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Study on Pumping Technology of Thulium Doped Fiber Laser

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Abstract: Fiber laser is a small volume laser using rare earth doped fiber as laser medium. If the fiber laser can emit laser, it must be provided with a certain amount of energy by the outside world. The technology that provides energy for fiber lasers is laser pumping technology. With the continuous development of laser technology and laser devices, there is a growing demand for high power, high efficiency, high beam quality and compact lasers in various fields. Compared with traditional gas and solid state lasers, fiber laser has been developed rapidly because of its high efficiency, miniaturization, excellent beam quality and good heat dissipation performance. Laser pumping is a technology to obtain energy from external energy sources. In order for the fiber laser to output laser, the pump power that provides energy must be higher than the laser threshold of the laser. In order to obtain higher laser power, it is necessary to continuously increase the laser pump power. However, due to the structural characteristics of the optical fiber, the diameter of the optical fiber is usually very small. When the external pump power is relatively large, the optical fiber will generate higher temperature after absorbing energy, which will lead to the damage of the optical fiber. In order to improve the laser output power of the fiber without damaging the fiber material, various laser pumping methods have been developed. The appearance of double clad fiber is undoubtedly a breakthrough in the field of laser pumping, which makes the production of high power fiber lasers and high power optical amplifiers come true. The structure of optical fiber is analyzed, and various laser pumping modes are discussed. The simulation of laser pumping is carried out. The results show that the dual symmetric simultaneous pumping mode is a superior method.

Keywords: Fiber Laser, Thulium Doped, Symmetrical Pumping, Inner Cladding, Outer Cladding

1. Introduction

Fiber lasers have important applications in communications [1-3]. In recent years, in order to meet the requirements of large capacity of optical communication systems, fiber laser technology has been developed rapidly [4-6]. Fiber laser can produce not only continuous laser output, but also picosecond (ps) to femtosecond (fs) ultrashort laser pulses. This expands the application field of fiber lasers [7-12]. In the future, the communication technology will gradually transform from electric communication to optical communication. At present, the light source of optical communication system is generally fiber laser. Therefore, fiber laser has become the core device of an optical communication system. The working medium of the fiber laser is the fiber doped with rare earth elements [13-16]. From the atomic point of view, the laser medium will have many different energy levels, so that atoms can absorb the external light energy and realize the energy level transition. There are two kinds of common atomic energy level radiation, one is three-level lasing, the other is four level lasing. Through nonradiative transitions, electrons usually reach the upper level band of the laser. When there are enough particles in the upper level, the inversion of the particle number is formed. When the atomic energy level jumps to the lower level, photons will radiate outward. These photons oscillate back and forth after entering the optical resonator. In the resonant cavity, if the gain of the photon is greater than its loss in the cavity, then the laser will be formed and output to the outside. In recent years, fiber lasers with large wavelengths have been developed rapidly [17-20]. Tm doped fiber laser is one of the most widely used lasers. Tm doped fiber laser can emit a laser wavelength of 2000nm, which is just near the absorption peak of water molecules, which is very conducive to medical surgical treatment. The Tm doped fiber laser, when used as a scalpel, only produces very small mechanical damage, and the area of biological tissue damage at the incision is also very small. It will not produce too much bubble formation, tissue fragments, and broken tissue, which is very beneficial to patients. Tm doped fiber lasers can emit many wavelengths, and their output power can be adjusted in a large range and can be operated in pulse mode. The Tm doped fiber laser of IPG Company has shown good results in removing tumors and treating stones, which has aroused great interest and concern. However, the Tm fiber laser also has a disadvantage, that is, the power is too small, which limits the application range of the laser. In order to improve the power of Tm fiber laser, pumping technology is very important. The pumping technology of the laser is deeply studied, and the influence of different pumping technologies on the laser is analyzed.

2. Structure and Characteristics of Optical Fiber

For a fiber laser, the gain fiber plays a key role in the laser. Optical fiber is mainly composed of fiber core, cladding and coating layer. The fiber core is made of highly transparent medium material and is the transmission medium of light waves. Cladding is a layer of dielectric material with a refractive index slightly lower than that of the core, which forms an optical waveguide with the core. The outermost layer of optical fiber is a protective layer, which is generally made of high loss soft materials. The main function of the protective layer is to protect the optical fiber from water vapor erosion and mechanical scratches, while increasing the flexibility of the optical fiber.

