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Influence of fiber parameters to the erbium-doped fiber amplifier (EDFA) gain: A theoretical modeling

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Abstract. This paper studies the theoretical analysis of erbium-doped fiber (EDF) amplification. The EDF amplification is investigated in order to understand its behavior and identify the relevant parameters that are used for formulating the amplification process related to spontaneous and stimulated emission. Results show that under certain condition, the selected fiber parameters such as fiber length, EDF pump power, signal power and pump direction would significantly contribute to the EDFA gain enhancement.

1 Introduction

Multiwavelength fiber lasers have attracted great interest due to their applications in optical sensors, microwave optics, spectroscopy and optical communication systems to name a few. One technology where these fiber lasers can be realized is by a combination of two optical gains namely erbium-doped fiber (EDF) and Brillouin amplification or commonly known in literature as multiwavelength Brillouin-erbium fiber lasers (BEFLs). Compared with other technologies, multiwavelength BEFLs have advantages such as low threshold power and ultra-narrow linewidth [1]. Literature suggests that performances of multiwavelength BEFLs can be improved when the residual waves are recycled back into the laser cavity [2]. Characteristics of residual waves are studied thoroughly in [3-4] to gain higher number of channels. This paper intents to optimize the EDF amplification in the multiwavelength BEFLs to improve the performance further. Therefore in this work, erbium-doped fiber amplifier (EDFA) parameters for different pumping powers and different EDF length are investigated to realize a high performance EDFAs.

2 Mathematical Modelling of EDFA

The basic configuration of a typical EDFA is illustrated in Fig. 1. An EDFA consists of a wavelength division multiplexer (WDM) coupler to combine the pump with the input signal light. The combined pump and signal light is injected into a 20 m EDF and an optical isolator is placed after the EDF, ensuring unidirectional operation of the EDFA. The pump source is of a 980 nm laser diode.

Fig. 2 illustrates the energy levels and transitions of Er^{3+} ions in the EDF when it is pumped with the 980 nm laser diode. It is based on a two-level assumption. At first, the ions absorb the pump power, enabling them to transit to the high level. The ions stayed at the level for a period of τ_3 before jumping to the meta-stable state, resulting in emission of photons [5]. Due to the small value of τ_3, it can be neglected and hence simplifies the three-level system to the two-level [6]. A radiative transition towards the ground energy level then takes place. As a result, photons at 1550 nm are emitted. The rate equations, eqs. (1) – (3) describe the effects of absorption, stimulated and spontaneous emission on the ions populations of the ground state N_1 and metastable states N_2 [7-8]

$$\frac{dN_1}{dt} = -[W_{sa}(z) + W_P(z)]N_1 + \left[\frac{1}{\tau_{21}} + W_{se}(z)\right]N_2, \quad (1)$$

$$\frac{dN_2}{dt} = [W_{sa}(z) + W_P(z)]N_1 - \left[\frac{1}{\tau_{21}} + W_{se}(z)\right]N_2, \quad (2)$$

$$N_1(z) + N_2(z) = N_T \quad (3)$$

where τ_{21} is the spontaneous emission lifetime, N_T is the dopant density of the EDF, W_{sa}, W_{se}, and W_P are the stimulated absorption, stimulated emission and pumping rates respectively. Further elaborations can be found in [9] and summarizes as

$$W_{sa}(z) = \sum_{v} \frac{\xi_{sa}(v)}{A_{eff} hv}[P_S + P_{ASE}^+(z,v) + P_{ASE}^-(z,v)]\eta(v)dv, \quad (4)$$

$$W_{se}(z) = \sum_{v} \frac{\xi_{se}(v)}{A_{eff} hv}[P_S + P_{ASE}^+(z,v) + P_{ASE}^-(z,v)]\eta(v)dv, \quad (5)$$

$$W_P(z) = \frac{1}{A_{eff}} \frac{\xi_{pa}(v_P)}{hv_P}[P_P^+(z) + P_P^-(z)]\eta(v_P), \quad (6)$$

where P_S is the signal power, P_P^+ and P_{ASE}^+ represent the forward propagating of EDF pump powers and amplified spontaneous emission (ASE) powers at frequency v, respectively, while P_P^- and P_{ASE}^- are the backward propagating of EDF pump powers and ASE powers at frequency v, correspondingly, ξ_{sa}, ξ_{pa}, ξ_{se}, and ξ_{pe} are

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the absorption and emission cross sections at the pump and signal wavelength. A_{eff} is the effective area of the EDF and h is the Plank's constant. Meanwhile, $\eta(v)$ is the overlapping factor between each radiation and fiber fundamental modes.

