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Erbium-doped fibre amplifiers: modelling and experimental verification of gain and noise figure

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Results obtained from a numerical modelling for erbium-doped fibres have been demonstrated and discussed. Differences between theoretical calculations and experimental data are explained.

1. Introduction

Optical amplification plays an important role in the 1550 nm wavelength optical communication systems. The key component is an erbium-doped fibre amplifier. It is important to predict the performance of an amplifier while working conditions vary and choose optimal ones that usually depend on an application [1]. One can use a few easy measurable parameters of erbium-doped fibres to model an amplifier if they are not characterized well. On the other hand, it is convenient to use their accurate parameters obtained from a manufacturer, especially if the fibres are not short enough to measure basic parameters and if they are connectorized.

In this paper, we present results obtained from a numerical modelling for erbium -doped fibres. These theoretical results of the gain and the noise figure are compared to the experimental ones obtained for the setup of our erbium-doped fiber amplifier [2].

2. Theory

The presented model constitutes the model described in detail in [3] and is based on a two-level laser system. The modelling of the gain and ASE (amplified spontaneous emission) for a given length of an erbium-doped fibre can be done under certain assumptions, without direct determination of cross-sections. In this effective overlap approximation, a fibre is completely characterized knowing only a few parameters that can be directly obtained from measurements. They are: the small signal gain g_k^*, the small signal attenuation α_k, and the fibre saturation parameter ζ. Index k is used to keep track of the wavelength λ_k. The small signal gain and the small signal attenuation are mutually related and, in fact, it is enough to measure the small signal attenuation,

α_k only, and then the small signal gain g_k^* can be computed from the McCumber analysis [4].

The third main parameter which has to be known in modelling is the fibre saturation parameter ζ

$$\zeta = \frac{\pi b^2 n_t}{\tau} \tag{1}$$

where b is the doped region radius of the fibre, n_t – the erbium ion density, and τ – the metastable lifetime.

The fibre saturation parameter ζ can also be determined another formula [3]

$$\zeta = \frac{P_k^{sat}(\alpha_k + g_k^*)}{h\nu_k} \tag{2}$$

where P_k^{sat} is the fibre saturation power which is the necessary parameter to obtain ζ, h – Planck constant and ν_k denotes optical frequency [5]. Hence the fibre saturation parameter ζ can be determined from absorption α_k and emission g_k^* spectra and the fibre saturation parameter P_k^{sat}, all of which can be find experimentally.

The assumptions of the so-called effective parameter model are as follows. The average density of erbium ions in the transverse dimension $\bar{n}_t$ is considered. The same concerns densities of ions $\bar{n}_1$ and $\bar{n}_2$ in the ground and excited states, respectively. The overlap integrals defined as overlaps of the light fields with the ion density distribution in the ground and excited states are assumed to be equal and independent of the pump power. This assumption is justified in the case of confined erbium-doped fibres. Then small signal gain and small signal attenuation written in terms of the overlap parameter are:

$$\alpha_k = \sigma_{ak}\Gamma_k n_t,$$

$$g_k^* = \sigma_{ek}\Gamma_k n_t \tag{3}$$

where σ_{ak} and σ_{ek} are the absorption and emission cross-sections, respectively, Γ_k – the overlap integral between the dopant and optical mode.

Finally, we can use two basic equations [3]:

$$\frac{\bar{n}_2}{\bar{n}_t} = \frac{\displaystyle\sum_k \frac{P_k(z)\alpha_k}{h\nu_k\zeta}}{1 + \displaystyle\sum_k \frac{P_k(z)(\alpha_k + g_k^*)}{h\nu_k\zeta}} \tag{4}$$

for the population in the upper state, and

$$\frac{dP_k}{dz} = u_k(\alpha_k + g_k^*)\frac{\bar{n}_2}{\bar{n}_t}P_k(z) + u_k g_k^* \frac{\bar{n}_2}{\bar{n}_t} 2h\nu_k\Delta\nu_k - u_k(\alpha_k + \alpha_k^0)P_k \tag{5}$$

for the propagation equation of each light field with index k (including full spectra of pump, signal and forward and backward ASE powers), u_k is equal to +1 for a forward -propagating field, and −1 for a backward-propagating field. The α_k^0 accounts for fibre background loss.