Ordinary optical fiber is composed of fiber core, cladding and protective layer. A single fiber core is used as the waveguide of signal light and pump light, and its structure is shown in figure 1.

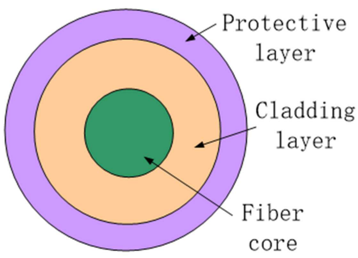

Figure 1. *Fiber Structure.*

The fiber doped with rare earth elements becomes the laser medium. When the external energy is absorbed into the laser medium, the atoms in the laser medium will produce excited states. When the number of particles in the excited state of an atom exceeds the number of particles in its ground state, the number of particles can be reversed. In this case, atoms can generate stimulated radiation and emit photons to the outside world. These photons are injected into a resonant cavity for reciprocating oscillation, and then output laser to the outside world. Because the energy absorption efficiency of ordinary optical fiber is not high, in order to improve the energy absorption of optical fiber, people have carried out new design on optical fiber structure. In order to absorb more external energy, a double clad fiber is designed. This double clad fiber has obvious advantages over ordinary single clad fiber. In terms of the structure of double clad fiber, double clad fiber has two cladding layers: internal and external. The fiber core is composed of optical fibers doped with rare earth elements. The transverse size of the inner cladding is much larger than that of the fiber core, and its refractive index is smaller than that of the fiber core. The purpose of this design is to make the energy transmitted from the outside better absorbed by the fiber, minimize the energy loss, and improve the energy absorption efficiency. In the double clad optical fiber structure, the outermost protective layer is a hard plastic, which can resist the damage of external forces and play a certain role in protecting the optical fiber. The structure of double clad optical fiber is shown in figure 2.

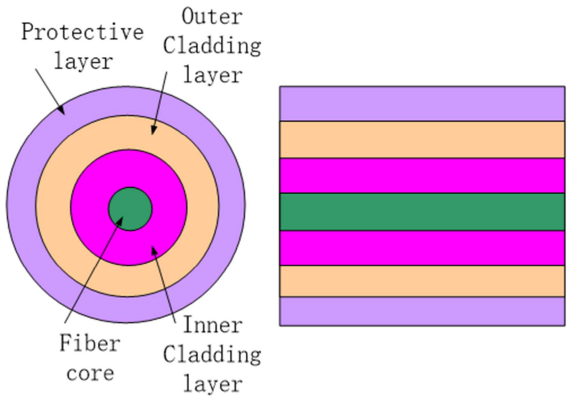

Figure 2. *Double Clad Optical Fiber Structure.*

For double clad fiber, there are many factors that will affect the absorption efficiency of pump light in gain fiber. Common influencing factors include the area ratio of core to inner cladding, the doping concentration of gain fiber, the shape of inner cladding, etc. In the early days of fiber cladding pumping technology, the inner cladding of double clad fiber was mostly circular. However, this circular structure will affect the absorption efficiency of the gain fiber to the pump light, resulting in the low absorption efficiency of the fiber core to the pump light. Later, people found that double clad fiber has more advantages than single clad fiber, so double clad fiber technology has developed rapidly. The most popular optical fibers are double clad optical fibers.

At first, the inner cladding of double clad optical fiber was circular structure. However, it was later found that the circular inner cladding optical fiber, due to its symmetry, would adversely affect the energy absorption. In this circular structure fiber, there is a large amount of spiral light in the inner cladding of the pump light. This spiral light hinders the energy absorption, causing a large amount of light energy loss, leading to the decline of the pump light absorption efficiency of the gain fiber, and seriously affecting the high power output of the laser. In order to overcome the shortcomings of the round structure of the cladding, people have designed different cladding structures. Theoretically analyze the factors that affect the energy absorption of optical fibers, it is found that as long as the circular structure of the cladding is changed, the distribution of light in the optical fiber can be changed, so that the pump light can be more fully absorbed by doped ions when passing through the fiber core within a limited distance, improving the energy absorption efficiency. Theoretical analysis shows that all kinds of non-circular symmetric inner cladding fibers have high energy absorption efficiency.

