Design of Fiber Laser Based on Erbium-ion

Yijun Hu*

International College, Chongqing University of Posts and Telecommunications, Chongqing, China

* Corresponding Author Email: 2020214539@stu.cqupt.edu.cn

Abstract. Erbium ions (Er^{3+}) exhibit good characteristics of fiber lasers in the 1500-1550 nm band, including three-level systems, high tilt efficiency, and large emission cross sections. This article focuses on studying the spectral characteristics of erbium ions, simulating the power propagation equation of erbium-doped ion fiber lasers, and calculating the pump power threshold and output power. The findings of the simulation indicate that the laser begins to produce 10 W of pump optical power. The laser power hits 34.38 W and the oblique power is determined to be 38.20% as soon as the pump power exceeds 100 W. Experimental results show that when pump light propagates forward, the forward propagation power of the pump light will weaken, the forward propagation power of the signal light will increase, the reverse propagation of the signal light will weaken and the reverse propagation of the pump light will Transmission will also weaken, with directional transmission remaining largely unchanged. This study carried out numerical simulations on the experimental parameters of the fiber laser doped with $Er^{3+}$and finally obtained the output power of pump light and signal light under these conditions, providing better data support for the preparation of 1500-1550 nm fiber laser doped with erbium ion.

Keywords: Erbium ion spectral characteristics; signal light output power; pump light output power; transmission power.

1. Introduction

Fiber laser doped with Er^{3+} is a laser that uses Er^{3+} as the excitation medium. This fiber laser is widely used due to its compact design, efficient energy transmission, low transmission loss, and suitability for fiber optic communications and other fields. Erbium ions are one of the key materials in the field of optical communications in the 1500-1550 nm band. Since fiber lasers have the advantages of low insertion loss when used in fiber optic communication systems, and erbium-doped fiber corresponds to the low-loss window of fiber optic communication in the 1500-1550 nm band[1], fiber lasers doped with Er^{3+} have increasingly become a popular topic for domestic and foreign scholars.

Initially, Morkel et al. The University of Southampton, UK, and others achieved the single-frequency 1555 nm laser output of erbium-doped fiber for the first time[2]. The output power is 1mW and the line width is less than 60kHz.Subsequently, Smith et al. Reports from the United States stated that a continuously adjustable single-frequency erbium-doped fiber laser output was achieved by inserting an acoustic-optic filter into the cavity[3]. Due to the high sensitivity of traveling wave cavities to temperature drift and other external disturbances, the laser mode is not easy to stabilize. To improve the mode hopping phenomenon of traveling wave cavity erbium-doped single-frequency lasers, saturable absorbers can be introduced to reduce mode hopping. After that, Cheng et al. from the University of Southampton used unpumped erbium-doped fiber as a saturable absorber for the first time to achieve stable mode-hopping-free single-frequency fiber laser doped with Er^{3+} output[4]. Next, Chien et al. Jiaotong University and others reported for the first time an S-band single-frequency erbium-doped fiber ring cavity laser with an adjustable range covering 1482~1512 nm[5]. In the same year, the team increased the output power of this fiber laser in this frequency band to 10 mW[6].Since then, Polynkin and others at the University of Arizona have used highly erbium-doped phosphate fiber as the gain medium to break the output power of the ring cavity single-frequency laser to the watt level, achieving an output power of 700 mW. However, mode hopping still exists at higher powers situations [7]. Subsequently, Yang et al. from Shanghai Jiao Tong University added an amplification structure to the ring cavity to increase the output power to 867 mW[8].However,

there is a relative lack of research based on erbium-doped fiber lasers, and the research results have shortcomings such as low efficiency, poor stability, and high cost. This paper studies the spectral characteristics of erbium-doped ion optical fiber, and realizes the design of fiber laser in the 1500 ~ 1550nm band in the experiment. According to experimental data, the three-level system transition of erbium ions under 980 nm pump light stimulation readily leads to particle number inversion and generates laser oscillation.

This article introduces the three-level structure and spectral characteristics of Er^{3+}, solves the pump power propagation equation, and calculates the changes of pump power and emission power with transmission length. This article also uses Matlab and numerical methods to solve the pump power threshold and output power of the fiber laser doped with Er^{3+}, and then derives and calculates the total power of the pump light.

