Research on key technologies for 2μm band of thulium-doped fiber laser

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Abstract. The gain material of 2μm wavelength thulium-doped fiber laser is a thulium-doped fiber doped with rare earth element thulium. Rare earth doped optical fiber as gain medium is the basic structure of optical fiber laser. This type of laser is mainly composed of pump source, coupler, gain optical fiber doped with rare earth elements, cavity and other optical devices. The pump source is generally a combination of one or several high-power laser diodes. The light emitted by the pump source enters the gain optical fiber doped with rare earth elements through a certain pumping mode. The inversion of the number of particles occurs when the doped optical fibers absorb photons, and then the light waves stimulated from the doped optical fibers are emitted by the laser after the oscillation. Since the connection structure and parameters between optical fibers and optical components can be maintained stable over a long period of time, thulium-doped lasers do not need to be maintained regularly and are based on output power. They have smaller volume and weight, lighter weight and longer life than solid-state lasers. However, in general, the power of a 2μm wavelength thulium-doped fiber laser is not too high, while a high-power 2μm wavelength thulium-doped fiber laser can meet people's needs and play a greater role. Therefore, improving the power of 2μm wavelength thulium-doped fiber laser is an important direction for the development of thulium-doped fiber laser. The energy level structure of thulium ion is analyzed, the doping concentration of thulium ion is studied, and the method to increase the power of a 2μm wavelength thulium-doped fiber laser is given.

1. Introduction
In recent years, with the rapid growth of output power of optical fiber lasers, great breakthroughs have been made in the research of high-power optical fiber lasers. Fiber laser is based on optical fiber. It has a series of advantages, such as high efficiency, compact, narrow line width, low threshold, good stability, high cost-performance and tunable [1]. It is a new direction for the development of optical communication technology. Rare earth doped optical fiber is the gain medium of optical fiber laser. Because of the rich energy level structure of rare earth ions, there are many energy level transition modes from ultraviolet band to infrared band. So the laser output of the laser can be obtained by using different doped ions. Rare earth ions have a wider energy level and a wider glass fiber spectrum, so a laser with a wider tuning range can be achieved by inserting an appropriate wavelength selector. From the structure of the optical fiber, the diameter of the optical fiber is relatively small, which makes it
very easy to form a larger energy density at the fiber core position [2-4]. In addition, the surface-to-volume ratio of the optical fiber is also very high, which is very helpful for the heat dissipation of the optical fiber laser. It does not cause thermal damage to the gain medium at very high power, which is an advantage of a fiber laser over a solid-state laser. Fiber laser has a high efficiency of energy conversion. Energy conversion efficiency is high, which can reduce the operating cost of a fiber laser. Rare earth doped optical fibers are attractive for applications such as optical lasers, amplifiers and sensors because of their good temperature stability and heat dissipation performance. It is characterized by cylindrical waveguide structure, small core diameter, easy to achieve high-density pumping, low lasing threshold, good thermal performance, and the integration of transmission and active optical fibers. Therefore, optical fiber lasers are the basis for all-optical communication. With the development of integrated optical and optical communication, micro-fiber lasers and amplifiers are required. Rare earth doped optical amplifier can directly amplify the optical signal, which is conducive to large-capacity, long-distance communication and make greater development of optical communication. Among various rare earth doped fibers, thulium doped fibers have special significance [5,6]. A fiber laser consisting of thulium-doped fibers has a wide wavelength range capable of emitting lasers with a wavelength of 1.6μm to 2μm. It also contains water absorption peaks near 2μm. However, 2μm laser has a shallow penetration depth, a small wound and a good hemostatic performance. The advantages of other lasers are also compatible, and the 2μm wavelength is within the safe wavelength range of the human eye. Therefore, 2μm thulium-doped fiber laser has attracted much attention.

2. Rare earth ion doped fiber laser

Thulium doped fiber laser has a wide range of applications. Compared with previous solid-state lasers, thulium-doped fiber lasers have some obvious advantages. The main development direction of thulium-doped optical fiber lasers is medical treatment, laser weapons, advanced manufacturing technology, optical communication and remote sensing for human eye safety.

The beam quality of a thulium-doped fiber laser is good. The quality of the laser beam output from a fiber laser is determined by the structure of the internal waveguide of the fiber, which does not change with temperature. Fiber laser can easily obtain single longitudinal mode laser output, and it has the advantages of good monochrome, high stability and directionality. As thulium-doped fiber lasers generally use a semiconductor laser as the pump source, thulium-doped fiber as the gain medium, and use common optical devices such as fiber grating, coupler, etc. Therefore, the mechanical and optical path of a thulium-doped optical fiber laser does not need to be adjusted. The whole system is compact and easy to integrate. However, thulium-doped fiber laser does not contain all kinds of electronic components such as electronic circuits, so thulium-doped fiber laser also has a strong anti-electromagnetic interference ability. From the point of view of light transmission, optical fiber laser is a waveguide type of cavity. Laser transmission occurs in optical fibers. Therefore, a thulium-doped fiber laser is actually a Fabry-Perot cavity structure, as shown in figure 1.

![Figure 1. The fiber laser structure.](image-url)
For a fiber laser, the gain fiber absorbs the energy of the pumped light wave, then inverts the number of particles, and finally generates the stimulated emission and the output laser in the doped optical medium.