In order to improve the absorption efficiency of pump light, people have constantly put forward a variety of fiber structure designs. Some people move the center of the circle to a position far away from the center to form an off center optical fiber structure, as shown in figure 3.

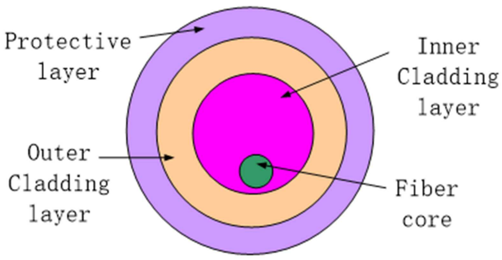

Figure 3. *Off Center Structure of Optical Fiber.*

Later, it was found that if the geometry of the cladding was changed, the absorption efficiency of the pump light could also be significantly improved. Therefore, the center cladding is changed into a rectangle, as shown in figure 4.

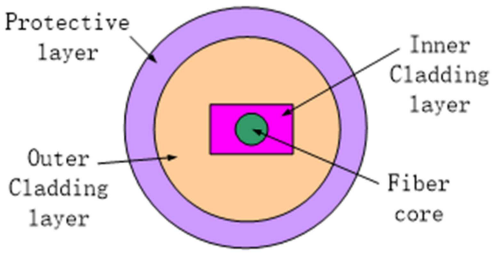

Figure 4. *Rectangular Cladding Structure.*

In order to continue to improve the absorption efficiency of the pump light, people try to change the various geometric shapes of the inner cladding. It is found that if the geometric shape of the inner cladding is changed to a D-shaped shape, the absorption efficiency of the pump light will be further improved. The D-shaped optical fiber structure is shown in figure 5.

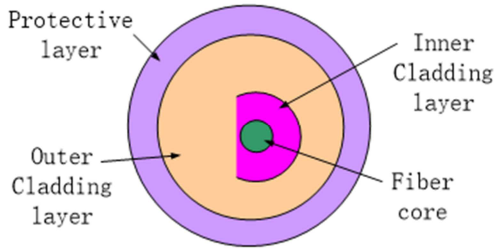

Figure 5. *D-shaped Cladding Structure.*

3. Structure Analysis of Fiber Laser

Fiber lasers can be divided into two types according to their geometric structures, one is linear lasers, the other is ring lasers.

Linear fiber laser, that is, the laser resonator is straight, with no bend in the middle. From the design point of view, the linear fiber laser is simple in structure, easy to design, and requires few optical elements. The linear fiber laser is shown in figure 6.

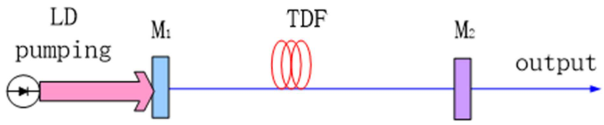

Figure 6. *Linear Cavity Structure.*

In this linear fiber laser, M1 is a total mirror that completely reflects the incident light, while M2 reflects part of the light but transmits part of it. In the design process of this linear fiber laser, the cavity mirror must be close to the end of the fiber, so as to avoid the scattering of light and the loss of valuable energy, which requires high coupling accuracy of the cavity mirror on the end of the fiber. As long as the optical fiber end face or cavity mirror is slightly inclined, the loss of the end face will increase rapidly. Therefore, the relative position of the optical fiber or cavity mirror must be carefully and accurately adjusted to minimize unnecessary energy loss. On the other hand, the surface of the mirror should be very clean and free of minor defects. Because the mirror is directly coupled with the optical fiber end face, the mirror requires a very good polishing performance of the optical fiber end face. If the reflector is uneven, when the high power density pump light passes through the end cavity mirror, it will damage the insulating coating of the cavity mirror, causing damage to the cavity mirror, which will reduce the energy absorption efficiency of the laser. In a linear fiber laser, the external energy is not directly injected into the fiber, but is coupled into the fiber through a wavelength division multiplexing coupler.