3. Simulation results and discussion

In order to solve the propagation Eq. (5), a special computer programme was written in Matlab language. It applies the 4-th and 5-th order Runge–Kutta method. The following figures present results obtained from simulations. We assume small signal operations at 980 nm pumping for 1550 nm signals. Two fibres based on silica glass host that differ in erbium ion densities and background losses were used. Their parameters are listed in the Table and their gain spectra are presented in Fig.1.

We calculated the signal gain values as a function of the length of the erbium doped fibre, for different levels of the launched pump power. An optimal length as the length for which an amplifier has the highest gain was defined.

Table. Fibre parameters used in the modeling

Parameter	Fibre A	Fibre B
Core radius a	1.5 μm	1.5 μm
Doped core radius b	1.5 μm	1.5 μm
Aperture NA	0.23	0.23
Metastable lifetime τ of erbium-doped silica fibre	10.2 ms	10.2 ms
Erbium ion density $\bar{n}_t$	5.76×10^{24} m^{-3}	2.06×10^{25} m^{-3}
Length L	10 m	6.7 m
Peak absorption 1530 nm	6.3 dB	14.6 dB
980 nm absorption	4.7 dB	11.5 dB
Background loss	4.4 dB/km	25 dB/km

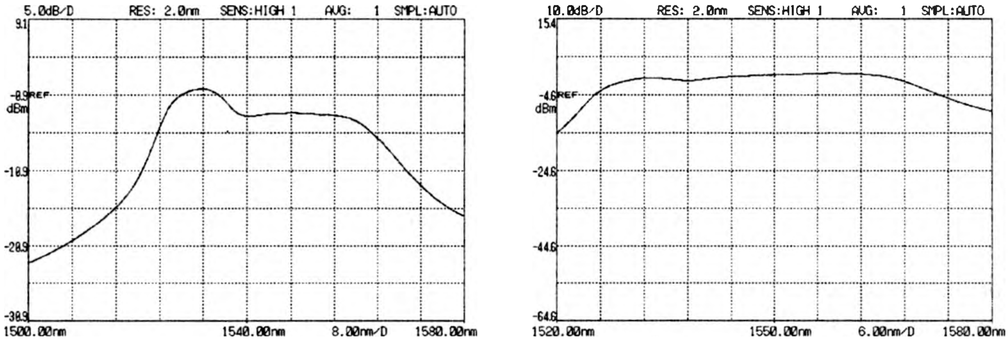


Fig. 1. Gain spectra of fibre A (on the left) in the bandpass 1500–1580 nm and fibre B (on the right) in the bandpass 1520–1580 nm. The launched pump power was 40 mW, the launched signal power was –27 dBm (2 μW).

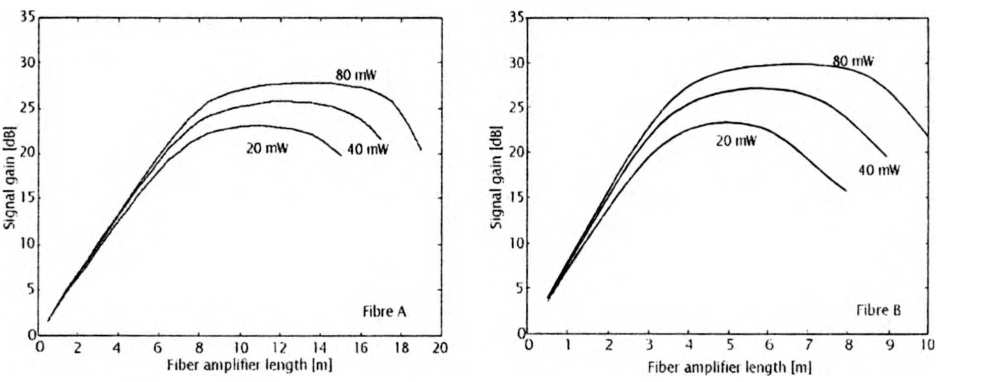


Fig. 2. Signal gain at 1550 nm for 980 nm pumping of fibre A (left) and fibre B (right), as a function of fibre amplifier length. The launched pump power is a parameter (20, 40, 80 mW), the launched signal power is –27 dBm.

