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THE EFFECT OF BOLTZMANN FACTOR ON THE PERFORMANCE OF EDFA'S WITH RESPECT TO PUMPING WAVELENGTH

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Abstract : It is examined that how the population ratio between E_2 and E_3 energy levels of the Er^{+3}-doped fiber amplifiers (EDFA) changes by the Boltzmann factor (β) in the different temperatures (from - 80 ^oC to + 40 ^oC) for the pumping with 980 *nm* and 1480 *nm* wavelengths. Relative population differences of the amplifier are calculated by using the rate equation model modified by us and it is seen that the relative population inversion decreases with increasing temperature when it is pumped at 1480 *nm*.

Keywords : Optical amplification, Erbium-doped fiber amplifier, The Boltzmann factor

POMPALAMA DALGA BOYUNA GÖRE EDFA'LARIN PERFORMANSI ÜZERİNE BOLTZMANN FAKTÖRÜNÜN ETKİSİ

Özet : Er^{+3}-katkılı fiber kuvvetlendiricilerin E_2 ve E_3 enerji seviyeleri arasındaki doluluk oranının farklı sıcaklık bölgelerinde (-80 ^oC'den +40 ^oC ye kadar) Boltzmann faktörü (β) ile nasıl değiştiği 980 *nm* ve 1480 *nm* dalga boylu pompalama için incelendi. Kuvvetlendiricinin bağıl doluluk farkları, geliştirdiğimiz oran denklemi modeli yardımı ile hesaplandı ve bağıl ters doluluğun, kuvvetlendirici 1480 *nm*'de pompalandığı zaman, artan sıcaklık ile azaldığı görüldü.

Anahtar Kelimeler : Optik kuvvetlendirme, Erbium-katkılı fiber kuvvetlendirici, Boltzmann faktörü.

1. Introduction

Optical communications have been widely introduced into trunk and local areas in order to provide a high speed and broadband communication services. Expansion of the transmission length is essential to reduce the system cost. The fiber amplifier is one of most attractive candidates, for this aim. Erbium-doped fiber amplifier (EDFA) has been tried in the 1,5 μm region such as ultra-long distance systems [1].

Traditionally, the task of signal regeneration in fiber optic communications had been done through the use of electronic repeaters. However, there are some limitations in the information rate of systems having electronic repeaters. These are come into existence because of the danger of misreading the digital signal and the presence of amplifying noise, which is a distortion in the information, and large number of repeaters, one per 70 km, making maintenance operations difficult and costly. What is the way of avoidance from these drawbacks? The solution of this question is obtained under the auspices of exploration of optical amplifiers. The basic concept of a traveling wave optical amplifier was first introduced in 1962 by Geusic and Scovil [2] and about two years after, optical fiber amplifiers were invented in 1964 by E. Snitzer [3]. Snitzer fabricated fiber amplifiers and lasers from Nd^{3+} laser glasses. About a decade later, another major advance was achieved with the operation of end-pumped glass-clad Nd^{3+}-doped silica fiber lasers [4]. In this dates, interestingly, rare earth doped lasers in a small diameter crystal fiber form were searched thoroughly as potential implements for fiber transmission systems [5].

In the course of time, the advantages of rare-earth doped fiber amplifiers in comparison with electronic repeaters have appeared and production of lanthanum-doped fiber amplifiers has more and more importance to communication [6]. An in-line amplifiers system has constructed with erbium-doped fiber amplifiers spaced at 100 km and 80 km intervals and an 1000 km fiber loop with 31 Er-doped fiber amplifiers has used for evaluating the transmission performance of ultra-long distance optical communication systems with Er-doped fiber amplifiers [7].

2. Light Amplification in Erbium-Doped Single-Mode Fibers

If one wants to excite a medium doped by ions, there must initially be at least two discrete energy states which consist of the ground and upper-level states. Then, using an appropriate pumping source such as high-power semiconductor laser, all the ions which are present in the minimum energy state of physical system can be moved into upper energy states. When a light signal enters such a physical medium, the signal wave brings about two changes in the ionic distributions: Ground-state ions which absorb the energy of light signal are excited to the upper energy state, and upper-level ions become ground-state ions by stimulated emission. Absorption is such a process that, when a great number of ions are in the ground state, the energy of the signal is absorbed and thus the signal wave is attenuated by the medium. However, the stimulated emission is to release the energy stored by ions, in the form of the electromagnetic radiation. The electromagnetic energy emitted by stimulated emission is coherent with that of the signal. When more ions are initially in the upper level, signal wave is amplified through the medium because a certain amount of the net energy is coherently transferred to the signal wave. The remaining energy is relaxed to the medium as phonon radiation [8].

