

Design of 1450-1500nm Bismuth-doped Fiber Laser

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Abstract. With the rapid development of information technology, people's demand for the transmission capacity of fiber optic communication networks is increasing. How to broaden the bandwidth of communication systems has become one of the key issues in the field of communication. Researchers have found that the operating bandwidth of amplifiers mainly limits the bandwidth of communication systems. Although multiple solutions have been proposed and implemented to address this issue, there are still many gaps in the design of full-band multi wavelength-related light sources. By studying the three-level system of bismuth ions, the rate equation and power transfer equation of a bismuth ion doped fiber laser are simulated, and the pump power threshold and output power are calculated. Using MATLAB for simulation experiments, the relationship between laser power and pump power, as well as their variation with propagation distance, were ultimately obtained. The simulation results show that under 830 pump lights, the pump light threshold power is 10W. After reaching the threshold power, the pump light power and laser power have a linear relationship, and as the propagation distance increases, the pump light power gradually decreases and the laser power gradually increases. The analysis shows that the power generated by the signal light in this band meets the theoretical standards, which verifies the correctness of the scheme.

Keywords: Bismuth-doped; three-level system; rate equation; power transmission equation.

1. Introduction

The volume of information is growing exponentially due to the quick advancement of information technology, which raises the need for optical fiber communication capacity. A single optical fiber's transmission rate in the commercial communication network is currently 10 Tbit/s, while it is 100 Tbit/s in the laboratory. In the next 20 years, people's need for a single fiber transmission rate will approach 100–1000 Pbit/s due to the annual expansion of users' information capacity of 30%–40%[1]. There are three main solutions to improve the transmission bandwidth of communication systems: increasing the modulation rate of each optical channel wavelength. Reducing the channel spacing of wavelength division multiplexing systems to increase the number of channels; and increasing the total fiber optic transmission bandwidth[2].

In addition to creating additional dispersion compensation problems, the first approach—raising the modulation rate—will also cause electronic bottlenecks in the current electronic system. The second technique involves lowering the optical channel's wavelength interval to or below, which will result in four-wave mixing within the system. The third technique is to create appropriate broadband optical amplifiers and laser sources to increase the bandwidth of fiber optic communication[3]. Using the third method to expand transmission bandwidth and increase the number of channels is more advantageous. Therefore, expanding the gain bandwidth has become a problem to be solved in current fiber optic communication systems Ease of Use. Therefore, people's interest stems from the extensive applications provided by amplifiers and lasers in these wavelength bands[4-9].

Regarding the research on bismuth-doped laser amplifiers, the pioneering work by E. M. Dianov and colleagues in 2008 introduced the first bismuth-doped fiber amplifier. Subsequent studies in 2009 revealed limitations in gain compared to erbium-doped amplifiers, indicating a need for further research. By 2011, advances were made with Raman fiber laser-pumped amplifiers achieving a gain of 35 dB. In 2016, a novel bismuth-doped tunable fiber laser was developed, and separately a bismuth-doped amplifier for 1720 nm wavelength was reported. Finally, in 2017, a significant improvement

was seen with an erbium-bismuth co-doped amplifier exhibiting a high gain and a flat gain spectrum above 1600 nm. This amplifier performs really well spectrally[10].

In this paper, the energy level and transition structure of a bismuth-doped fiber amplifier are introduced. The rate and power transmission equations of the numerical model are solved in a three-level system. The relationship between the laser power and the pump power and the variation of these variables with the length is determined under certain conditions.

2. Methods and Models

2.1. Experimental Feasibility Verification

In this study, bismuth erbium co-doped quartz fiber was selected as the fiber type, and the center wavelength of the pump light was 830nm. Observing the absorption and radiation coefficients of the bismuth-doped fiber in Fig.1, it can be concluded that the dashed line represents the radiation spectrum, with a central wavelength of 1420nm. The study wavelength range of 1450-1500nm can be well covered by the 830nm pump light.

