SIMULATION OF THE GAIN CHARACTERISTICS OF EDFA

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ABSTRACT

In this study, one of the most important characteristics of Erbium-Doped Fiber Amplifier (EDFA), gain is simulated and analyzed. In used slicing method, Erbium-doped fiber (EDF) is divided into many small splices in which the Er^{3+} population densities of EDF at metastable state and ground state is assumed to be unchanged. Simulation results show that EDFA gain is affected by some parameters such as fiber length, signal wavelength, pump wavelength, input signal power and pump power. Generally, the EDFA gain is the non-linear function of these parameters. Each has different effect on the gain. These results are consistent with published materials.

1. INTRODUCTION

Erbium-doped Fiber Amplifier (EDFA) is an optical amplifier which has had a significant impact on optical fiber communication systems [1], especially in Wavelength Division Multiplexing (WDM) systems. With the characteristics such as polarization-independent gain, low interchannel crosstalk, wide optical bandwidth and low-noise generation [1], it has been used to compensate for signal propagation loss along high speed single mode fiber optical links.

Among the characteristics of EDFA, gain is one of the most important ones. Together with saturation power and noise, it is often referred in the literature as EDFA performance [2]. The highest gain is expected. However, the gain of EDFA is unequal at different operation conditions. It depends on some parameters such as signal wavelength, pump wavelength, input signal power, pump power and the length of Erbium-doped Fiber (EDF). Therefore, understanding the effects of these parameters on gain characteristics and EDFA performance generally is required to study and improve its performance in optical fiber communication systems.

In this study, the gain characteristics of EDFA are simulated and analyzed. To achieve this purpose, slicing method in which EDF is divided into many small slices is used. It will be presented in more details in the Section 2.

Based on this method, by changing appropriately the values of signal wavelength, pump wavelength, signal power, pump power and the length of EDF, the characteristics of gain versus these parameters are simulated and analyzed. The simulation results of these characteristics will be presented in the Section 3.

2. METHODOLOGY

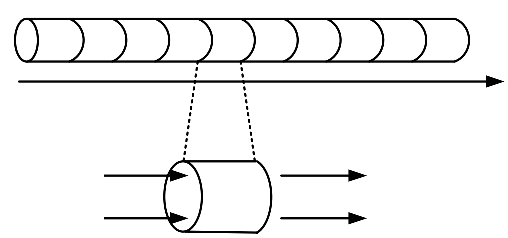

Fig.1 Erbium-doped fiber is represented as a series of individual gain slices

The method used in this study is shown in Fig.1. In this method, Erbium-doped fiber (EDF) is divided into many small slices with the length of Δz. In each slice, the population density at metastable state $N_2(z)$ and the population density at ground state $N_1(z)$ are assumed to be unchanged. As a result, an EDFA is considered as a concatenation of many amplifiers of the incremental length Δz [1].

The gain g(z) and the pump loss $\alpha_p(z)$ in a slice of fiber can be determined as follows [1]:

$$g(z) = \Gamma_s[\sigma_{e,s}N_2(z) - \sigma_{a,s}N_1(z)] \quad (1)$$

$$\alpha_p(z) = \Gamma_p[\sigma_{e,p}N_2(z) - \sigma_{a,p}N_1(z)] \quad (2)$$

where Γ is the overlap factor between field and erbium ion population; σ_e and σ_a are simulated emission and absorption cross-section, respectively. In the discussion, subscripts s and p refer to signal and pump, respectively.

Simulated emission and the absorption cross-sections represent the strength of transition. In other words, they represent the ability to produce gain and absorption [1]. These cross-sections depend on the kind of EDF and the wavelength of light. The absorption and emission cross-sections of Er^{3+} ions of Al-Ge-Er codoped silica fiber [3] which is used to simulate and analyze the gain characteristics of EDFA in this study are shown in Fig.2.

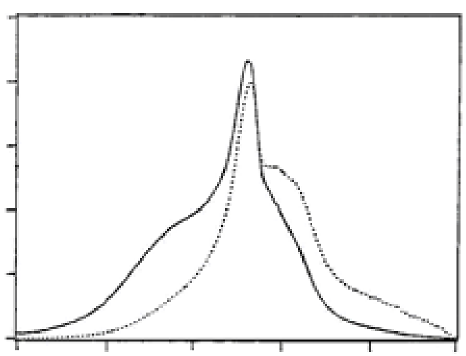

Fig.2 Absorption and emission cross-sections of Er^{3+} ions of Al-Ge-Er codoped silica fiber [3].

Overlap factor can be calculated by following equation [4]:

$$\Gamma = \left(1 - e^{-R^2/\omega^2}\right) \quad (3)$$

where R is Er^{3+} distribution radius; ω is spot size which is determined as follows [5]:

$$\omega = \frac{a}{\sqrt{2}}\left(0.65 + \frac{1.619}{V^{1.5}} + \frac{2.879}{V^6}\right) \quad (4)$$

where a is core radius of fiber and V is normalized frequency of fiber.