The notation ${}^4I_{15/2}$ for ground state of trivalent erbium ion (Er^{3+}) is referred to the symbol ${}^{2S+1}L_J$, where $L = 0,1,2,3,4,5,6...$ corresponding to capital letters $S,P,D,F,G,H,I...$, respectively, (see Fig. 1).

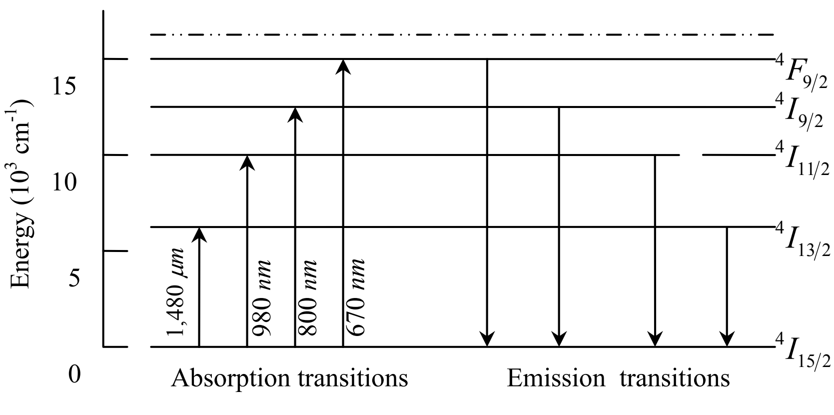

Figure 1. Energy level structure of Er^{3+}.

In a multielectron atom, the total angular momentum number J is the vector sum of the angular momenta L and spin S. The spin multiplicity is $2S+1=4$. As it is shown in the Fig.1, the ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er^{3+} in glass hosts such as silica or fluorozirconate, corresponds to about $1,5\,\mu m$ wavelength region, which is a principal optical communications window.

Let the energies and populations of the relevant three levels of the rare-earth ion be E_1, E_2, E_3 and N_1, N_2, N_3, respectively, in the thermal equilibrium (Fig.2). By definition, level 1 is the lowest or ground state, level 2 is the metastable state, and level 3 is the pump level. R_p is the stimulated transition probability between level 1 to level 3 by any method of pumping and R_s is the stimulated transition probability between E_2 and E_1.

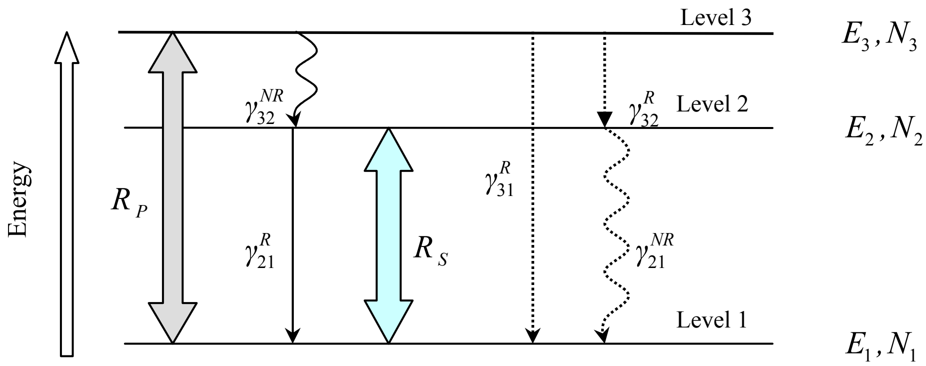

Figure 2. Energy level diagram corresponding to a basic three level model for Er^{3+}-doped fiber amplifier.