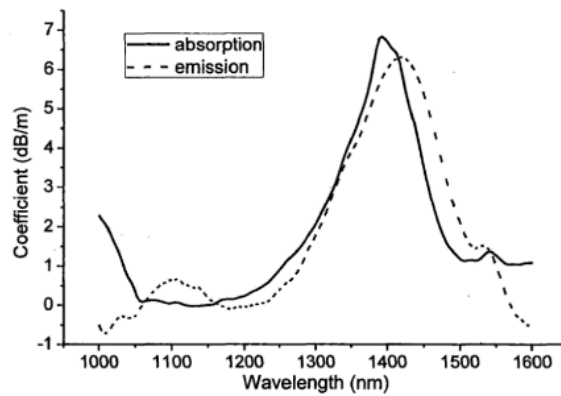


Fig 1. Radiation spectrum of bismuth doped fiber under 830 pump light[11]

2.2. Energy Level Systems and Electronic Transition Processes

The energy level system of bismuth ions can be summarized as a three-level structure in the Fig.2[12].

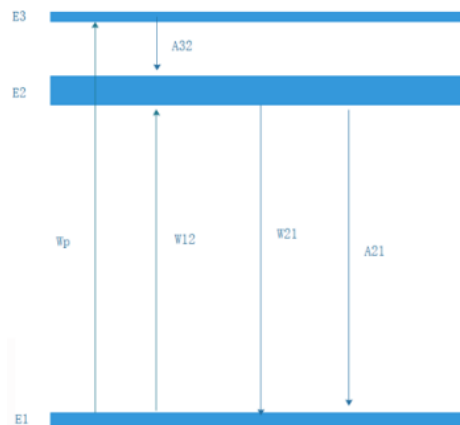


Fig 2. The energy level system of bismuth ions

Where E1 is the lower level (also the excited state level), E2 is the upper level, and E3 is the excited state level. $N(z)$ is the number of particles in each energy level. W_p , W_{12} , W_{21} , A_{32} , A_{21} represent the pump light absorption rate, signal light absorption rate, signal light excitation rate, non-radiative transition rate, and radiative transition probability, all in units of /s.

According to the energy level system diagram, the rate equation for bismuth ions can be obtained[13].

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

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

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

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

Where:

$$W_p(z) = \frac{\sigma_{13}P_p(z)}{h\nu_{13}A_{eff}} \quad W_{12}(z) = \frac{\sigma_{12}(v_{12})P_s(z)}{h\nu_{12}A_{eff}} \quad W_{21}(z) = \frac{\sigma_{21}(v_{21})P_s(z)}{h\nu_{21}A_{eff}} \quad A_{eff} = \pi r^2$$

Where σ_{13} represents the absorption cross section of the pumped light, σ_{12} represents the absorption cross section of the fiber laser, σ_{21} represents the emission cross section of the fiber laser, and r represents the fiber core radius.

2.3. Power Propagation Equations

An example diagram of the variation of pump power and laser power with propagation length is shown in Fig.3:

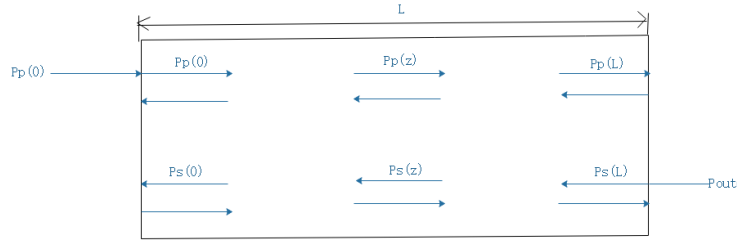


Fig 3. The distribution of pump power and laser power in space

Where P_p is the pump power and P_s is the laser power.

The power propagation equations describing pump and signal through the fiber are expressed as:

$$\frac{dP_p^+(z)}{dz} = \Gamma_p(-\sigma_p N_1(z) - \alpha_p)P_p^+(z) \quad (5)$$

$$\frac{dP_p^-(z)}{dz} = -\Gamma_p(-\sigma_p N_1(z) - \alpha_p)P_p^-(z) \quad (6)$$

$$\frac{dP_s^+(z)}{dz} = \Gamma_s(\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s)P_s^+(z) \quad (7)$$

$$\frac{dP_s^-(z)}{dz} = -\Gamma_s(\sigma_{21}N_2(z) - \sigma_{12}N_1(z) - \alpha_s)P_s^-(z) \quad (8)$$

Where $P_p^+(z)$ represents power of pump light propagating from left to right. $P_p^-(z)$ represents power of pump light propagating from right to left. $P_s^+(z)$ represents the power of laser light propagating from left to right. $P_s^-(z)$ represents the power of laser propagation from right to left. Generally, $\sigma_{12} = \sigma_{21}$. And the fiber material's loss coefficients at the excitation and pumping wavelengths are represented by α_p and α_s .

