

Design of the 1650-1700nm U band doped fiber laser

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Abstract. Increasing the power of thulium-doped fiber lasers is an important direction for the future development of fiber lasers. Thulium ions exhibit excellent optical properties in the U-band, making them valuable for research. This paper has established a modular design process for fiber lasers, investigating the energy level system of Thulium ions, electron transition processes, power propagation equations, pump power threshold, laser output power, and Bragg grating reflectance for specific wavelength photons. The reflectance of the front and rear cavity mirrors and Bragg grating was also redesigned. Finally, by establishing a physical model and employing numerical simulations, the relationship between laser onset power and pump light input power was determined: when the pump light input power reaches 10.1W, a population inversion occurs, and the fiber laser begins to generate laser output power. The laser output power linearly increases with the increase in pump light input power. When the pump light input power reaches 100W, the laser output power reaches its maximum value of 14.17W. This provides valuable data support for the laboratory preparation of 1650-1700nm thulium-doped fiber lasers.

Keywords: Thulium-Doped Fiber Laser ; Bragg Grating ; Matlab Simulation.

1. Introduction

Fiber laser is a kind of laser emitting device with optical fiber as the working medium, which converts the pump wavelength into a specific wavelength through the two processes of laser generation and amplification. The laser can be used in medical diagnosis and treatment, communication technology, manufacturing, and other fields, and has a wide application value. Compared with other fiber lasers, fiber doped laser has some obvious advantages: maintenance-free, wide wavelength range and easy tuning, high conversion efficiency, and strong anti-interference performance. With the increase of people's demand for communication capacity, high-speed optical communication systems not only need to make full use of the limited wavelength resources of the C wave, but also to expand to L band, S band, and wider and higher band range, and increasing the power of fiber laser with 1650nm ~1700nm fiber laser is an important direction of the development of fiber laser. The experiment has effectively proved that the 1700nm band laser can effectively enhance spatial coherence [1], but the discussion in this field is still insufficient, so the research of the doped fiber laser has a strong academic value and research space.

Since the 1960s, Snitzer et al. have proposed the idea of the application of optical fiber in laser [2], and soon developed the first optical fiber laser with Nd-doped glass fiber, which marks the beginning of a new development period for the development of laser research. Then, in the 1980s, Poole et al of the University of Southampton in the UK made the first silver-mode fiber, and completed the production of fiber laser, which started the practical stage of fiber laser [3]. Compared with other solid optical waveguide materials, optical glass fibers as optical waveguide devices have the maximum surface area to volume ratio and good beam transmission quality. In 1991, AT & T Bell Laboratory for research devoted to long-distance communications transmission, Promoted the coherent communication technology to a new height [4]. In the early 21st century, The research of fiber laser is more precise, On this basis, in 2003, Tian et al. studied the gain characteristics of L-band source dual-wavelength pump mixed fiber amplifier [5], By using a 1,051-nm laser and a tunable L-band light source, On the gain distribution of the fluoride TDF in the S band, Improved the degree

of exploration of the S-band region; In 2003, The Saint Louis Institute proposed a diode pump, as the report goes, in the optimal pump geometry, Pulse energy can be increased to as much as 20 times the ASE energy, Significantly improving the output efficiency of [6], In 2005, The institute again reported that a diode-pumped doped dual ELAD fiber amplifier, It provides a peak power of [7] of up to 5kW at a short pulse duration of 30nm and a repetition rate of 33.5kHz. In 2015, Wang Xiong et al. proposed a single fiber amplifier (TDFA), to realize the function of widely tuning the narrow-band hyper fluorescence source [7,8]. In 2022, The study of 1.7 μ m doped ultrafast fiber laser by Ziilin et al, Paved the way for the development of ultra-short-pulse laser sources, applied in the three-photon deep tissue imaging in, During that year, the study of 1.7 μ m all-fiber structure[9]. Gao et al, Provide ideas for the design of the 1.7 μ m ultrafast fiber laser, Add to the possibilities for fiber laser reference in a wider range of fields [10].