As the cavity mirror is a discrete component, it is not well coupled with the optical fiber. Now other components have been used to replace the cavity mirror. The most commonly used component is called fiber Bragg grating (FBG). In linear fiber lasers, fiber Bragg gratings can completely replace the high reflectivity mirrors at both ends of the F-P cavity. The so-called FBG is to engrave the FBG directly on the optical fiber in the laser cavity, or fuse the engraved FBG on the optical fiber in the laser cavity, so that the cavity mirror does not need to exist in the laser cavity. FBG can replace the cavity mirror. One advantage of this is that the coupling loss between the cavity mirror and the optical fiber is eliminated, and the energy loss is less. The FBG laser is shown in figure 7.

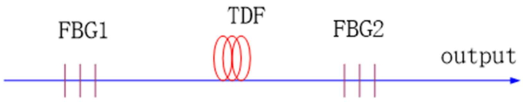

Figure 7. *FBG Linear Fiber Laser.*

In addition to linear fiber lasers, the other is ring cavity lasers. Because linear lasers have some shortcomings, people have redesigned the laser structure and proposed a fiber laser with ring structure. Compared with the linear laser, the ring fiber laser occupies less space and has a longer cavity length. The core of a ring fiber laser is a fiber directional coupler. The two arms of the coupler are connected together to form a ring laser cavity connected with the doped fiber, and a ring resonator is formed in which light is transmitted. The ring laser is shown in figure 8.

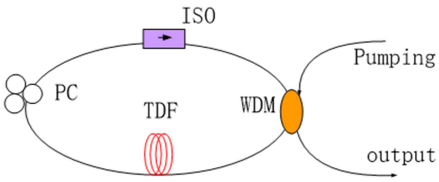

Figure 8. *Ring Fiber Laser.*

In the ring fiber laser structure, the two ends of the wavelength division multiplexing (WDM) coupler are connected together to form a ring resonator, in which doped fibers are connected in series, that is, the laser medium. In order to control the unidirectionality of light, it is also necessary to insert an isolator (ISO) on the optical transmission path to ensure the unidirectional transmission of laser. If the doped fiber is a non polarization maintaining ordinary fiber, under this condition, it is necessary to add a component, namely, a polarization controller (PC). This component PC is used to control the polarization state of light.

4. Laser Pumping

The laser operates by providing energy from the outside. Because the optical fiber is very thin, how to improve the energy absorption efficiency of the optical fiber has always been an important problem to be studied in laser pumping [21-25]. Excellent pump coupling technology is the key factor to obtain high power fiber lasers. However, it is not easy to couple tens or even hundreds of watts of LD pump power into the inner cladding of double clad optical fibers with diameters of only hundreds of micrometers. This is because the high power energy will make the optical fiber generate a lot of heat, which will damage the performance of the optical fiber. At present, there are two common pumping methods in fiber lasers, one is end pumping, the other is side pumping. The advantage of end pumped coupling technology lies in its simple operation and easy realization of pump structure. Once the diameter of the tail fiber core, cladding diameter and numerical aperture of the pump source in the laser match with the diameter of the inner cladding and numerical aperture of the fiber, it is easier to achieve high pump coupling efficiency. The end pumping is shown in figure 9.

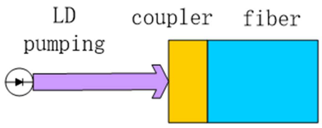

Figure 9. *End Pump.*

The laser is end pumped, which can make the structure of the laser simpler and easier to manufacture. Since all connecting lines are optical fibers, end pumping is conducive to the realization of all optical fiber of the laser, and there will no longer be separate optical elements in the laser. However, the end pumping technology has very high requirements for the fusion of optical fibers and is technically difficult.

Because the end pumping method is difficult to achieve high power laser output, in order to better improve the output power of the laser, now more methods are to use side pumping. The side pump is shown in figure 10.