2.4. Calculation of Pump Power Threshold

The relationship between N_1, N_2, N_3 and N (formula(1-4)) can be obtained from the steady-state rate equation, and combined with the propagation equation(formulas(5-8)), the following can be obtained:

$$p_{th} = \frac{(N\Gamma_s\sigma_{12} + \alpha_s)L + \ln\left(\frac{1}{\sqrt{R_1R_2}}\right) \frac{v_p}{v_s} P_{s,sat}}{1 - \exp(-\beta)} \quad (9)$$

$$\beta = \frac{(\sigma_{31} + \sigma_{13})\Gamma_p}{(\sigma_{21} + \sigma_{12})\Gamma_s} [(N\Gamma_s\sigma_{12} + \alpha_s)L + \ln\left(\frac{1}{\sqrt{R_1R_2}}\right)] - (N\Gamma_p\sigma_{13} + \alpha_p)L \quad (10)$$

Where p_{th} is the threshold power. β is the laser parameter. And v_p and v_s are the frequencies of the pump and signal light, respectively.

2.5. Laser Output Power

According to the power propagation equation system in formulas (5-8) (organizing the equation system into ordinary differential equations and transforming it into a two-point boundary value problem).

The boundary conditions for a linear resonant cavity laser are:

$$P_p^+(0) = P_p^l \quad (11)$$

$$P_p^-(L) = P_p^r \quad (12)$$

$$P_s^+(0) = R_1 P_s^-(0) \quad (13)$$

$$P_s^-(L) = R_2 P_s^+(L) \quad (14)$$

$$P_s^+(L) = \frac{\sqrt{R_1} p_{p,sat}}{(1 - R_1)\sqrt{R_2} + (1 - R_2)\sqrt{R_1}} \left[(1 - \exp(-\beta)) \frac{V_s}{V_p} \cdot \frac{P_p^+(0) + P_p^-(L)}{p_{s,sat}} - (N\Gamma_s\sigma_{12} + \alpha_s)L - \ln\left(\frac{1}{\sqrt{R_1R_2}}\right) \right] \quad (15)$$

By combining formulas(11-15), it can be obtained that:

$$p_{p,sat} = \frac{h\nu_p A_c}{\tau\Gamma_p(\sigma_{13} + \sigma_{31})} \quad (16)$$

$$p_{s,sat} = \frac{h\nu_s A_c}{\tau\Gamma_s(\sigma_{12} + \sigma_{21})} \quad (17)$$

$$P_{out} = (1 - R_2)P_s^+(L) = \frac{(1 - R_2)\sqrt{R_1} p_{p,sat}}{(1 - R_1)\sqrt{R_2} + (1 - R_2)\sqrt{R_1}} \left[(1 - \exp(-\beta)) \frac{V_s}{V_p} \cdot \frac{P_p^+(0) + P_p^-(L)}{p_{s,sat}} - (N\Gamma_s\sigma_{12} + \alpha_s)L - \ln\left(\frac{1}{\sqrt{R_1R_2}}\right) \right] \quad (18)$$

$$p_{lout} = \frac{[p_{out} - p_{th} + \text{abs}(p_{out} - p_{th})]}{2} \quad (19)$$

Where $p_{p,sat}$ is the static power of the pump light, $p_{s,sat}$ is the static power of the laser light. P_{out} is the output power of the fiber laser and p_{lout} is the output power of a fiber laser with a threshold.

3. Results and Discussion

3.1. Parameter Table

The following Table.1 shows the parameters used in this study[3][13].

Table 1. Parameters

Symbol	Physical parameters	Value	Unit
λ_{sp}	Pump light center wavelength	830	nm
λ_s	Fiber laser center wavelength	1475	nm
τ	Average energy level lifetime on bismuth ions	725	us
σ_{ap}	Absorption cross-section of pumping light	1.3×10^{-20}	cm^2
σ_{ep}	Emission cross-section of pumping light	0.2×10^{-20}	cm^2
σ_{as}	Absorption cross-section of fiber laser	2.7×10^{-21}	cm^2
σ_{es}	Emission cross-section of fiber laser	1.5×10^{-20}	cm^2
A_c	The cross-sectional area of the fiber core	3.1416×10^{-6}	cm^2
N	Doping concentration of bismuth ions in the fiber core	5.535×10^{19}	cm^3
α_p	Loss of pump light in double clad optical fibers	2×10^{-5}	cm^{-1}
α_s	The loss of Double Clad Fiber on Laser	4×10^{-6}	cm^{-1}
L	The length of double clad optical fibers	1	m
Γ_p	Pump light power fill factor	0.0024	
Γ_s	Laser power filling factor	0.82	
R_1	Front cavity mirror reflectivity	0.99	
R_2	Rear cavity mirror reflectivity	0.35	