This paper aims to introduce the two-level structure of an ion-doped fiber laser, the electron transition rate equation and the power propagation equation based on the two-level structure. Then the research calculates the pump power and signal optical power with the forward transmission length, and designs the reflectivity of the front and rear cavities. Finally, the formula of laser output power is derived and then the relation of the laser initial power is solved. Finally, the design results of Bragg grating and the results of Matlab numerical simulation are shown.

2. Physics Models and Research Methods

2.1. Energy Level System and Electron Transition Rate Equation of Thulium Ions

2.1.1. Energy Level System

When Thulium ions absorb pump light of different wavelengths, they exhibit distinct energy level structures. Specifically, when pumped with light at a wavelength of 793nm, thulium ions manifest a four-level structure. However, the average lifetimes of the 3F_4 and 3H_5 levels are relatively short, leading to rapid spontaneous emission and transition to the 3H_4 level [11]. This process results in significant power loss for the pump light, substantially reducing the pump light power utilization efficiency. Therefore, in this study, we opt for a pump light with a wavelength of 1570nm for Thulium ion irradiation. Thulium ions exhibit a two-level structure when absorbing pump light at this wavelength, as illustrated in Fig. 1.

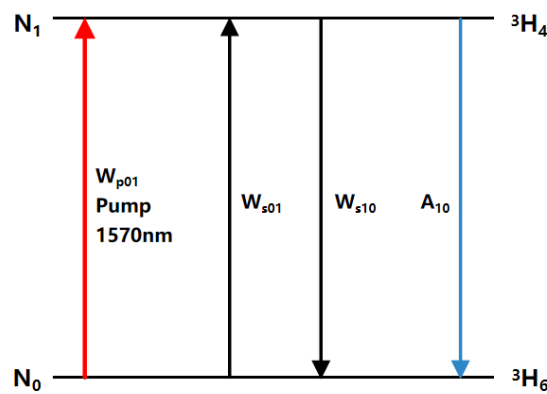


Fig 1. Energy Level System of Thulium ion

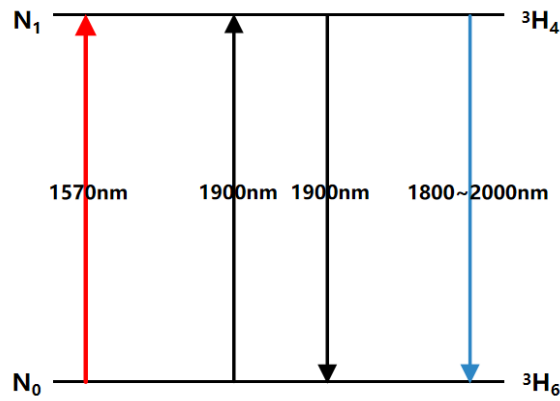


Fig 2. Schematic Diagram of Thulium Ion Two-Level Structure

2.1.2 Electron Transition Processes in the Two-Level Structure

As shown in Fig. 2, in the two-level structure exhibited by thulium ions when absorbing pump light, there are several electron transition processes:

Firstly, an electron in the 3H_6 level is excited by the 1570nm pump light and transitions to the 3H_4 level. Due to the broadness of the 3H_4 level, electrons in the 3H_4 level undergo spontaneous emission, transitioning back to 3H_6 and emitting photons with a spatial distribution in the range of 1800~2000nm. Some of these photons, perpendicular to the reflective mirror (i.e., the Bragg grating, which will be detailed later), undergo oscillation within the resonant cavity, generating stimulated emission.

Stimulated emission involves both the absorption process from 3H_6 to 3H_4 and the emission process from 3H_4 to 3H_6 . In the former, photons with a central wavelength of 1900nm are absorbed, while in the latter, simultaneous absorption results in the radial emission of twice the number of absorbed photons. With the excitation of pump light, an increasing number of electrons are excited from 3H_6 to 3H_4 , leading to a population inversion between the two energy levels, which is a necessary condition for laser formation.