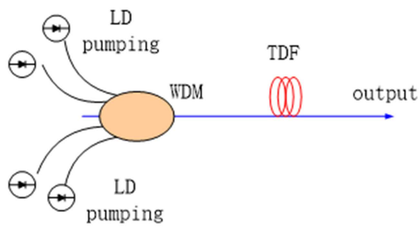

Figure 10. *Side Pump Coupling.*

The side pump coupling technology is adopted in the laser, which can make the pump light more evenly distributed in the fiber without causing additional loss of the signal light. In addition, this method can save space and does not occupy both ends of the optical fiber. This design structure is conducive to the input and output of the laser. The output power can be increased simply by increasing the number of LDs. In particular, this side pumping method is more conducive to rapidly increasing the number of pump sources, which is very important for improving the output power of the laser. The structure of the laser with multiple pump sources is shown in figure 11.

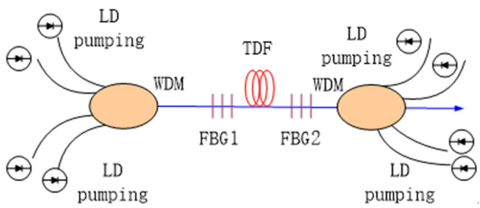

Figure 11. *Laser with Multiple Pump Sources.*

When the pump source is placed at different positions of the laser medium, different energy absorption effects will be produced. In particular, the distribution of pump power density in optical fibers is different. The following three situations are discussed respectively.

The first case is forward pumping mode, as shown in figure 12.

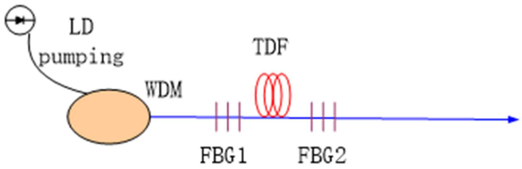

Figure 12. *Forward Pump.*

Under the condition of forward pumping, the power density distribution of the pump light in the optical fiber is shown in figure 13.

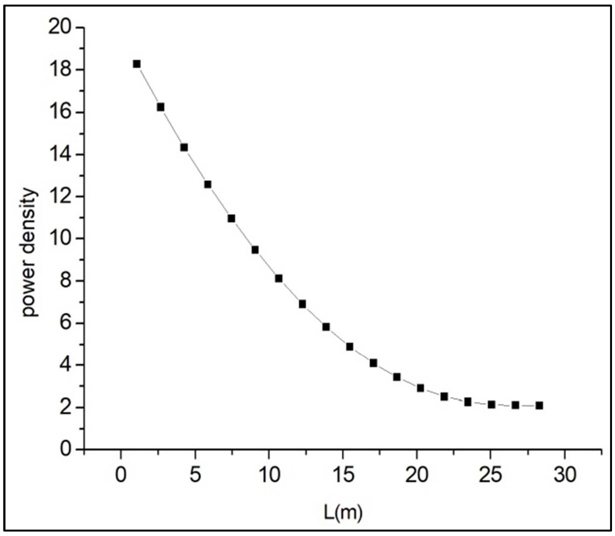

Figure 13. *Simulation of Optical Power Intensity distribution in forward pumped optical fiber.*

Forward pumping can separate the pump injection end from the laser output end, so pump coupling is most convenient. However, the optical power distribution and gain distribution in the optical fiber are very uneven, which is easy to cause fiber melting at the injection end under the condition of high-power pumping.

The second case is the backward pumping mode, as shown in figure 14.

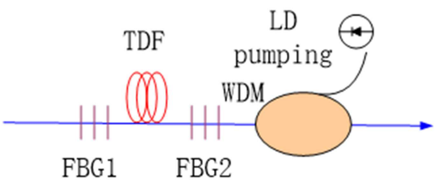

Figure 14. *Backward Pump.*

Under the condition of backward pumping, the power density distribution of the pump light in the optical fiber is shown in figure 15.