$N_1(z)$ and $N_2(z)$ can be determined as follows [3]:

$$N_2(z) = \frac{\frac{\tau\sigma_{a,s}\Gamma_s}{h\nu_s A}P_s(z) + \frac{\tau\sigma_{a,p}\Gamma_p}{h\nu_p A}P_p(z)}{\frac{\tau(\sigma_{a,s}+\sigma_{e,s})\Gamma_s}{h\nu_s A}P_s(z) + \frac{\tau(\sigma_{a,p}+\sigma_{e,p})\Gamma_p}{h\nu_p A}P_p(z)} N \quad (5)$$

$$N_1(z) = N - N_2(z) \quad (6)$$

where $P_s(z)$ and $P_p(z)$ are signal power and pump power at the position z of the fiber; A is effective cross-sectional area; τ is the lifetime of Er^{3+} at the metastable state $^4I_{13/2}$, N is the total ion population density; ν_s and ν_p are optical pump and signal frequencies, respectively; h is Planck's constant.

The gain of EDFA with length L is composed of the contributions of all the gain elements of n slices along the amplifier fiber [3]:

$$G = \lim_{\Delta z \to 0}\left\{e^{g(z_1)\Delta z} \times e^{g(z_2)\Delta z} \times \ldots \times e^{g(z_n=L)\Delta z}\right\} = \exp\left(\int_0^L g(z)dz\right) \quad (7)$$

The gain of EDFA can also be determined as follows [3]:

$$G = \exp[(\overline{N_2}\sigma_{e,s} - \overline{N_1}\sigma_{a,s})\Gamma_s L] \quad (8)$$

where $\overline{N_1}$, $\overline{N_2}$ are the average ion population densities at ground and metastable state, respectively. They can be calculated as follows [3]:

$$\overline{N_1} = \frac{1}{L}\int_0^L N_1(z)dz \quad (9)$$

$$\overline{N_2} = \frac{1}{L}\int_0^L N_2(z)dz \quad (10)$$

The equations from (1) to (10) show that EDFA gain is changed along the fiber. It depends on material and structural parameters of EDF (absorption and emission cross-sections, effective cross-sectional area, Er^{3+} distribution radius…), fiber length, pump wavelength, signal wavelength, signal power and pump power. By changing the values of these parameters, the performance of EDFA gain at different operation conditions will be simulated. Simulation results are presented in the section 3.

3. SIMULATION RESULTS:

The simulation results of gain characteristics of EDFA are shown in the figures from Fig.3 to Fig.6. In simulation, the Al-Ge-Er codoped silica fiber with the absorption and emission cross-sections of Er^{3+} as shown in Fig.2 is used. This fiber has structural parameters as follows: core radius a=1.4μm, numerical aperture NA=0.28, Er^{3+} distribution radius R=1.05μm, total population density N=5.5x10^{24} m^{-3}. These material and structural parameters of simulated EDFA are similar to those of EDFA presented in [3]. Therefore, to validate the simulation results, published results of [3] are also shown in the figures.

In Fig.3, the characteristic of EDFA gain versus signal wavelength and pump wavelength is presented. It is simulated with fiber length L=14m, pump power P_p=40mW and input signal power P_s^{in}=-40dBm. We can see that the gain is not equal over wavelength range. It is highest at nearly 1530nm when pump wavelengths are 980nm or 1480nm. The nearly 1530nm wavelength is sensitive to pump power because emission cross-section of Er^{3+} ions at this wavelength is highest as shown in Fig.2. We have a good agreement between simulation results and published works [3] shown in this figure.

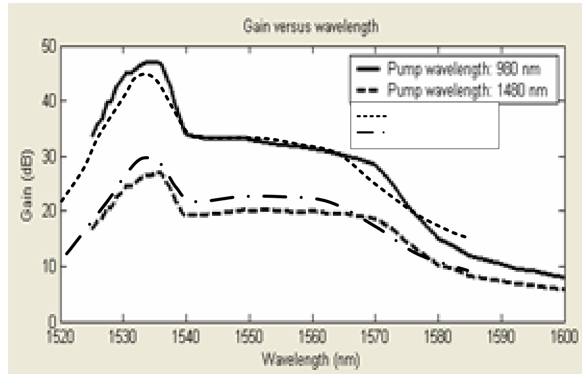

Fig. 3 Simulation results and published results [3] for gain versus pump wavelength and signal wavelength with P_p=40mW, L=14m and P_s^{in} = -40dBm.

From Fig.3, we can also see that the EDFA gain at 980nm pump wavelength is higher than that at 1480nm pump wavelength. Therefore, inversion factor at 980nm is higher than that at 1480 nm. This result is consistent with the theory of EDFA presented in [4], [5].