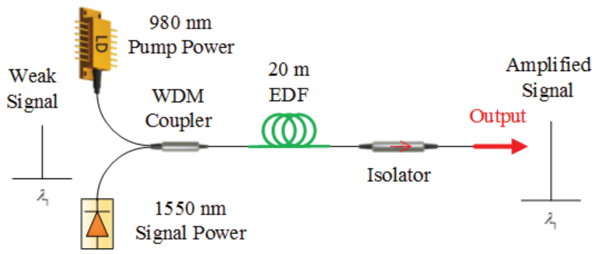

Fig. 1. Basic configuration of the EDFA.

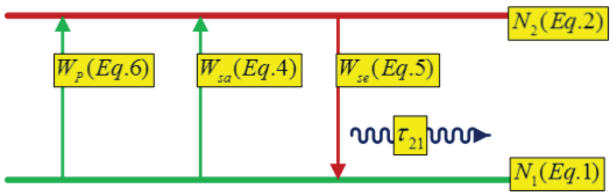

Fig. 2. Energy level diagram of Er^{3+} doped in silica.

Propagation of light through the EDF is shown in Fig. 3(a). The light in the EDF is assumed to propagate as a number of optical beams of frequency bandwidth Δv. The wave propagation of signal P_S, pump $P_P^{\pm}$ and noise power $P_{ASE}^{\pm}$ can be expressed as [10]

$$\frac{dP_S(z)}{dz} = (N_2\xi_{se} - N_1\xi_{sa})\eta(v_S)P_S(z), \quad (7)$$

$$\frac{dP_P^{\pm}(z)}{dz} = \pm(N_2\xi_{pe} - N_1\xi_{pa})\eta(v_P)P_P^{\pm}(z), \quad (8)$$

$$\frac{dP_{ASE\_n}^{\pm}(z)}{dz} = \pm[N_2\xi_{se}(v) - N_1\xi_{sa}(v)]\eta(v)P_{ASE\_n}^{\pm}(z) \pm d, \quad (9)$$

where $d = 2hv\Delta vN_2\eta(v)\xi_{se}(v)$ is the ASE power caused by the spontaneous emission.

In order to solve for power from the eqs. (1) – (6). the EDF with length z is divided into segments along the forward and backward propagation as illustrated in Fig. 3(b). Each segment contains its own population densities. The pump, signal and ASE powers which propagate in the first segment (segment 0) are solved by using the initial condition as shown in Table 1. Then, the power of the earlier segment is used as the input for the next consecutive segments. The eqs. (7) - (9) are numerically solved through a trial and error technique known as relaxation method. This method makes iterative adjustment to the solution where an initial set of boundary is chosen for the first integration. Utilizing this method, accuracy of 0.01% is achieved for P_S, $P_P^{\pm}$, and $P_{ASE}^{\pm}$ [11-12].

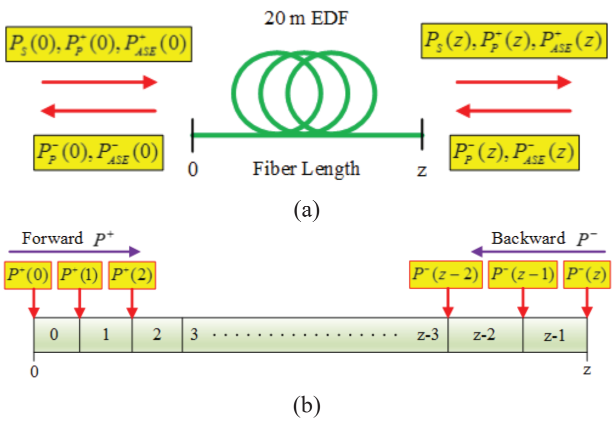

Fig. 3. (a) Lightwave propagation along the EDF.
(b) Schematic of the numerical fiber model.

Table 1. Initial condition.