How to pump the energy of a thulium-doped fiber laser is also a very important issue. Existing pumping methods generally use the end face for energy pumping. Because the optical fiber diameter is small, how to pump to provide the maximum energy absorption efficiency is a problem worth studying. In order to increase the energy absorption of the optical fiber, double-clad optical technology is now commonly used, and end-coupling technology is used to focus the pump light on the end of the inner clad of the double-clad optical fiber, which is directly coupled to the double-clad optical fiber. The most important feature of this technology is that it is simple in structure and easy to implement. Therefore, the end pump technology is still a widely used pumping method in the early development of clad pump technology. Later, in order to improve the pumping efficiency, a suitable lens group was designed according to the numerical aperture and spot size of both the pumping light and the receiving double-clad optical fiber, and the pumping light was coupled into the double-clad optical fiber. In this way, when the pump power is high, the method is limited by the area of light, and the optical density at the end of the optical fiber is very high, which can easily cause damage to the end of the optical fiber. Another major drawback is that the area absorbed by the end face of the optical fiber is so small that a slight offset of the end face of the optical fiber causes a sharp drop in the pumping optical coupling efficiency relative to the coupled spot. Therefore, some improvements have been made to the end-pumping technology, using a conical optical coupling technology, as shown in figure 2.

![Figure 2. Tapered fiber coupling.](image)

Although the conical fiber coupling method improves the pumping mode of laser energy and the pumping efficiency, the conical fiber coupling method also has its drawbacks. Because the tapered fiber coupling mainly depends on the tapered fiber, the large mode field diameter spot output by the tail fiber is compressed into the double-clad fiber with relatively small cross-section. Although the coupling efficiency of this method is higher than that of the ordinary end-pump coupling method, its disadvantage is also obvious, that is, it cannot achieve the ring laser cavity structure type, and it is not suitable for simultaneous pumping of multiple laser pump sources. In order to further improve the pumping mode of the laser and realize simultaneous pumping of multiple pumping sources, a new coupling method, the optical coupler technology, has been found after the study of the conical optical coupling technology. Optical fiber coupler technology is shown in figure 3. In this optical fiber coupler technology, the bundle of multiple multimode fibers shrinks gradually to a single bundle until it matches the size of the double-clad fibers and then connects to the double-clad fibers.

![Figure 3. Fiber coupler.](image)
Optical fiber coupler technology is suitable for pumping multiple high power LDs with tails simultaneously. It can replace a multimode optical fiber at the center of the fiber bundle with a single-mode optical fiber suitable for signal light transmission and a double-clad optical fiber core fused. In this way, the pump light can be coupled from a multimode optical fiber to the internal cladding of the doped gain optical fiber, and the signal light can be coupled from the central single mode optical fiber to the fiber core. In this way, the optical coupler completely solves the disadvantage that the original conical optical fiber cannot achieve the ring cavity structure of the laser, and achieves the mode of energy supply of multi-pump, as shown in figure 4. This lays a good foundation for the design of high power fiber laser.

![Diagram](https://example.com/diagram.png)

**Figure 4.** Energy supply by multiple pumps.

3. Optical properties of doped optical fibers
Fiber lasers can be divided into two categories, doped and stimulated scattering fiber lasers, depending on the gain medium. Rare earth optical fibers are the main gain medium for doped laser, and the laser generation mechanism is stimulated radiation. The emission mechanism of stimulated scattering fiber laser is nonlinear, mainly stimulated Raman scattering and stimulated Brillouin scattering. Doped fiber laser is the main research area in this paper. In a doped optical fiber laser, the gain medium is the optical fiber doped with rare earth ions. The analysis results for gain optical fibers show that the ion concentration in rare earth doped optical fibers has an important influence on the luminescence efficiency of doped optical fibers. The wavelengths of various rare earth doped optical fibers are different, as shown in figure 5.

![Graph](https://example.com/graph.png)

**Figure 5.** Wavelengths of various rare earth doped optical fibers.

Tm ions have a very rich energy level structure. The energy levels and emission wavelengths of Tm ions are shown in figure 6. According to Einstein's radiation theory, so-called laser amplification is to realize laser amplification by utilizing the gain mechanism caused by rare earth doping in optical fibers. In the thermal equilibrium state, the number of particles in each energy level of rare earth ions obeys the Boltzmann statistical distribution. To achieve light amplification, the prerequisite is that rare
earth ions in doped optical fibers must be in a so-called particle number inversion state in order to achieve laser amplification effect.

![Diagram of energy levels and emission wavelengths of Tm ions.](image)

**Figure 6.** Energy levels and emission wavelengths of Tm ions.

However, under normal conditions, the doped optical fibers are in a thermal equilibrium state, at which time the number of particles in the high energy level is less than that in the low energy level, and light amplification cannot be achieved. When the pump light passes through the rare earth doped fiber, the number of stimulated absorbed photons is always greater than the number of stimulated radiated photons, so the fiber in thermal equilibrium can only absorb photons. Only when the outside supplies energy to the rare earth-doped optical fibers, so that the rare earth ions in the optical fibers are in a non-thermal equilibrium state, can the number of particles be reversed, so the pumping process is a necessary condition for light amplification. In general, the higher the concentration of doped rare earth ions, the greater the laser output power. But the laser power will not increase all the time. When it reaches a certain critical point, the output power will begin to decrease instead. The simulation results are shown in figure 7.

![Diagram showing the relation of output power with doped concentration.](image)

**Figure 7.** The relation of output power with doped concentration.
As can be seen from figure 7, the output power increases with the increase of Tm ion doping concentration. When the doping concentration increased to a certain extent, the output power reached the highest point, and then with the increase of doping concentration, the output power began to decrease. Therefore, the output power of the laser does not always increase with the increase of doping concentration.

4. Conclusion
A 2µm fiber laser doped with Tm element was studied and the effect of doping concentration on laser output power was analyzed. The results show that the increase of doping concentration is beneficial to increase the output power of 2µm laser. But when the concentration increases to a certain extent, a critical point will appear. When the doping concentration crosses this critical point, the output power of 2µm laser begins to decrease instead, which is of great significance for the design of 2µm Tm-doped fiber laser.

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