2. Methods and Models

2.1. Energy Level Structure of Er^{3+}

The energy level shift of the electrons in the electronic layer is what causes the erbium ions in the erbium-doped optical fiber to glow. The energy level structure of the erbium ion luminescence process under pump light excitation is shown in Fig. 1. The ground state energy level 4I15/2 of erbium ions is pushed up to a high energy level, jumps to the upper energy level 4I13/2 of the laser in a non-irradiation crossover, and then jump back to the ground state and emit in the form of either an unprompted or prompted emission. Photons. Since the fluorescence lifetime of the upper energy level of the laser is very long, a particle number inversion can be formed between the upper energy level of the laser and the base, thereby achieving light amplification or broad-spectrum spontaneous emission.

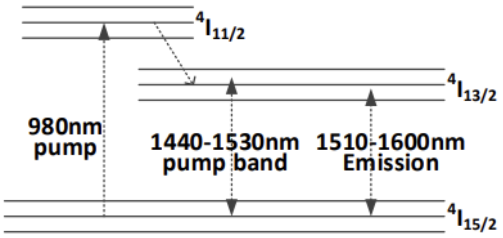


Fig 1. Energy level structure diagram of Er^{3+}

2.2. Energy System and Electron Jump Processes

The pump light designed for this experiment was 980 nm. Figure 1 displays the energy system image when the fiber laser doped with Er^{3+} is illuminated by a 980 nm pump light. The rate equation for the Er-doped ion fiber laser is as follows.

$$\frac{\partial N_1(z)}{\partial t} = -[W_p(z)+W_{12}(z)]N_1(z) + A_{21}N_2(z)+W_{21}(z)N_2(z) \quad (1)$$

$$\frac{\partial N_2(z)}{\partial t} = W_{12}(z)N_1(z) - W_{21}(z)N_2(z) - A_{21}N_2(z) + A_{32}N_3(z) \quad (2)$$

$$\frac{\partial N_3(z)}{\partial t} = W_p(z)N_1(z) - A_{32}N_3(z) \quad (3)$$

$$N=N_1(z)+N_2(z)+N_3(z) \quad (4)$$

In the above equations, N1, N2 and N3 represent the concentration of particles on the Er3+ energy levels 4I11/2, 4I13/2 and 4I15/2, respectively. N is the total number of particle numbers. Wp is the

pump light absorption rate, W12 is the signal light absorption rate, W21 is the signal light stimulated emission rate, A32 is the nonradiative transition rate, and A21 is the radiative transition rate. The unit is /s.

$$W_p(z) = \frac{\sigma_{13} P_p(z)}{h v_{13} A_{eff}} \tag{5}$$

$$W_{12}(z) = \frac{\sigma_{13}(v_{12}) P_s(z)}{h v_{12} A_{eff}} \tag{6}$$

$$W_{21}(z) = \frac{\sigma_{21}(v_{21}) P_s(z)}{h v_{21} A_{eff}} \tag{7}$$

$$A_{eff} = \pi r^2 \tag{8}$$

2.3. Power Propagation Equation and Pump Power

The change of pump power and lasing power (P_p,P_s) with the propagation length is called the power propagation equation.

Fig. 2 shows a schematic diagram of an Er^{3+} doped photonic crystal fiber laser. Pout is the laser power output, while Pp(0) is the input pump light. R_1 and R_2 are plane mirrors respectively. The reflectivity of the R_1 plane mirror designed in the experiment is 0.99, and the reflectance of the R_2 plane mirror is 0.035. $P_s^+(z)$ represents the forward transmission power of the laser at the optical input end, and $P_s^-(z)$ represents the reverse transmission power at the optical fiber input end. $P_s^+(z)$ and $P_s^-(z)$ represent the forward transmission and reverse transmission power of the pump light respectively[9].

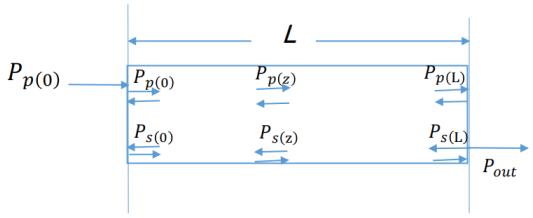


Fig 2. Schematic diagram of Er^{3+} doped photonic crystal fiber laser

$$\frac{dP_p^+(z)}{dz} = \Gamma_p(-\sigma_p N_1(z) - \alpha_p) P_p^+(z) \tag{9}$$

$$\frac{dP_p^-(z)}{dz} = -\Gamma_p(-\sigma_p N_1(z) - \alpha_p) P_p^-(z) \tag{10}$$

$$\frac{dP_s^+(z)}{dz} = \Gamma_s(\sigma_{es} N_2(z) - \sigma_{as} N_2(z) - \alpha_s) P_s^+(z) \tag{11}$$