The atomic rate equations for the population changes are given as follows [9],

$$\frac{dN_3}{dt} = R_p\left(N_1 - N_3\right) - \gamma_3 N_3; \qquad \gamma_3 = \gamma_{31}^{R} + \gamma_{32}^{R} + \gamma_{32}^{NR}, \tag{1a}$$

$$\frac{dN_2}{dt} = -R_s\left(N_2 - N_1\right) - \gamma_2 N_2 + \left(\gamma_{32}^{R} + \gamma_{32}^{NR}\right) N_3; \qquad \gamma_2 = \gamma_{21}^{R} + \gamma_{21}^{NR}, \tag{1b}$$

$$\frac{dN_1}{dt} = -R_p\left(N_1 - N_3\right) + \gamma_2 N_2 + R_s\left(N_2 - N_1\right), \tag{1c}$$

where $\gamma_{31}^{R}, \gamma_{32}^{R}$ and γ_{32}^{NR} represent radiative (R) and nonradiative (NR) transition probabilities from the excited level to relevant levels. In the steady-state, the populations are time invariant, i.e., $\frac{dN_i}{dt} = 0$ ($i = 1, 2, 3$), $\gamma_{32}^{NR}\left(\equiv \gamma_3\right) >> \gamma_{31}^{R} + \gamma_{32}^{R}$, $\gamma_{21}^{R}\left(\gamma = \frac{1}{\tau}\right) >> \gamma_{21}^{NR}$ *(where τ is lifetime of metastable level).*

3. The Effect of Boltzmann Factor on the Performance of EDFAs

The population inversion procedure which is required for the optical amplification in the doped-fiber amplifiers is an action of pumping more than half of the total number of Er^{+3} ions from the ground state (level N_1) into the excited state (level N_2). The relative population difference or fractional inversion between N_1 and N_2,

$\frac{\Delta N}{N}=\frac{N_2-N_1}{N}$, is obtained from the atomic rate equations. Equations (1) can be written as a function of the normalized pump photon flux φ_p/φ_{th} and the normalized signal photon flux φ_s/φ_{th}, where φ_p is the incident light intensity flux at the pump frequency (number of photons per unit time per unit area); φ_s is the incident light intensity flux at the signal frequency; φ_{th} is the threshold pump flux that corresponds to the case of $N_1 = N_2$ and N is the total population of Er^{+3} ions.

Using Eq. (1a), in the steady-state, the population of level 3 can be written as,

$$N_3=\frac{1}{1+\gamma_{32}/R_p}N_1 \tag{2}$$

Putting Eq.(2) into Eq. (1b) gives

$$-R_s\left(N_2-N_1\right)-\gamma_2 N_2+\frac{\gamma_{32}N_1}{1+\gamma_{32}/R_p}=0 \tag{3}$$

The total population N is given by $N = N_1 + N_2 + N_3$. Inserting Eq. (2) into this equality, one can be obtained a relation as follow:

$$N=N_1+N_2+\frac{N_1}{1+\gamma_{32}/R_p} \tag{4}$$

When γ_{32} is large compared to the pumping rate (R_p) to level 3, the last term in Eq. (4) is very close to zero, so that the total population consists of N_1 and N_2. Therefore, the populations N_1 and N_2 are obtained from Eq. (3) and Eq. (4),

$$N_1=\frac{R_s\tau+1}{R_p\tau+2R_s\tau+1}N \tag{5}$$

$$N_2=\frac{R_p\tau+R_s\tau}{R_p\tau+2R_s\tau+1}N \tag{6}$$

Hence, the relative population difference is given,

$$\frac{\Delta N}{N}=\frac{N_2-N_1}{N}=\frac{R_p\tau-1}{R_p\tau+2R_s\tau+1} \tag{7}$$

In addition, Eq. (7) can also be written in terms of $\varphi_p/\varphi_{th}=R_p\tau$ and $\varphi_s/\varphi_{th}=R_s\tau$, [1],

$$\frac{\Delta N}{N} = \frac{N_2 - N_1}{N} = \frac{\varphi_p / \varphi_{th} - 1}{\varphi_p / \varphi_{th} + 2\varphi_s / \varphi_{th} + 1} \tag{8}$$

