spectrum as shown in Figure 6. We noted that the McCumber theory overestimates by a factor of two the emission cross-section around 1060 nm compared to the fluorescence spectrum. This is critical because the ASE at 1.0 µm was mostly produced at 1060 nm in our erbium ytterbium amplifier experiment. We corrected this difference and then obtained a good correlation between the ASE at 1.0 µm predicted by the model and the experimental results as shown in Figure 6.

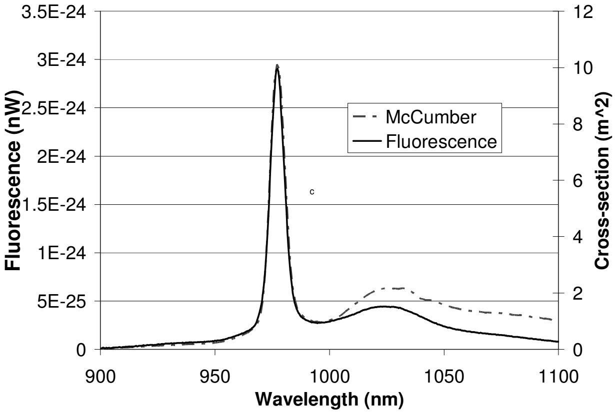

Fig. 5. Comparison of the emission cross-section predicted by the McCumber theory and the emission cross-section spectral shape revealed by a fluorescence measurement

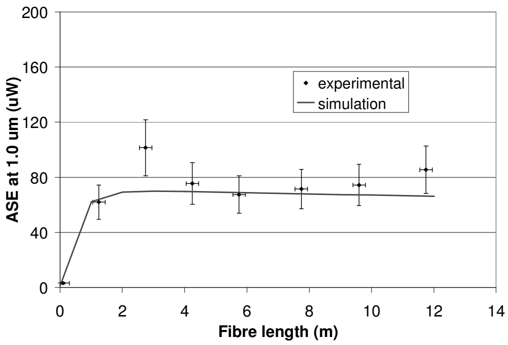

Fig. 6. Adjusted amplified spontaneous emission (ASE) at 1.0 µm through a fit of the ratio of the peak emission to the peak absorption cross-section of ytterbium

3.3 Experimental validation of the model

Once the theoretical parameters have been adjusted, we have to make sure that the good agreement obtained between the theory and the experiment was not just a one time artefact. We thus tested our model against different inputs such as switching to counter-propagation pumping, changing the pump wavelength and the fibre length. Therefore, two different amplifiers configuration were tested: firstly a signal of 8 mW at 1556 nm was amplified in a 10-m fibre pumped in counter-propagation at 915 nm; secondly a signal of 9 mW at 1556 nm was amplified in a 2.0-m fibre pumped in co-propagation at 975 nm. The results (Figures 7 and 8) show an excellent agreement between the experimental results and the simulations. We obtained an excellent agreement for a 4 W output power amplifier in counter-propagation. ASE at 1.0 µm is not shown in Figure 7 since it was negligible in the configuration used. For the co-propagation scheme presented in Figure 8, the small deviation between the experiment and the theory seen is simply due to the detuning of the pump wavelength with respect to the narrow ytterbium absorption band at 975 nm since the pump wavelength drifts as the pump power is increased.

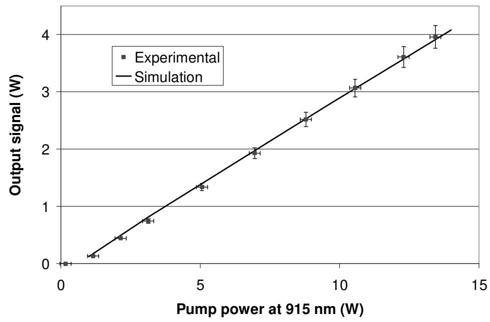

Fig. 7. Output signal power as a function of pump power for an input signal of 8 mW amplified in a 10-m fibre pumped in counter-propagation at 915 nm

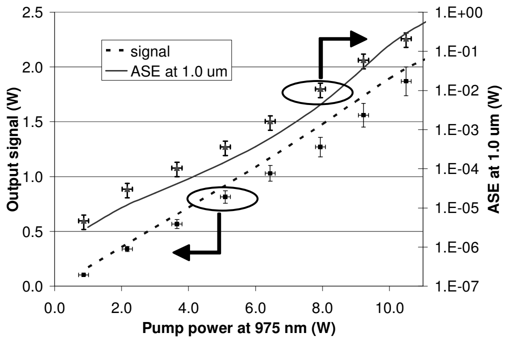

Fig. 8. ASE at 1.0 μm and output signal as a function of pump power for an input signal of 9 mW generated in a 2.0-m fibre pumped in co-propagation at 975 nm.

4. CONCLUSION

We developed a theoretical model that simulates erbium ytterbium fibre amplifiers using a simple electronic structure to represent the erbium and ytterbium ions. We have fully characterized the fibre parameters to fix the simulation parameters. From a simple amplifier experiment, we determined the transfer rate K_{tr} between ytterbium and erbium and the non-radiative transition time τ_{32} of erbium that are used in the modeling. With the knowledge of these parameters, our model happens to accurately predict the performance of double-cladding erbium ytterbium amplifiers under different experimental conditions. We obtained an excellent agreement for a 4 W output power singlemode counter-propagation amplifier. We observed that the McCumber theory overestimates the emission cross-section of the ytterbium ions around 1060 nm. After correcting this, the model also adequately predicts the emission of amplified spontaneous emission (ASE) at 1.0 μm.

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