2.1.3. Equation for Electron Transition Rate

The rate equations for the four electron transition processes depicted in Fig. 1 are as follows:

$$\frac{\partial N_0(z)}{\partial t} = -[W_{p01}(z) + W_{s01}(z)]N_0(z) + [W_{s10}(z) + A_{10}]N_1(z) \quad (1)$$

$$\frac{\partial N_1(z)}{\partial t} = [W_{p01}(z) + W_{s01}(z)]N_0(z) - [W_{s10}(z) + A_{10}]N_1(z) \quad (2)$$

$$N = N_0(z) + N_1(z) \quad (3)$$

In the above equations, N_0 and N_1 represent the concentrations of thulium ions in the 3H_6 and 3H_4 energy levels, respectively. N is the total number of thulium ions.

When the energy levels are in a steady state, exactly, at dynamic equilibrium, the left sides of equations (2) and (3) are both equal to 0. Where W_{p01} represents the pump light absorption rate, W_{s01} and W_{s10} denote the signal light absorption rate and stimulated emission rate, respectively. A_{10} is the spontaneous emission transition probability. The units for these four rates are all s^{-1} .

$W_{p01}(z)$, $W_{s01}(z)$, $W_{s10}(z)$ are expressed specifically as follows:

$$W_{p01}(z) = \frac{\sigma_p P_p(z)}{h\nu_p A_c} \quad (4)$$

$$W_{s01}(z) = \frac{\sigma_{as}(v_s)P_s(z)}{h\nu_s A_c} \quad (5)$$

$$W_{s10}(z) = \frac{\sigma_{es}(v_s)P_s(z)}{h\nu_s A_c} \quad (6)$$

In the above equations, σ_p represents the absorption cross-section of the pump light, σ_{as} is the absorption cross-section of the signal light, σ_{es} is the emission cross-section of the signal light, ν_p is the frequency of the pump light, ν_s is the frequency of the signal light, and A_c is the cross-sectional area of fiber core. The specific meanings and calculation formulas for $P_p(z)$ and $P_s(z)$ will be explained in the next section.

2.2. Power Propagation Equation

In order to quantitatively study the relationship between pump light power and laser output power, we will introduce the concept of power propagation. Fig. 3 illustrates the abstract structure of a Thulium-doped fiber laser. $P_p(0)$ represents the input power of the front-end pump light, and P_{out} represents the output power of the laser. L is the length of the resonant cavity. M1 and M2 are the front cavity mirror and the rear cavity mirror, both of which are Bragg gratings.

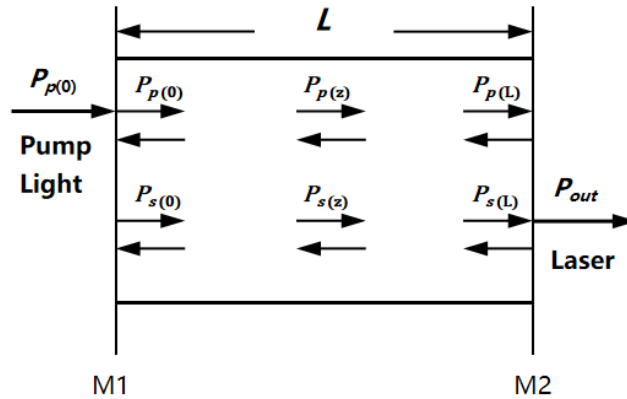


Fig 3. Abstract Structure of Fiber Laser

This paper designed the reflectivity of M1 and M2 for the signal light separately, and the design process and results will be explained in the following sections. Assuming the propagation direction from M1 to M2 as the positive direction, the power propagation equation is as follows:

$$\frac{dP_p^+(z)}{dz} = \Gamma_p [-\sigma_p N_0(z) - \alpha_p] P_p^+(z) \quad (7)$$

$$\frac{dP_p^-(z)}{dz} = -\Gamma_p [-\sigma_p N_0(z) - \alpha_p] P_p^-(z) \quad (8)$$

$$\frac{dP_s^+(z)}{dz} = \Gamma_s [\sigma_{es} N_1(z) - \sigma_{as} N_0(z) - \alpha_s] P_s^+(z) \quad (9)$$

$$\frac{dP_s^-(z)}{dz} = -\Gamma_s [\sigma_{es} N_1(z) - \sigma_{as} N_0(z) - \alpha_s] P_s^-(z) \quad (10)$$

In the above equation, Γ_p and Γ_s represent the pump power filling factor and laser power filling factor, respectively. α_p and α_s represent the losses of the fiber for pump power and laser power.