The above investigations, which are made for 980 *nm* pumping configuration, can also be applied to the Er^{+3} doped fiber amplifier pumped by 1480 *nm* pump source. In this case, the total population of Er^{+3} ions becomes $N = N_1 + N_2 + N_3$. E_2 and E_3 levels will be very closely spaced for 1480 *nm* pumping configuration, the population of N_3 is not equal to zero due to the population ratio between these two levels quickly reaches the Boltzmann population ratio:

$$\beta = \frac{N_3}{N_2} = e^{-\Delta E_3 / k_B T} \tag{9}$$

where the β quantity is called as the Boltzmann factor and $\Delta E_3 = E_3 - E_2$.

Putting $N_3 = \beta N_2$ in Eq.(1c) gives for the steady-state,

$$-R_p\left(N_1 - \beta N_2\right) + \gamma_2 N_2 + R_s\left(N_2 - N_1\right) = 0 \tag{10}$$

Using the relation between N_1, N_2 and N_3 in terms of β $\left(N_1 = N - N_2\left(1+\beta\right)\right)$ in Eq. (10) gives,

$$N_2 = \frac{R_p\tau + R_s\tau}{(1+2\beta)R_p\tau + (2+\beta)R_s\tau + 1} N \tag{11}$$

$$N_1 = \frac{\beta R_p\tau + R_s\tau + 1}{(1+2\beta)R_p\tau + (2+\beta)R_s\tau + 1} N \tag{12}$$

Hence, the relative population difference can be written in terms of φ_p / φ_{th}, φ_s / φ_{th} and β,

$$\frac{\Delta N}{N} = \frac{N_2 - N_1}{N} = \frac{(1-\beta)\varphi_p / \varphi_{th} - 1}{(1+2\beta)\varphi_p / \varphi_{th} + (2+\beta)\varphi_s / \varphi_{th} + 1} \tag{13}$$

The behavior of the relative population difference in various temperature ranges for 1480 *nm* pumping wavelength is represented by Eq. (13).

4. Results and Discussion

Fig. 3 shows plot of $\Delta N/N$ versus φ_p/φ_{th} for pumping wavelength at 980 *nm* (Eq. 8).

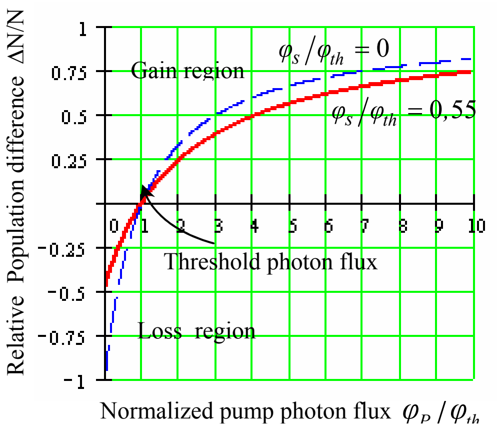

Figure 3. Relative population difference versus normalized pump photon flux for two different normalized signal photon flux with the pumping wavelength at 980 *nm*.

It is seen from the figure that, 980 *nm* pumping wavelength achieves population inversion nearly 75 % with an inserting normalized signal photon flux of $\varphi_s/\varphi_{th} = 0,55$. And population inversion increases when the value of normalized signal photon flux φ_s/φ_{th} is equal to zero. In addition, it can also be seen that, the condition $\phi_p/\phi_{th}(R_p\tau) \geq 1$ is required for jumping to gain region.

ΔE_3 energy difference between second and third levels in 1480 *nm* pumping configuration becomes about 200 cm^{-1} at the room temperature [10]. This energy difference between "– 80 °C and + 40 °C ", which is our investigation range, remains nearly constant and independent of temperature $(i.e. \Delta E_3 \neq f(T))$. In our case, β parameter has five different values for – 80 °C, – 40 °C, 0 °C, + 20 °C and + 40 °C. For numerical calculations, the values of β parameter obtained from Eq. (9) are given in Table 1. We have used and $\varphi_s/\varphi_{th} = 0$.

Table 1. The β values for different temperatures at 1480 *nm* pumping configuration.

