Optimization and Application of High Power Thulium-Doped Fiber Laser

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Abstract. In recent years, with the continuous progress of laser technology, fiber laser has been developed rapidly. Compared with the traditional laser, fiber laser has the advantages of good beam quality, small volume, easy integration, high luminous efficiency, strong anti-interference ability and good heat dissipation. As a kind of fiber laser, thulium doped fiber laser not only inherits the above advantages, but also has the rich energy level structure and spectral characteristics of thulium ion, which determines that thulium doped fiber laser plays an important role in the research field of long wavelength fiber laser. This paper discusses the influence of the length and concentration of doped fiber on the output of high power laser system. For a given laser system, all parameters have an optimal value. In order to make the high power thulium doped fiber laser work in the best state, we need to carefully select these parameters. Based on the rate equation, the relationship between the dopant concentration and the length of the optical fiber is given in theory. The experimental results show that the optimal fiber length is different for different pump power. The higher the pump power, the larger the optimal fiber length. The experimental results have guiding significance for the manufacturing technology of high power fiber lasers.

1. Introduction
Fiber laser has a long history. In 1987, the erbium-doped laser amplifier was jointly developed by the University of Southampton in England and Bell laboratory in the United States, which is a sign of the development of fiber lasers in the communication era. In the 1990s, in order to improve the output power of the laser, people invented the double clad fiber technology, which makes the power of the fiber laser get a great improvement. Fiber laser has many advantages[1]. Compared with other lasers, fiber laser has the advantages of high stability, simple integration, good beam quality, small volume, low threshold, high efficiency, tunable, narrow linewidth, strong anti noise ability, good heat dissipation and high cost performance[2]. Therefore, the fiber laser is welcomed by the communication industry and has become one of the focuses of laser technology research in various countries. The basic conditions of laser generation can be explained from physics: atoms have energy levels[3]. When the number of particles at high energy level is more than that at low energy level, the number of particles will be reversed and photons will be emitted. If a stable laser oscillation can be formed, the laser will be output[4]. It is usually composed of laser gain medium, pump source and optical resonator. Although high power thulium doped fiber laser is different from other types of fiber laser in morphology, material and internal structure, its basic working principle is the same, which is
composed of pump source, gain medium and resonator[5]. Due to the good optical properties of laser, laser is completely different from ordinary light. Therefore, laser is widely used in various fields and has a profound impact on the development and reform of science, technology, economy and society. Laser, atomic energy, semiconductor and computer are regarded as the four major modern inventions in the 20th century, which play an important role in the progress and development of human society. Now, laser is expanding its application fields in both breadth and depth, and has gradually penetrated into various fields of the national economy. In the field of equipment manufacturing, high-power laser equipment plays an important role in cutting, welding, measuring, marking and other aspects of high-end equipment manufacturing such as aviation, aerospace, automobile, high-speed rail, ships and other high-end equipment manufacturing fields[6]. High power thulium doped fiber laser needs more energy pumping. Due to the rich energy levels of thulium atom, a variety of pump light can be selected to provide energy for thulium doped fiber, which has high conversion efficiency and good stability. Because the whole laser is mainly composed of thulium doped fiber and pump laser, and the fiber has good flexibility and can be bent and coiled, compared with other lasers, thulium doped fiber laser occupies a small space, compact structure and convenient maintenance. The main material of high power thulium doped fiber laser is thulium doped fiber, and the main component is silica. It has strong tolerance to dust, acid and alkali, water vapor, jitter and electromagnetic field in the environment. As long as it is not folded, it will hardly affect the performance of the laser, and can adapt to the harsh working environment. It has great advantages in industrial application. Therefore, high power thulium doped fiber laser has become a hot research technology.

2. Rate Equation of Laser

There are more and more kinds of lasers, and the output power is increasing. At present, according to the working medium, lasers mainly include gas lasers, solid-state lasers, semiconductor lasers and fuel lasers, etc. However, no matter what kind of laser, their working principle is the same, the main difference is that the working medium is not the same. The rare earth ions in the doped fiber are used as the gain medium in the rare earth doped fiber laser, which is mainly composed of pump source, doped fiber, coupler, mirror and some optical devices. The pump light generated by the pump source is coupled into thulium doped fiber. After thulium ion absorbs the pump light, the number of particles is flipped, and then the laser is emitted. After the laser is reflected back and forth in the resonant cavity, the amplification is formed, and finally the laser output is formed. Rare earth ions commonly used in doped fiber include thulium, Er, etc. Sometimes laser materials are made by doping several ions together. Of course, the energy levels of different ions are different, so when the ions absorb the pump light of different wavelengths, the laser wavelengths are also different. For a laser system, thulium doped fiber is undoubtedly the most important optical device, its quality can directly determine the quality of the laser output beam. In order to simplify the energy level diagram of thulium atom, we can regard the energy level of thulium atom as a three-level system, which is simpler to discuss and easier to see the transition process of thulium atom. Energy level diagram is as shown in figure 1.