Initial condition	Operating wavelength (nm)
$P_{P1}(0) = P_P$	$\lambda = 980$
$P_S(0) = P_S$	$\lambda = 1550$
$P_{ASE}^+(0,v) = P_{ASE}^-(z,v) = 0$	$1450 \le \lambda \le 1600$
$P_{ASE}^+(z,v) = P_{ASE}^-(0,v) \ne 0$	$1450 \le \lambda \le 1600$

3 Results and Discussions

A series of numerical simulations are performed for the EDFA modelling using parameters of an EDF from OFS Model MP980. These parameters are $N_T = 3 \times 10^{23}$, $N_{2\_initial} = 10^{-10}$, $L_{EDF} = 20$ m, $\Delta v = 5 \times 10^{10}$ Hz, $\tau_{21} = 10^{-2}$ s, $\xi_{pa} = 0$, $\xi_{pe} = 3.28 \times 10^{-25}$ m^2, $A_{eff} = 50$ µm^2, $c = 3 \times 10^8$ m/s, and $h = 6.63 \times 10^{-34}$ Js.

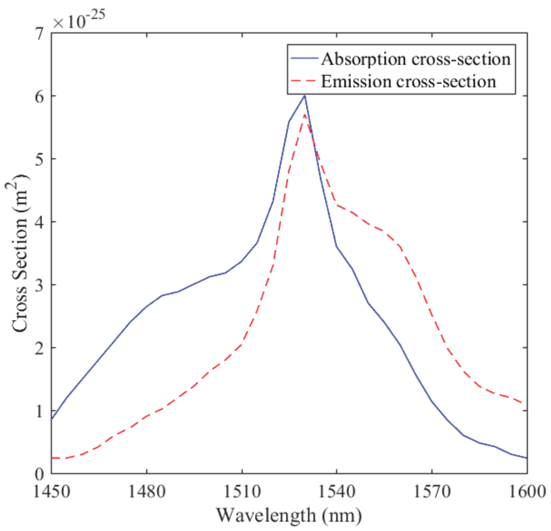

Fig. 4. Absorption and emission cross sections spectra of ASE signals.

The ξ_{sa} and ξ_{se} for the EDF of different wavelengths are obtained by using curve fitting method as shown in Fig. 4. Notice that each wavelength has its own absorption and emission coefficients since photons can be absorbed to generate carriers via a stimulated absorption process while at the same time, new photons can be generated owing to the stimulated emission process. Fig. 5 depicted the ASE power of both backward and forward ASE along the EDF for forward pumping configurations. During the simulation, we found that $P_{ASE}^{-}(z)$ must be lower than 0.01 mW.

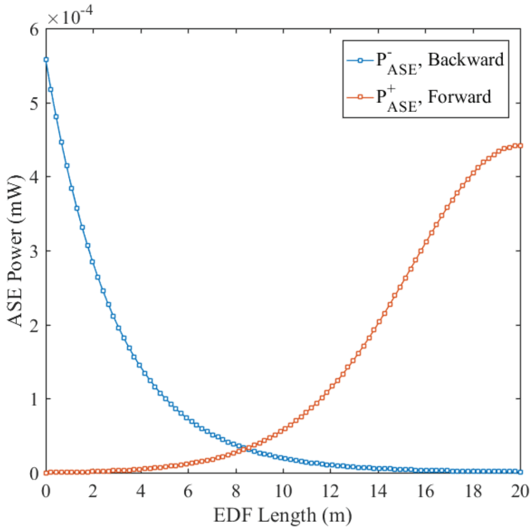

Fig. 5. Simulation output of forward and backward ASE.

The variation of gain, $G = P_S(z)/P_S(0)$ for different EDFs length and pump power is then investigated as shown in Fig. 6. With the EDF pump power increased from 30 mW to 100 mW for 20 m EDF, the gain in Fig. 6(a) was observed to increase along with the increasing EDF length. However, the gain started to decrease after reaching a maximum value. The reason is that the pump propagates through the EDF gets absorbed and hence the power reduces. After propagating a certain distance, the power becomes too small to create population inversion. As a result, the EDF would start to absorb the signal rather than amplify the signal. Therefore, there is an optimum EDF length to achieve maximum gain with variation of EDF pump power. Fig. 6 (b) depicted the variation of gain for different EDF length with the EDF pump power of 100 mW. For EDF length from 10 m to 20 m, the gain is expected to increase as the EDF pump power increase. When the EDF pump power increase, the population inversions are created gradually. No more Er^{3+} ions are available when all the Er^{3+} ions are excited, and thus the gain would saturate.