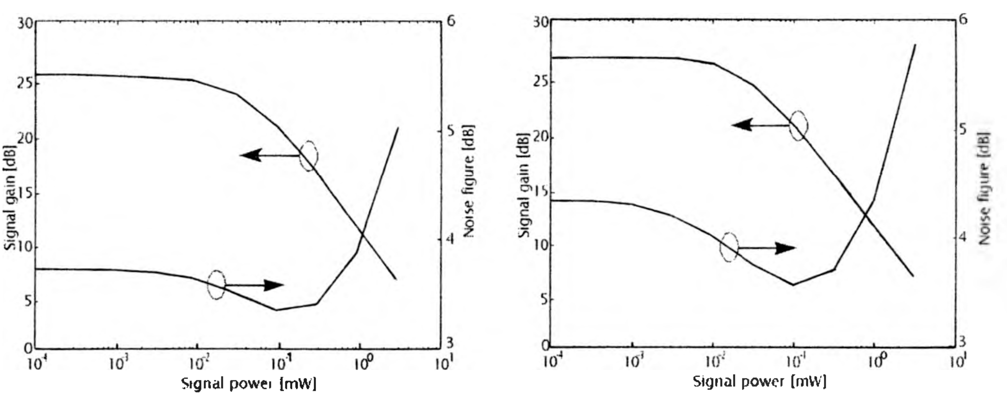


Fig. 3. Signal gain and noise figure at 1550 nm for 980 nm pumping of fibre A (left) and fibre B (right), as a function of input signal power. The launched pump power is 40 mW.

One can see from Fig. 2 that the optimal length depends on the launched pump power. It is worth noting that the signal gain is getting flatter with EDFA length for the increasing pump power, according to the principle: the higher the pump power is, the broader the range of the optimal length. For those three pump powers proposed we can distinguish a common range of length for the highest gain and the optimal length should be chosen from this range. It is 9–12 m and 4–5.5 m for A and B fibres, respectively.

The length 10 m of fibre A fits quite well into the flat parts of gain curves shown in Fig. 2. The length 6.7 m of fibre B is a bit too long.

In order to determine appropriate working conditions for small signal operation we calculated two important characteristics shown in Fig. 3 – gain and noise figure versus input signal power. To compare both fibres we chose –27 dBm (2 μW) input signal power and 40 mW pump power as working conditions. This value of the input power was taken to fulfil small signal operation conditions for both. This also proves that the input power chosen earlier (–27 dBm) for optimal length calculation (see Fig. 2) was set properly.