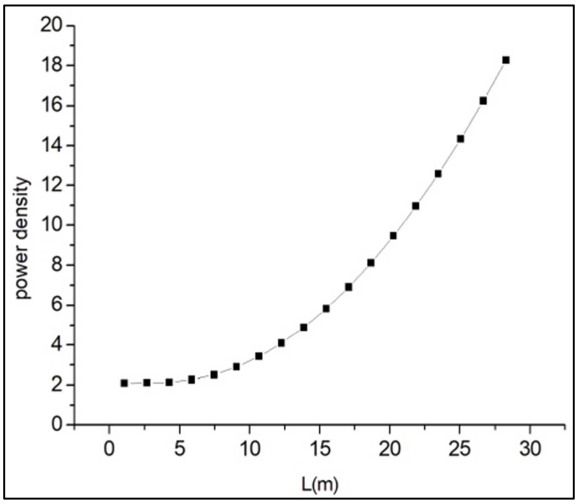

Figure 15. *Simulation of Optical Power Intensity Distribution in Backward Pumped Optical Fiber.*

The coupling injection of pump light in backward pumping is more complicated than that in forward pumping, and the problem of uneven pump light distribution is the same as that in forward pumping.

The third case is forward and backward pumping mode, as shown in figure 16.

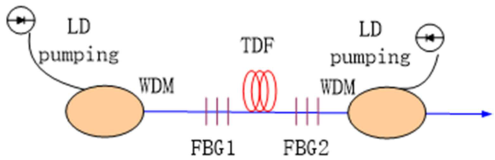

Figure 16. *Simultaneous Forward and Backward Pumping.*

Under the condition of simultaneous forward and backward pumping, the distribution of pump light power density in the fiber is shown in figure 17.

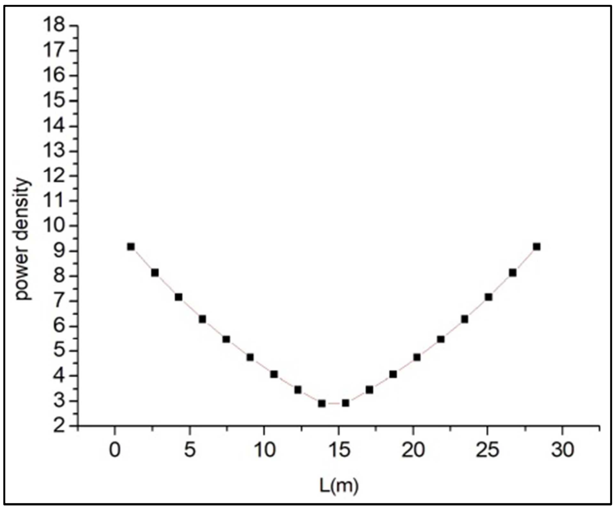

Figure 17. *Simulation of Optical Power Intensity Distribution in Optical Fiber Pumped Forward and Backward at the Same Time.*

The coupling structure of the two ends pumping mode is more complex, but it can greatly reduce the pumping power density at the injection end, and the power density and gain distribution in the fiber are relatively uniform. At the same position, when two ends pumping is adopted, the energy density in the fiber is less than that in the fiber pumped by one end, which helps to protect the fiber from damage and improve the output power of the laser. Therefore, the two ends pumping is a good choice for high-power fiber lasers.

5. Conclusion

In recent years, cladding pumping technology of lasers has been widely used. The appearance of double clad fiber is undoubtedly a breakthrough in the field of laser pumping, which makes the production of high power fiber lasers a reality. Fiber laser is a kind of laser using fiber as working material. At present, the most widely studied and used fiber laser is a rare earth doped fiber laser using rare earth doped fiber as working material. With the gradual maturity of cladding pump coupling technology and various fiber integrated device technologies, high-power Tm doped fiber lasers have been developed rapidly. The laser pumping technology is studied, and the influence of different pumping methods on the power distribution in the fiber is analyzed. The results show that the pump power distribution decreases gradually along the fiber when forward pumping, which is unfavorable to the fiber. When backward pumping, the pump power distribution increases gradually along the fiber, which will also adversely affect the fiber. When both ends are symmetrically pumped at the same time, the distribution of pump power along the fiber is relatively uniform, which is conducive to protecting the fiber and avoiding damage to the fiber caused by excessive temperature. Therefore, both ends are pumped symmetrically at the same time, which is the most favorable method for the laser.

Acknowledgements

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