2.3. Calculation of Laser Output Power

In deriving the formula for laser output power, it is necessary to first determine two crucial parameters: threshold power p_{th} and laser parameters β .

$$p_{th} = \frac{(N\Gamma_s\sigma_{as} + \alpha_s)L + \ln\left(\frac{1}{\sqrt{R_1R_2}}\right)}{1 - \exp(-\beta)} \cdot \frac{v_p}{v_s} \cdot P_{s,sat} \quad (11)$$

$$\beta = \frac{\sigma_p\Gamma_p}{(\sigma_{as} + \sigma_{es})\Gamma_s} \left[(N\Gamma_s\sigma_{as} + \alpha_s) + \ln\left(\frac{1}{\sqrt{R_1R_2}}\right) \right] - (N\Gamma_p\sigma_p + \alpha_p) \quad (12)$$

$$P_{s,sat} = \frac{h\nu_s A_c}{\tau\Gamma_s(\sigma_{as} + \sigma_{es})} \quad (13)$$

$$P_{p,sat} = \frac{h\nu_p A_c}{\tau\Gamma_p\sigma_p} \quad (14)$$

In the above equation, R_1 and R_2 are the reflectivities of the front cavity mirror and the rear cavity mirror, respectively. $P_{p,sat}$ and $P_{s,sat}$ represent the saturated pump power and saturated laser output power. Through a series of derivations, the formula for the laser output power at the rear end can be obtained. To account for the impact of the threshold, this paper uses P_{lout} to represent the laser output power achievable when surpassing the threshold.

$$P_{out} = \frac{(1 - R_2)\sqrt{R_1}P_{p,sat}}{(1 - R_1)\sqrt{R_2} + (1 - R_2)\sqrt{R_1}} \cdot \left[(1 - e^{-\beta}) \cdot \frac{p_{th}}{P_{s,sat}} - (N\Gamma_s\sigma_{as} + \alpha_s) - \ln\left(\frac{1}{\sqrt{R_1R_2}}\right) \right] \quad (15)$$

$$P_{lout} = [P_{out} - p_{th} + |P_{out} - p_{th}|]/2 \quad (16)$$

Based on all the equations mentioned above, this paper can provide an assessment of all the major parameters required for the fiber laser. Table 1 presents a comprehensive compilation of all the experimentally measured data used in this study [11]:

Table 1. Values of numerical parameters

Symbol	Quantity	Value
λ_{sp}	In-band pump wavelength.	1570nm
λ_s	Signal wavelength.	1840nm
τ	Lifetime of level 3H_4	$6.5 \times 10^{-4}s$
σ_{ap}	Laser absorption cross section at 1570nm.	$7.8 \times 10^{-25}m^2$
σ_{as}	Laser absorption cross section at signal wavelength 1840nm.	$0.65 \times 10^{-25}m^2$
σ_{es}	Laser emission cross section at signal wavelength 1840nm	$3.7 \times 10^{-25}m^2$
A_c	Cross sectional area of the core.	$3.01 \times 10^{-11}m^2$
N	Total Thulium Ion Doping Concentration	$8.4 \times 10^{25}m^{-3}$
α_p	Intrinsic absorption at the pump wavelength 1570nm.	$1.2 \times 10^{-2}m^{-1}$
α_s	Intrinsic absorption at the signal wavelength.	$2.3 \times 10^{-3}m^{-1}$
L	Fiber Length	5m
Γ_p	Pump Power Filling Factor	0.0024
Γ_s	Laser Power Filling Factor	0.82