$$\frac{dP_s^-(z)}{dz} = -\Gamma_s(\sigma_{es} N_3(z) - \sigma_{as} N_2(z) - \alpha_s) P_s^-(z) \tag{12}$$

$$p_{th} = \frac{(N\Gamma_s\sigma_{as} + \alpha_s)L + \ln\left(\frac{1}{\sqrt{R1R2}}\right)}{1 - e^{-\beta}} \cdot \frac{v_p}{v_s} \cdot p_{s,sat} \tag{13}$$

$$\beta = \frac{(\sigma_{es} + \sigma_{as})\Gamma_p}{(\sigma_{ep} + \sigma_{ap})\Gamma_s} \cdot \left[(N\Gamma_s\sigma_{as})L + \ln\left(\frac{1}{\sqrt{R1R2}}\right)\right] - \left(N\Gamma_p\sigma_{ap} + \alpha_p\right)L \quad (14)$$

The loss coefficients of the fibre material at the pumping and excitation wavelengths, denoted by αp and αs, respectively, are expressed in the above formula.pth is the threshold power. β is the laser parameter. αp and αs are the loss coefficients of the fiber material at the pump wavelength and excitation wavelength, respectively.τ is the mean energy lifetime of erbium ion. The saturation power of the signal and pump light is obtained from the final result of the experiment, and then the expression for the total power is obtained by the transformation of Eq. This experiment also considers the output power under the influence of the threshold, denoted as pout. This method is the numerical method used in this experiment and its main ability is used to simulate the effect of threshold in physical systems.Its significance is to ensure that the output power is less than the threshold power, and the resulting pout will be set to zero or a positive value.

$$p_{s,sat} = \frac{h\nu_s A_c}{\tau\Gamma_p(\sigma_{es} + \sigma_{as})} \quad (15)$$

$$p_{p,sat} = \frac{h\nu_p A_c}{\tau\Gamma_p(\sigma_{ep} + \sigma_{ap})} \quad (16)$$

$$p_{out} = \frac{(1-R_2)\sqrt{R_1}\cdot p_{p,sat}}{(1-R_1)\sqrt{R_2}+(1-R_2)\sqrt{R_1}} \cdot \left[\left(1 - e^{-\beta}\right)\frac{\nu_s}{\nu_p} \cdot \frac{p_p^{+}(0)+p_p^{-}(0)}{p_{p,sat}} - (N\Gamma_s\sigma_{as} + \alpha_S)L - \ln\left(\frac{1}{\sqrt{R1R2}}\right)\right] \quad (17)$$

$$p_{out,final} = [p_{out} - p_{th} + \mathrm{abs}\,(p_{out} - p_{th})] \quad (18)$$

2.4. Experimental parameters of fiber laser doped with Er^{3+}

Based on the rate equation, power equation, threshold power and output power, the main performance parameters of fiber laser doped with Er^{3+} are given in this paper. The experimental parameters are shown in Table 1.

Table 1. Experimental Setup of Erbium-doped Fiber Lasers

Symbol	Physical parameter	Numerical value	Unit
λ_{sp}	Central wavelength of pump light	980	nm
λ_s	Fiber laser center wavelength	1540	nm
τ	Mean energy lifetime of erbium ion	1.1×10^{-2}	s
σ_{ap}	Absorption cross section of pump light	1.04×10^{-20}	cm^2
σ_{ep}	Emission cross section of pump light	0	cm^2
σ_{as}	Absorption cross section of fiber laser	1.75×10^{-21}	cm^2
σ_{es}	Fibre laser emission cross section	0.83×10^{-21}	cm^2
A_c	The area of the core's cross-section	3.1416×10^{-6}	cm^2
N	Doping concentration of erbium ion in fiber core	5.535×10^{19}	cm^3
a_p	Loss of pump light by double clad fiber	2×10^{-5}	cm^{-1}
a_s	Laser loss of double clad fiber	4×10^{-6}	cm^{-1}
L	Length of double-clad optical fiber	10	m
Γ_p	Pump optical power fill factor	0.0024	
Γ_s	Laser power filling factor	0.82	
R_1	Reflectance of front cavity mirror	0.99	

R_2	Reflectance of posterior cavity mirror	0.035

In this experiment, a novel research architecture was used. This research architecture consists of numerical methods including physical and mathematical methods, Matlab tools to provide code with drawing and literature sources. This research architecture allows to experiment the output power of any kind of doped ions and draw the correct image. In this report the topic of research is fiber laser for Er^{3+}. The Er^{3+} is obtained by reviewing the literature and then the energy level structure, power propagation equation, pump power threshold, and fiber laser output power of this ion are analyzed and calculated based on numerical methods. Finally, the numerical analysis is coded using Matlab, the output results are reproduced in Matlab, and the final required graphs are plotted[10].