Temperature (°C)	– 80 ^oC	– 40 ^oC	0 ^oC	20 ^oC	40 ^oC
β	0,230	0,297	0,354	0,380	0,404

In this study, three level system representing the erbium-doped fiber has been investigated from the viewpoint of temperature dependence, for both 1480 *nm* and 980 *nm* pumping wavelengths. For all practical purposes, as the β parameter is effectively zero for 980 *nm* pumping wavelength, this creates considerable differences between 1480 *nm* and 980 *nm* pumping configurations as shown in Fig. 5.

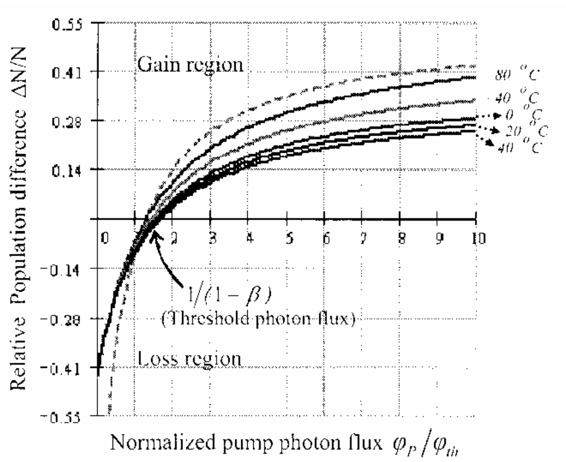

Figure 4. Relative population difference versus normalized pump photon flux (solid lines for $\varphi_s/\varphi_{th} = 0,55$, doted line for $\varphi_s/\varphi_{th} = 0$) and different β values at 1480 *nm*.

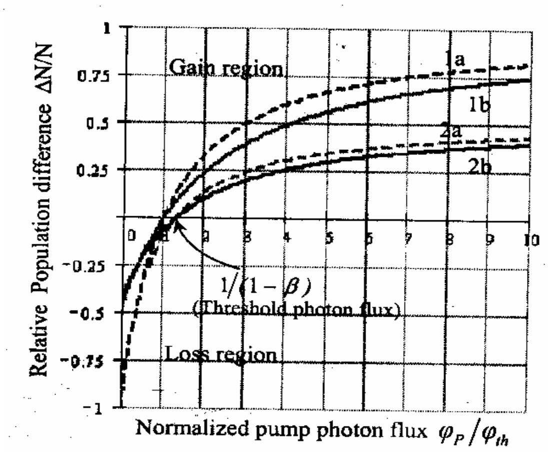

Figure 5. Relative population difference with respect to normalized pump photon flux. Curves (1a) and (1b) indicate the case of $\varphi_s/\varphi_{th} = 0$ and the case of $\varphi_s/\varphi_{th} = 0,55$, respectively, at 980 *nm*. Curves (2a) and (2b) indicate the case of $\varphi_s/\varphi_{th} = 0$ and the case of $\varphi_s/\varphi_{th} = 0,55$, respectively, in the temperature value of – 80 °*C* at 1480 *nm*.

5. Conclusion

Relative population differences of the system in the various temperature values (from -80 °C to +40 °C) have been calculated by using the rate equation model modified by us. Population inversion is bigger when the pump wavelength is 980 *nm* (Fig. 3). Population inversion decreases with increasing temperature when the system is pumped at 1480 *nm* (Fig. 4). 1480 *nm* pumping configuration is not more productive than 980 *nm* pumping configuration in the gain region. Thus, 980 *nm* pumping configuration yields higher relative population inversion than a 1480 *nm* pumping configuration. Therefore, we can say that the gain value is higher when the erbium-doped fiber is pumped at 980 *nm* wavelength for all temperatures. The point $1/(1-\beta)$ in Fig. 4 and Fig. 5, at which the value of relative population inversion is zero, is called the transparent (threshold) point. It gives minimum normalized pump photon flux which is required for population inversion in different values of the β parameter.

It is demonstrated that the fractional inversion (relative population difference) reduces when the temperature increases from -80 °*C* to +40 °*C* as shown in Fig. 3.4 for 1480 *nm* wavelength. Within these temperatures range, the variation of the population difference with the normalized pump photon flux is about 13% at 1480 nm wavelength.

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