![Figure 1. Simple energy level of Tm³⁺.](image-url)

According to Einstein's theory, for a three-level atomic system, the relationship between the number of particles at each level and time is
\[
\frac{dN_3}{dt} = W_{13}N_1 - K_{3212}N_3N_1 + K_{2123}N_2^2 - \frac{N_3}{\tau_3}
\]
(1)

\[
\frac{dN_2}{dt} = W_{12}N_1 - W_{21}N_2 + 2K_{3212}N_3N_1 - 2K_{2123}N_2^2 + C_{32}\frac{N_3}{\tau_3} - \frac{N_2}{\tau_2}
\]
(2)

\[
\frac{dN_1}{dt} = W_{21}N_2 - W_{12}N_1 - W_{13}N_1 - K_{3212}N_3N_1 + K_{2123}N_2^2 + C_{31}\frac{N_3}{\tau_3} + \frac{N_2}{\tau_2}
\]
(3)

In the above formula, the meaning of each parameter is as follows, \( N_i \) is the number of particles in the \( i \) energy level, \( \tau_i \) is the lifetime of the \( i \) level, \( C_{ij} \) is the spontaneous emission ratio from \( i \) energy level to \( j \) energy level, \( K_{ijmn} \) is the \( i \) energy level to \( j \) level and \( m \) level to \( n \) level cross relaxation, \( W_{12} \) represents the laser stimulated absorption coefficient, \( W_{13} \) represents the pump absorption coefficient, \( W_{21} \) represents the laser stimulated emission coefficient.

### 3. Laser Structure

The structure of laser is various, but no matter what the structure of laser is, the resonator is necessary. For the gain medium, the doping concentration can greatly affect the radiation quality of gain medium. The doping concentration not only directly determines the efficiency of the laser, but also affects the central wavelength of the laser output light. In doped fiber, the effective absorption coefficient of inner layer is an important parameter. From the structure of the laser, one of the simplest lasers is Fabry Perot cavity (F-P cavity), which is the most used type of resonator in the laser structure. Its structure is also very simple. There are two mirrors at both ends of the laser to form an oscillation cavity. F-P cavity is shown in figure 2.

![F-P cavity for fiber laser.](image)

**Figure 2.** F-P cavity for fiber laser.

In the F-P cavity, the mirror near the pump section (front mirror) has the characteristics of high transmission and low reflection to the pump wavelength. The cavity mirror far away from the pump end not only needs to feed back the laser to form oscillation, but also meets the laser coupling output. Therefore, the back cavity mirror is partially reflective. The other is a fiber Bragg grating (FBG) resonator, which uses FBG as cavity mirror. FBG has high transmittance for pump light, therefore, it is very suitable for the fiber pump as the first high light mirror. It is important to note that the reflectivity of FBG is not a constant value, but is related to the wavelength of the light reflected. If the wavelength is closer to the central wavelength of FBG, the reflectivity will be higher. Therefore, only the light close to the central wavelength can be reflected back by the grating, so as to form an oscillating light wave in the resonator. The structure of the laser composed of FBG is shown in figure 3.
One of the advantages of using fiber Bragg grating as the resonator of fiber laser is that this method can eliminate the coupling loss between the cavity mirror and the fiber, and realize the all fiber integration of the laser. This integration makes the structure of the laser simpler, and the adjustment of the resonator does not exist, which greatly improves the reliability of the fiber laser. On the other hand, using fiber Bragg grating as the resonator of fiber laser, we can also use fiber Bragg grating to select frequency, so as to obtain narrow linewidth laser output with specific frequency.

4. Power of Laser Cavity

For thulium doped fiber laser, due to the low coupling efficiency of pump beam, the output power is also relatively small, which is not enough for many applications. Therefore, how to improve the output power of thulium doped fiber laser and get high-power laser output has become one of the research hotspots of fiber laser. Because the fiber length, doping concentration and pump power have an important impact on the output power of the laser, in order to improve the output power of the laser, people put forward a variety of methods to improve the laser power. Let's analyze the pump energy problem in high power lasers.