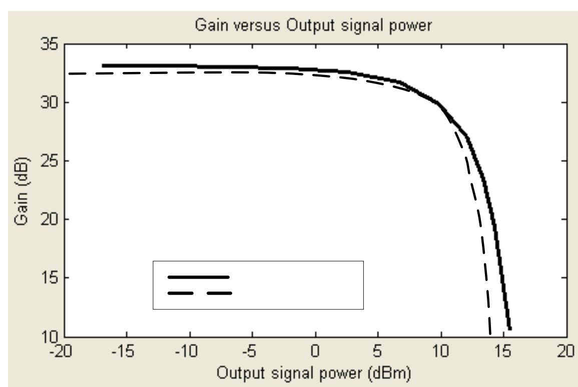

Fig.4 Simulation result (**—**) for gain versus output signal power with P_p=16dBm, L=20m, λ_s=1550nm, λ_p=1480nm and published result [3] (**---**)

The characteristic of EDFA gain versus output signal power is presented in Fig.4. It is simulated with P_p=16dBm, L=20m, signal wavelength λ_s=1550nm and pump wavelength

λ_p=1480nm. It shows that gain is nearly 33dB when output signal power is small. When the output signal power increases over 10dBm, gain decreases rapidly. The reason is that when input signal power is high, inversion level declines rapidly and pumping rate can not adapt to high input signal rate. The point at which gain reduces a half or 3dB is called saturation point. Output signal power at the saturation point is called output saturation power, which is the other important characteristic of EDFA [2].

There is discrepancy between simulation result and published result [3] shown in Fig.4. However, this discrepancy is small and acceptable.

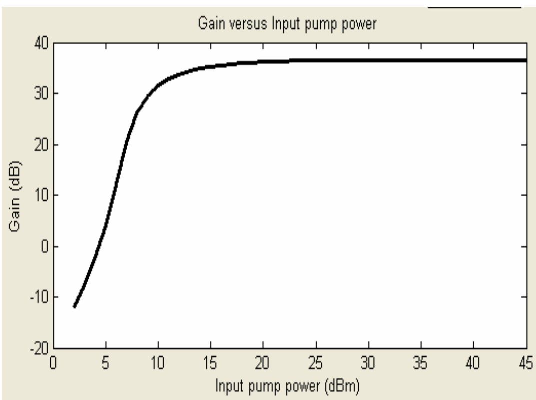

Fig.5 Simulation result for gain versus pump power with P_s=-40dBm, L=14m, λ_s=1550nm, λ_p=1480nm**.**

The characteristic of gain versus pump power is shown in Fig.5. We can see that when the pump power is very low (less than 5dBm), gain is less than 0 dB. In the other words, signal attenuates after passing the EDF. When pump power increases, gain increases almost linearly with pump power. However, when pump power reaches about 10dBm, gain increases more slowly and nearly unchanged when pump power is over 25dBm. It is because population inversion is low when pump power is low. When pump power increases, population inversion increases and so does gain. However, when pump power exceeds a certain level, population inversion seems unchanged because of the Er^{3+} population stability. This result is consistent with the theory of EDFA.

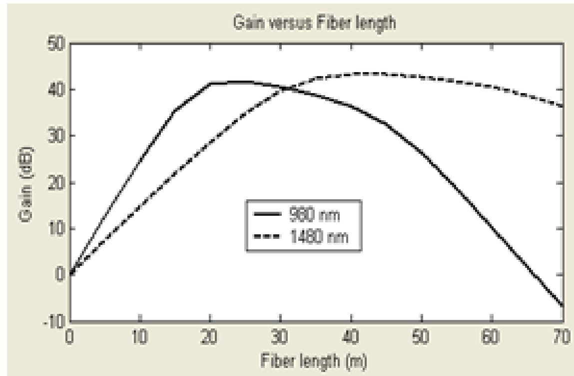

Fig.6 Simulation results for gain versus EDF length at the two pump wavelengths of 1480nm and 980nm with P_p=10mW, P_s^{in}=-40dBm, λ_s=1550 nm.

The characteristic of gain versus Erbium-doped fiber length is shown in Fig.6. It is simulated at two pump wavelengths of 1480 nm and 980 nm with P_p=10mW, P_s^{in}=-40dBm, λ_s= 550 nm. It shows that when fiber length is short, gain at the pump wavelength of 980 nm is higher than that of 1480 nm. However, when fiber length increases more, gain at 1480 nm is higher and reduces more slowly than that at 980 nm. It is consistent with [3], [7].

The Fig.6 also shows that with certain input pump power, gain increases when fiber length increases. It reaches maximum value at a certain fiber length, so called optimum fiber length L_{opt} [2]. For fiber lengths $L>L_{opt}$, gain decreases. In the other words, signal is reabsorbed along the fiber, as a result of the absence of population inversion in this fiber section. This result is consistent with [2].

4. CONCLUSION

In this study, the gain characteristics of EDFA were simulated and analyzed. The used simulation method was splicing method in which Erbium-doped fiber (EDF) was divided into many small slices with the length of Δz. In each slice, the population densities at metastable state and ground state are assumed to be unchanged. As a result, an EDFA is considered as a concatenation of many amplifiers of the incremental length Δz. Based on this method, the simulation of gain characteristics of EDFA was done.

The simulation results show that the gain of EDFA depends on many different parameters such as material and structural parameters of EDF, pump wavelength, signal wavelength, input pump power, signal power and fiber length. The influence of these parameters on the EDFA gain is different. Therefore, relying on the requirements of application, the values of these parameters should be chosen reasonably to achieve desired gain. These simulation results are consistent with published materials.

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