3.2. The relationship between laser power and pump power

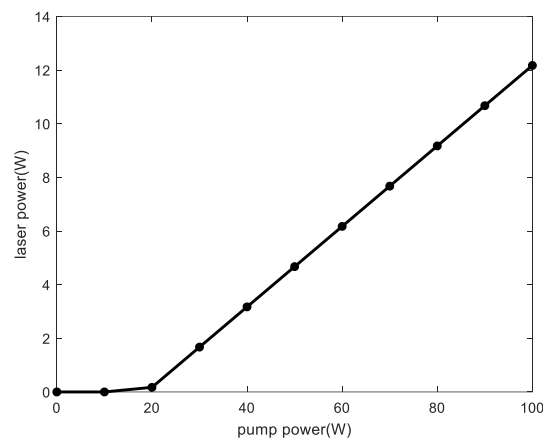


Fig 4. The relationship between laser power and pump power

As shown in Fig 4, through MATLAB simulation, it can be concluded that the threshold power of the pump light is 10W. After reaching the threshold power of the pump light, the laser power gradually increases, and the observation results can be summarized as a linear relationship. Between 10W-20W, the laser power increases slightly with the increase of pump power, with a slope of 0.017. Between 20W-100W, the laser power steadily increases with the increase of pump power, with a slope of approximately 0.15.

3.3. The relationship between laser power and pump power with length variation

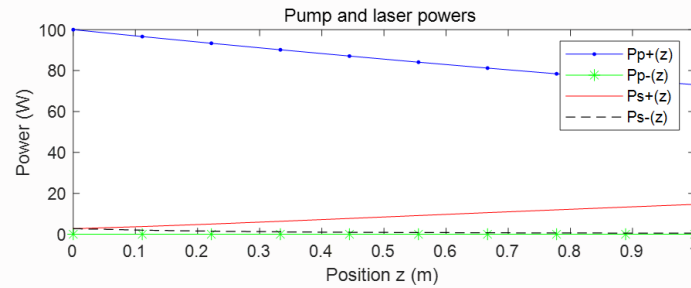


Fig 5. The relationship between laser power and pump power with length variation

Define power propagation from left to right as forward. As shown in the Fig.5, the forward propagation power of the pump light gradually decreases with the increase of transmission distance, with a large amplitude of change, decreasing from 100W to 73W. The backpropagation power of the pump light decreases with the increase of transmission distance, with a small change, from 2.7W to 0.5W. The forward propagation power of laser increases with the increase of transmission distance, with a significant change from 2.7W to 14.6W. The laser backpropagation power basically does not change with the increase of transmission distance, and the change amplitude is very small, approximately 0W.

4. Conclusion

This paper proposed a theoretical model for a bismuth-doped fiber amplifier operating in the 1450-1500nm wavelength range. Based on the energy level system of bismuth ions, rate equations, and power transfer equations, we developed a MATLAB program to investigate the variations in pump power and laser power for a fiber laser using a linear resonant cavity pumped with 830nm light.

Simulation results indicate that the signal light in the 1450-1500nm wavelength range exhibits favorable output power under 830nm pump light. This provides practical feasibility evidence for the design of a 1450-1500nm bismuth-doped fiber laser. The current study highlights potential applications and performance advantages of this design. Future research can build upon these simulation results, further refining the theoretical model and validating the accuracy and reliability of the simulations through experiments. In-depth investigations could involve optimizing waveguide structures, adjusting material parameters, and enhancing the laser fabrication process to improve performance and stability. This research aims to make a positive contribution to the field of laser communication technology.

The reflectivity of the front and rear cavity mirrors in the current study is chosen based on reasonable values under ideal conditions. Future studies should utilize the transfer matrix method to calculate the transmittance and reflectance from air vertically incident onto different periodic waveguides. This will aid in selecting optimal performance front and rear cavity mirrors.

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