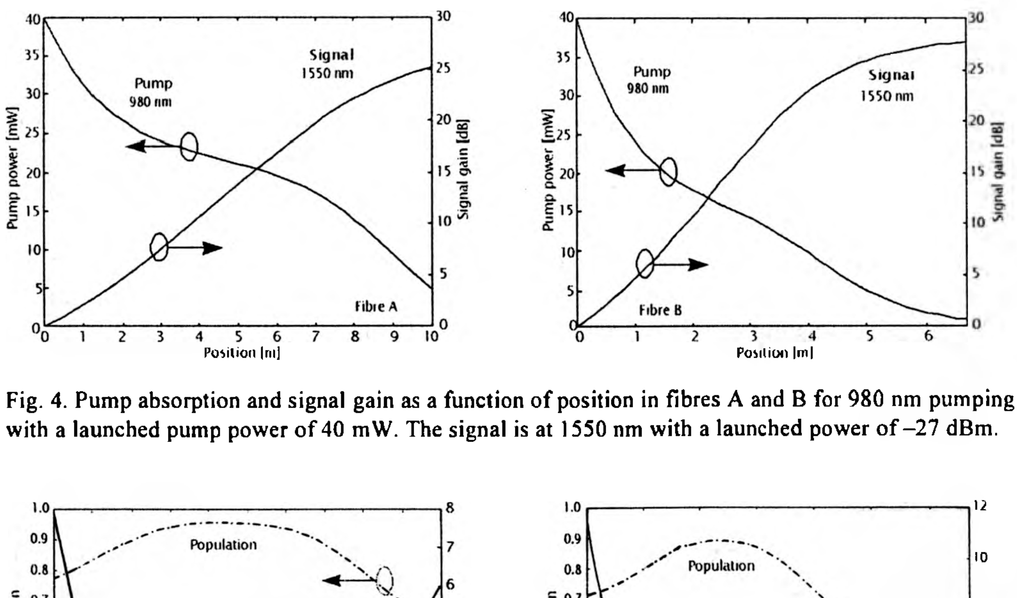


Fig. 4. Pump absorption and signal gain as a function of position in fibres A and B for 980 nm pumping with a launched pump power of 40 mW. The signal is at 1550 nm with a launched power of –27 dBm.

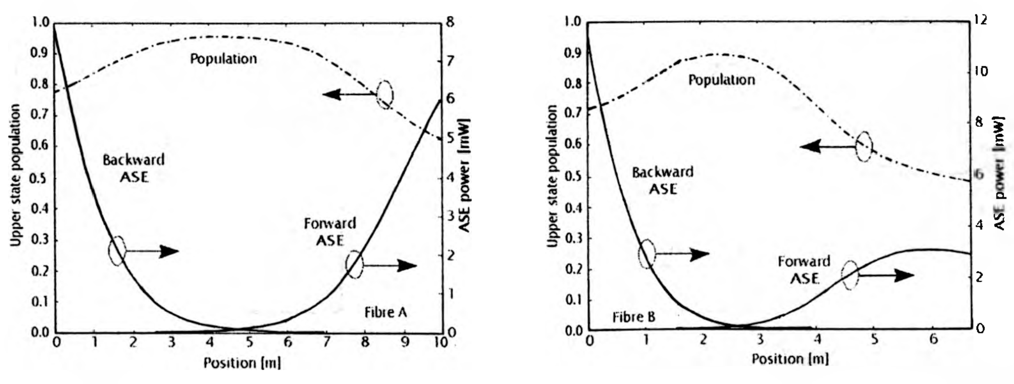


Fig. 5. Upper-state population and forward and backward ASE in fibres A and B for 980 nm pumping with a launched pump power of 40 mW. The signal is at 1550 nm with a launched power of –27 dBm.

For such working conditions we calculated additional characteristics that illustrate evolution of pump power, signal gain (Fig. 4) and upper-state population, ASE (Fig. 5) as a function of position as a fibre.

As can be seen from Fig. 4 almost all of the launched 980 nm pump power is absorbed in both fibres. The gain of the amplifier increases along the fibre and begins to reach the highest value as expected.

We can confirm here our former presumption that fibre B is a little bit too long because its gain begins to saturate. We can see the same in Fig. 5, where the upper -state population, $\bar{n}_2/\bar{n}_t$ (Eq. (4)), along the last 1.5 m distance of the fibre B drops to the value 0.5 and forward ASE is attenuated.

Unwanted backward ASE depletes inversion at the beginning of the fibre and it robs the gain at the expense of the signal. To eliminate backward ASE one can place an isolator in the middle of an amplifier, where backward ASE begins to increase [7]. We can determine the right position from Fig. 5. It is about 4.5 m and 2.5 m for fibre A and fibre B, respectively. Removing backward ASE is important especially in the case of applying EDFA as a preamplifier.

4. Experiment

The gain and noise figure of the fiber amplifiers were measured in a setup shown in Fig. 6. We used FC/APC connectors among all elements of the setup. The pump source was commercially equipped with a fibre pigtail with a cut-off wavelength below 980 nm. The same concerns WDM coupler/splitter. Nevertheless, differences in mode field sizes and numerical apertures among erbium-doped fibres, a coupler/splitter and a pigtailed pump source caused additional losses. Therefore, the measured gain is reduced by a constant value compared to theoretical one.