2.4. Principles of Bragg Grating Design and Derivation of Transfer Matrix

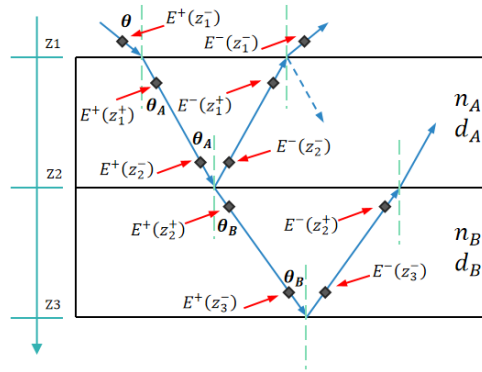


Fig 4. Schematic Diagram of Bragg Grating

A Bragg grating is a periodic arrangement of two materials with different refractive indices along one direction and can be considered as a one-dimensional photonic crystal. If the incident wavelength falls within the photonic crystal's bandgap, the incoming light will be reflected; otherwise, it will be transmitted. Fig. 4 illustrates a double-layered structure of a Bragg grating, composed of two materials with refractive indices n_A and n_B , and layer thicknesses d_A and d_B .

When the light propagates in the direction of the left arrow in the diagram, the electric field is positive. Assuming the region above the interface Z is denoted as Z^+ and below as Z^- , the electric field relationship can be expressed as follows:

$$E(z_i) = E^+(z_i^+) + E^-(z_i^+) = E^+(z_i^-) + E^-(z_i^-) \quad (17)$$

Through the phase difference, we can connect the expressions for the electric field at each interface:

$$\delta_A = \frac{2\pi}{\lambda} \cdot \frac{n_A d_A}{\cos \theta_A} \quad (18)$$

$$\eta_A = n_A \cos \theta_A \sqrt{\epsilon_0 / \mu_0} \quad (19)$$

$$E^+(z_2^-) = E^+(z_1^+) e^{-i\delta_A} \quad (20)$$

$$\mathbf{H} = \frac{n}{Z_0} \bar{\mathbf{k}} \times \mathbf{E} \quad (21)$$

Then, establishing a connection between the electric field and the magnetic field and presenting it in matrix form:

$$\begin{bmatrix} E(z_1) \\ H(z_1) \end{bmatrix} = \begin{bmatrix} \cos \delta_A & \frac{-i \sin \delta_A}{\eta_A} \\ -i \eta_A \sin \delta_A & \cos \delta_A \end{bmatrix} \begin{bmatrix} E(z_2) \\ H(z_2) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} E(z_2) \\ H(z_2) \end{bmatrix} \quad (22)$$

$$r = \frac{E^-(z_1^-)}{E(z_1)} = \frac{A\eta_A + B\eta_A^2 - C - D\eta_A}{A\eta_A + B\eta_A^2 + C + D\eta_A} \quad (23)$$

$$R = r \cdot r^* \quad (24)$$

In this study, the four parameters A , B , C , and D in the complex matrix of the above equation were denoted. Finally, the expression was obtained by solving according to the reflectance formula. If r is a complex number, r^* represents the complex conjugate of r .

2.5. Research Methodology

This paper employs a numerical simulation approach, combining physical theory modeling, formula derivation, and Matlab code, to establish a modular design process for fiber lasers. This process is theoretically applicable to any rare-earth ion that can be doped, as long as reliable numerical parameter values can be obtained.

3. Experimental Results and Discussion

3.1. Design Results of Bragg Grating

Through the Bragg grating design process explained in Section 2.4, this paper used Matlab code to fit the reflectance curve for the 1675nm wavelength signal light. The reflectivities R_1 and R_2 at specific wavelengths were obtained, as shown in Fig. 5 and 6. In particular, R_1 has a reflectance of 0.0057 at 1570nm, close to complete transmission, to maximize the transmission of pump light into the resonant cavity. At 1675nm, the reflectance is as high as 0.99 to prevent signal light from transmitting through the front cavity mirror. Meanwhile, R_2 has a reflectance of only 0.035 at 1675nm to facilitate better output of the signal light. The parameters used for the design of R_1 and R_2 are summarized in Table 2 and Table 3.