3. Results and Discussion

Fig. 3 illustrates the relationship between pump power and laser power. When the pump power crosses the lasing threshold, the laser will start to produce light. When the pump power in Figure 4 has not yet reached the required 10 W, at this time the laser has been generated but there is no antigeneration particle number reversal, which also reflects the fact that in the three-energy system, the particle number N3 of the upper energy system is not much larger than that of the system's lower energy system N2. After the pump optical power reaches 10 W, the particle number reverses, and the laser begins to be generated. The laser output power can reach 34.38 W and the slant efficiency is 38.20% when the pump power exceeds 100 W.

Fig. 4 shows the power of the pump power and the laser power for forward and reverse propagation respectively. The forward propagation strength of the pump light is shown in the picture to be gradually diminishing as it propagates forward, while the forward propagation power of the signal light is subsequently increased. At the same time the backward propagation power of the signal light is also decreasing. This is because the length of the waveguide causes changes in the pump power and signal power in the laser. When the pump light is continuously absorbed, the power of the pump light is getting smaller and smaller, which will cause the number of reversed particles to increase, and thus the intensity of the signal light will increase[11].

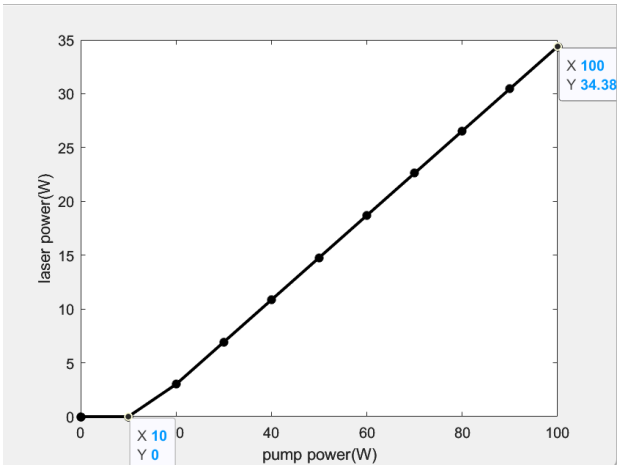


Fig 3. Pump power versus laser power

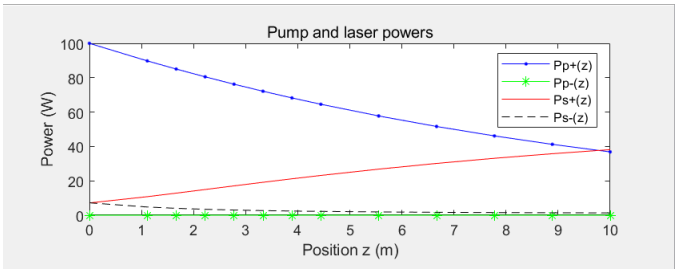


Fig 4. Pumping power laser power at different positions of power

4. Conclusion

This paper conducts in-depth research on the spectral characteristics of erbium ion crystal fibers, electron hopping in energy level systems, power transfer equations, pump power thresholds, Bragg grating reflectivity and the output power of fiber lasers doped with Er^{3+}. The novel erbium-doped fibre laser's reflectivity of its front and rear cavity mirrors, as well as the pump light's emission and signal light's absorption cross sections, were measured by looking through pertinent literature. Finally, based on the above parameters, a simulation experiment parameter table for the laser generated by the fiber laser doped with Er^{3+} was designed. This experiment uses numerical methods and Matlab models to simulate the laser generation of fiber laser doped with Er^{3+}. Experimental results show that when the pump power reaches 10W, the particle number will reverse. At this time, the fiber laser generates laser light. The laser intensity rises in tandem with the pump light output as it increases. The maximum laser power of 34.38W is reached when the pump optical power hits 100W and the tilt efficiency is 38.20% at this point. The experiment also explored the forward propagation power and reverse propagation power of pump light and signal light. According to experimental findings, the forward propagation power of the signal light increases as the forward propagation power of the pump light decreases during forward propagation. The pump light's reverse propagation will also lessen as the signal light's reverse propagation does, although the direction of propagation will essentially stay the same. In the future, new research directions can be to design and calculate erbium-doped fiber lasers in different media, analyze the output power and propagation rate in different media and select the most efficient erbium-doped fiber laser based on their respective tilt efficiencies.

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