Comparison between measured data and calculations is presented in Fig. 7. The shape of gain curves is almost identical but there is a constant difference in the gain

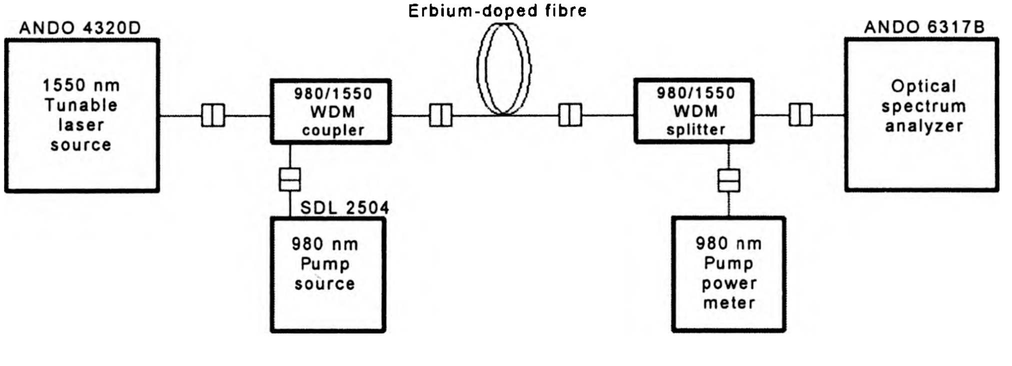
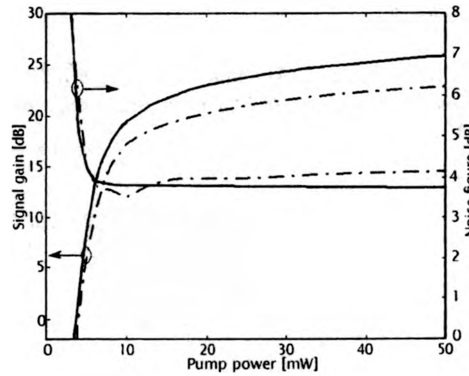


Fig. 6. Diagram of measuring setup.



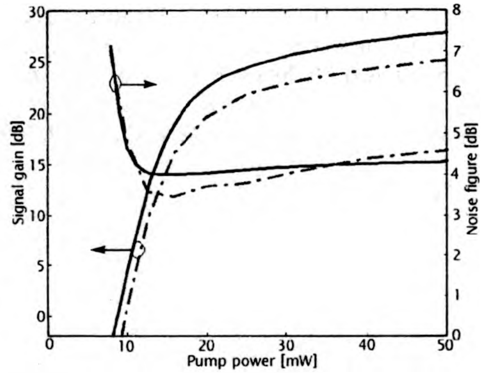


Fig. 7. Signal gain (solid line – calculated, dashed line – experimental) and noise figure in fibres A and B for 980 nm pumping with a launched pump power of 40 mW. The signal is at 1550 nm with a launched power of –27 dBm.

(about 3 dB) in the whole range of pump power due to the reasons mentioned above. The theoretical values of the pump thresholds are lower than the experimental ones in both cases. As can be seen from Fig. 7 for the case of fibre B, the value of the pump threshold was two and a half higher than for fibre A.

The shapes of the theoretical and experimental curves of noise figure are in quite a good agreement as well, with the accuracy better than 0.5 dB. The lowest value of noise figure for fibre A (comparable to the lowest value of noise figure for fibre B) is obtained for lower value of pump power (compared to fibre B). It makes fibre A relatively less noisy.

5. Conclusions

A useful model for Er^{3+} fibre amplifier has been presented. The evolution of the pump, signal and ASE optical powers along the fibre length was obtained for two different fibres. Results of investigation were discussed. The presented approach leads to close agreement between predicted and measured gains in erbium-doped fibres providing that all undesirable losses are removed.

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