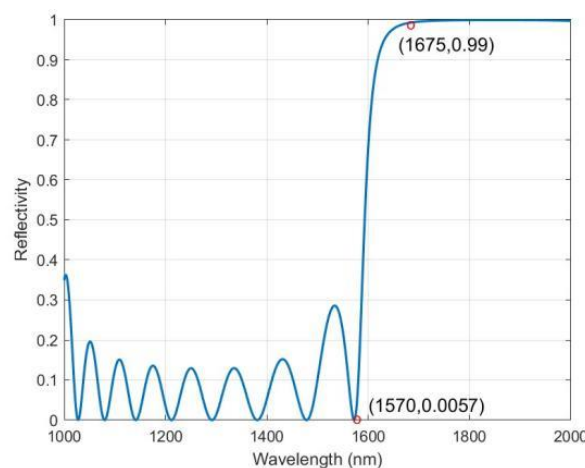


Fig 5. Relationship between Front Cavity Mirror Reflectance and Wavelength

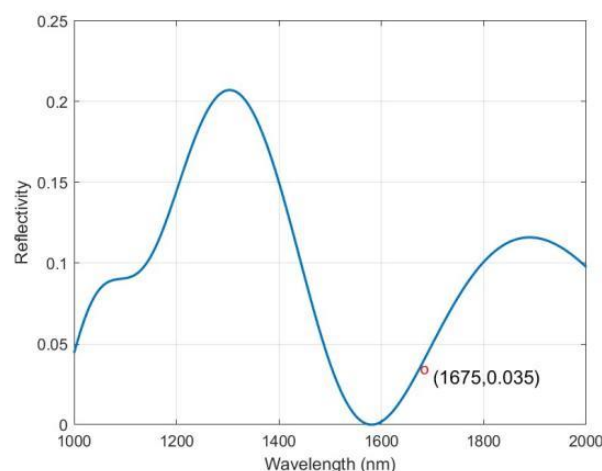


Fig 6. Relationship between Rear Cavity Mirror Reflectance and Wavelength

Table 2. Various Design Parameters of R_1

Symbol	Quantity	Value
n	Number of Periods	10
n_a	Refractive Index of the First Layer of Dielectric	1.46
n_b	Refractive Index of the Second Layer of Dielectric	2.35
d_a	Thickness of the First Layer of Dielectric	200nm
d_b	Thickness of the Second Layer of Dielectric	262nm

Table 3. Various Design Parameters of R_2

Symbol	Quantity	Value
n	Number of Periods	4
n_a	Refractive Index of the First Layer of Dielectric	1.45
n_b	Refractive Index of the Second Layer of Dielectric	1.31
d_a	Thickness of the First Layer of Dielectric	257nm
d_b	Thickness of the Second Layer of Dielectric	167nm

The relationship between pump light input power and laser output power is shown in Fig 7. When the pump light power is below 10.1W, the laser output power is 0, indicating that the laser power threshold has not been reached. At this point, laser generation has already occurred within the resonant cavity, but the population inversion of upper and lower energy levels has not taken place. However, when the pump light input power exceeds 10.1W, the population inversion of upper and lower energy levels occurs, forming the necessary conditions for laser emission. The laser output power starts to linearly increase from 0 with the increase of pump light input power. When the pump light input power reaches 100W, the laser output power is 14.17W.

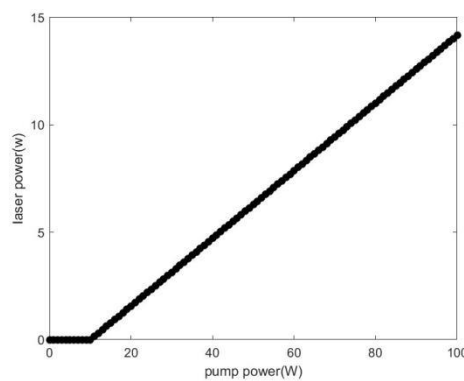


Fig 7. Relationship between Laser Output Power and Pump Light Input Power

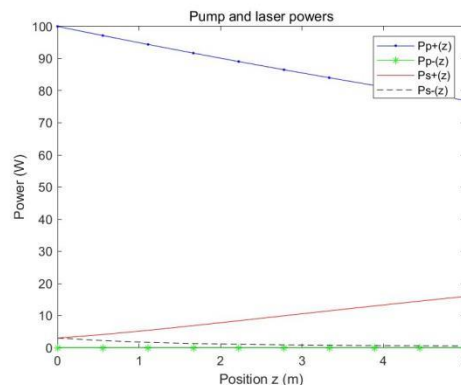


Fig 8. Relationship between Pump Light Power, Signal Light Power, and Resonant Cavity Position