Further we study the EDFA gain by plotting EDFA gain versus wavelength with varying signal power from -40 dBm to -10 dBm as depicted in Fig. 7. The results were obtained using a 20 m OFS MP980 of EDF and a 100 mW pump power at 980 nm wavelength. Initially, the gain spectrum of an EDFA is not uniform across the bandwidth. A narrow gain peak around 1530 nm and a relatively flat region between 1540 nm and 1560 nm can be observed in Fig. 7. When the input signal power increased from -40 dBm to -10 dBm, the optical gain at 1550 nm decreases from 37 dB to 15 dB, resulting by gain saturation. Apart from that, the spectral shape of the optical gain also changes with the input signal power. When the input signal power increase, the gain tends to tilt toward the longer wavelength side while the short wavelength peak around 1530 nm is suppressed. This situation has to be considered in designing gain-flattening techniques.

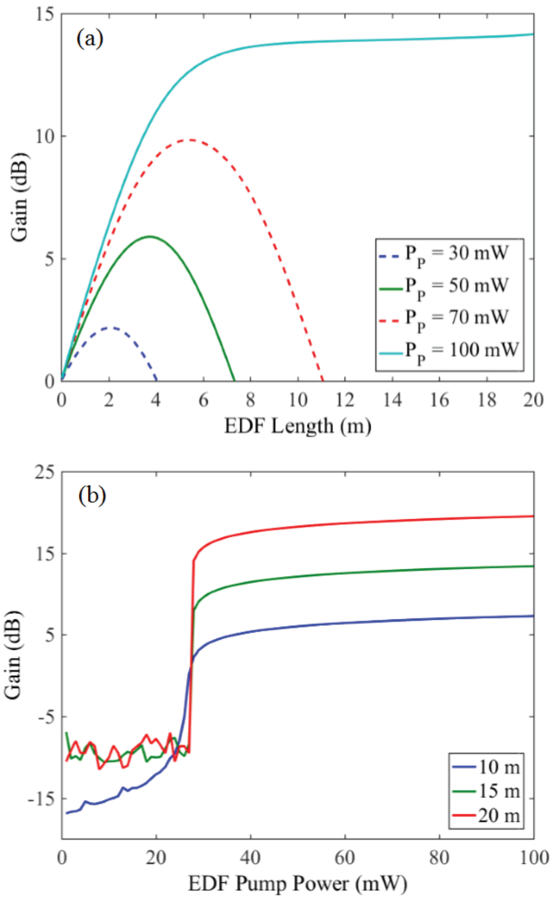

Fig. 6. The variation of gain with (a) EDF length and (b) Pump power

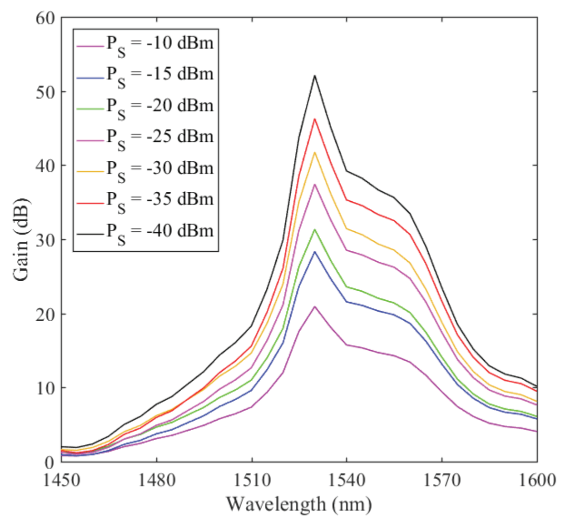

Fig. 7. EDFA gain at different input signal power with fixed EDF length of 20 m and pump power of 100 mW

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4 Conclusion

We have theoretically studied the effect of EDF parameters to the gain performance of C-band EDFAs. Theoretical analysis and simulation are carried out using the coupled rate and propagation equations, taking into accounts both the ground and excited states. The results show that the gain of EDFA is strongly dependent on the EDF length, pump power and input signal. When the pump power is sufficient enough, the EDFA shows that it could be operated in saturation regimes, leading to the maximum gain.

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