If it is set \( G \) as the magnification of single pass, \( \alpha_{\text{in}} \) is the loss in the cavity, then the \( G \) expression is

\[
G = \exp\left(\int_0^L \sigma_s [N_2(z) - N_1(z)] dz\right) \tag{4}
\]

Where, \( \sigma_s \) is the radiative transition cross section, \( N_1 \) is the number of lower level particles, \( N_2 \) is the number of particles in the upper level.

The threshold problem of laser is analyzed below. Let the fiber length be \( L \), the reflectivity of the two mirrors is \( R_1 \) and \( R_2 \), at this time, the threshold condition of the laser is:

\[
G^2 R_1 R_2 \exp(-2\alpha_{\text{in}} L) = 1 \tag{5}
\]

The pump power is obtained as follows,

\[
P_{\text{pump}}(0) = \frac{\alpha_L}{1 - \exp(-\alpha_p L)} \frac{\alpha_p}{\alpha_s} P_s^p \tag{6}
\]

Here, \( \alpha_p \) is the absorption coefficient of the pump wavelength, \( \alpha_s \) is the absorption coefficient of the signal wavelength, \( P_s^p \) is saturation power, \( \alpha \) is the total absorption coefficient.

5. Experimental Results

High power LD diode array is usually used as pump source for thulium doped fiber laser. The gain medium of the fiber laser is doped fiber. The doped fiber is placed between two cavity mirrors, and the pump light is coupled into the doped fiber from the front cavity mirror of the fiber laser. The cavity consists of two dichroic mirrors. We can directly coat the end of the fiber, or we can use the fiber grating or directional coupler to form an optical resonator. In order to make full use of the pump light and obtain high power laser output, it is required that the front cavity mirror should have high transmittance and low reflection to the pump light, and high reflection to the signal light, and the rear
cavity mirror should have a high reflection on the pump light and partly pass through the signal light. However, in the actual process, it is difficult for the rear cavity mirror to meet the transmission and reflection requirements of laser and pump light at the same time, which inevitably results in a small amount of pump light output from the rear cavity mirror. When the pump light passes through the doped fiber, it will be absorbed by the rare earth ions in the fiber core. The rare earth ions which absorb photon energy will jump to the upper level of laser and form a population inversion between the upper and lower energy levels. The inversion of the number of particles in the form of spontaneous emission or stimulated radiation and other forms of transition to the lower level of the laser, and the release of photons, photons in the cavity after many times of oscillation and amplification, will output laser. The power distribution in the fiber doped with different concentrations is shown in figure 4.

![Figure 4](image4.png)

**Figure 4.** Distribution of pump power along the length of optical fiber, curve A denotes $N_1=2.5 \times 10^{25}/m^3$, curve B denotes $N_2=5.0 \times 10^{25}/m^3$.

From figure 4, we can see that the curve of the fiber with high doping concentration drops faster because it absorbs more energy, while the fiber with low doping concentration has slower absorption energy, so the curve decreases more slowly.

Next, we will study the optimal length of optical fiber under different pump power. It is shown in figure 5.

![Figure 5](image5.png)

**Figure 5.** The fiber length with pump power in different pump power, curve C denotes pump 15W, curve D denotes pump 6W.
From figure 5, we find that the optimal length of the fiber varies with the pump power. At high pump power, the optimal length of optical fiber is longer, and at low pump power, the optimal length of optical fiber is also smaller. This shows that the optical fiber has a certain optimal length.

6. Conclusion
The gain fiber doped with rare earth elements is studied in this paper. Rare earth ions in doped fiber laser are used as gain medium. Thulium doped fiber laser has rich energy level structure, which leads to a wide absorption spectrum and emission spectrum. Therefore, we can use different light sources to pump and obtain different laser output. The energy level structure and pumping mode of thulium doped fiber laser are theoretically analyzed. The characteristics of fiber laser are simulated by using rate equation method. The effects of Tm$^{3+}$ doping concentration, fiber length and laser output power are analyzed. The experimental results show that the gain fiber with high doping concentration can absorb pump energy faster. On the other hand, under different pump power conditions, the gain fiber has an optimal length, and the high-power pump condition corresponds to a longer optimal fiber length. The experimental results are of great significance for the development of high power fiber laser technology.

Acknowledgements
This paper is sponsored by the National Natural Science Foundation of China (No. 61875014), the Academic Research Projects of Beijing Union University(No. JZ10202004), the Academic Research Projects of Beijing Union University(No. ZK70202007), and “New Start” Academic Research Projects of Beijing Union University(No. ZK10201705).

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