Fig. 8 illustrates the forward propagating pump light power $P_p^+(z)$, backward propagating pump light power $P_p^-(z)$, forward propagating signal light power $P_s^+(z)$, and backward propagating signal light power $P_s^-(z)$. From the graph, it can be observed that the forward propagating pump light power gradually decreases and reaches 76.98W at 5m. Meanwhile, the forward propagating signal light power gradually increases and reaches 15.98W at 5m. This is because, during forward propagation of pump light, particles in the ground state continuously absorb it. As more and more particles are excited to higher energy levels, the spontaneous emission of particles in the excited state will also enhance, thereby increasing the intensity of the signal light.

4. Conclusion

This paper has established a modular design process for fiber lasers, investigating the energy level system of thulium ions and the associated electron transition processes, power propagation equations, pump power threshold, laser output power, and Bragg grating reflectance for specific wavelength photons. Physical parameters of the thulium-doped fiber laser were collected. Ultimately, based on these parameters, a new thulium-doped fiber laser design was proposed.

The experimental results indicate that when the pump light input power reaches 10.1W, population inversion occurs, and the fiber laser begins to generate laser output power. The laser output power linearly increases with the increase in pump light input power. When the pump light input power reaches 100W, the laser output power reaches its maximum value of 14.17W. This paper also explores the forward and backward propagating power of pump light and signal light.

The experiments demonstrate that the forward propagating power of pump light gradually decreases, while the forward propagating power of signal light gradually increases. The backward propagating power of pump light is essentially zero, and the backward propagating power of signal light shows a slight increase. The results were finally fitted using Matlab. To enhance the utilization efficiency of the pump light input power, this paper also redesigned the reflectance of the front and rear cavity mirrors and Bragg grating.

In the future, this research can be applied to design fiber lasers for different wavelength ranges and with different doping ions. Of course, optimizing the design to continually enhance the performance of the designed fiber laser will remain a focus of our future research efforts.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

- [1] Kang Shuai. Study on high power wavelength tunable fiber laser. Beijing Jiaotong University, 2022.
- [2] Koester C J, Snitzer E. Amplification in a Fiber Laser. *Applied Optics*, 1964,3(10): 1182-1186.
- [3] Poole C D. Statistical treatment of polarization dispersion in single-mode fiber. *Optics Letters*, 1988,13(8): 687-689.
- [4] Park Y K. 1.7-Gb/s coherent optical transmission field trial: *Optical Fiber Communication*, San Diego, California: Optica Publishing Group, 1991.
- [5] Tanabe S, Tamaoka T. Gain characteristics of Tm-doped fiber amplifier by dual-wavelength pumping with tunable L-band source: *Optical Fiber Communications Conference*, Anaheim, California: Optica Publishing Group, 2002.
- [6] Eichhorn M. High-gain Tm-doped fluoride fiber amplifier[J]. *Optics Letters*, 2005,30(5): 456-458.
- [7] Eichhorn M. High-peak-power Tm-doped double-clad fluoride fiber amplifier[J]. *Optics Letters*, 2005,30(24): 3329-3331.
- [8] Wang X, Jin X, Zhou P, et al. High power, widely tunable, narrowband superfluorescent source at 2μm based on a monolithic Tm-doped fiber amplifier[J]. *Optics Express*, 2015,23(3): 3382-3389.

- [8] Zhang L, Zhang J, Sheng Q, et al. Intracavity Tandemly-Pumped and Gain-Switched Tm-doped Fiber Laser at 1.7 μ m. *Journal of Lightwave Technology*, 2022, 40(13): 4373-4378.
- [9] LIN Z, CHEN J, LI T, et al. 1.7 μ m figure-9 Tm-doped ultrafast fiber laser[J]. *Optics Express*, 2022, 30(18): 32347-32354.
- [10] KHAMIS M A, ENNSER K. Theoretical Model of a Thulium-Doped Fiber Amplifier Pumped at 1570 nm and 793 nm in the Presence of Cross Relaxation[J]. *Journal of Lightwave Technology*, 2016, 34(24): 5675-5681.