

Application and development direction of fiber laser

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Abstract

A fiber laser is a kind of laser emitting device based on fiber technology, which has the advantages of high power, high efficiency, and high beam quality. Therefore, fiber laser has wide application prospects in communication, medical treatment, material processing, and other fields. In the future, with the continuous progress of technology and the increasing demand, the application field of fiber lasers will be further expanded, and the development direction will be more diversified and specialized. In this paper, through the study of the application of fiber lasers, the development of fiber lasers in recent years is introduced, and its application status and development trend in communication, medical treatment, material processing, military, and other fields are summarized.

Keywords: fiber laser; Optical fiber application; Laser technology; Optical fiber communication

1. Introduction

Since the 1960s, rare-earth-doped fiber lasers have been developed gradually, but the loss of fiber materials is too large, which limits the performance of lasers. In the 1980s, the University of Southampton used metal chemical vapor deposition (MCVD) to produce low-loss erbo-doped fiber, and the emission wavelength of erbo-doped fiber laser happened to be located in the low-loss window of optical communication, and fiber communication was developed rapidly^[1]. With the development of optoelectronic science, lasers have been widely used in medicine, communication, material processing, measurement, military and other fields^[2]. Fiber laser is a kind of laser with fiber as the laser medium. The importance of fiber laser for developing modern lasers is that fiber laser pulse light source has a very narrow duration, high energy, and high peak power characteristics. It has high reliability, high beam quality, high stability, and easy compatibility with optical fiber systems and other performance advantages, which is an important carrier for the future development of ultrafast laser technology^{[3][4]}. Fiber laser is a special form of solid-state laser, which uses light as a laser medium and injects energy into the fiber to excite the laser amplification medium, thereby generating laser output. Fiber lasers usually use doped fiber doped with dopants as the laser medium, such as thulium-doped fiber laser, erbium-doped fiber laser, etc.^{[5][6]}. The selection and concentration of dopants have an important impact on the performance of the laser. In this paper, the application and classification of fiber lasers are introduced, and the application prospects of fiber lasers are prospected, aiming to promote the development of fiber laser technology and broaden its application channels.

2. The basic principle of fiber laser

2.1 The structure and working principle of fiber laser

Fiber laser is a laser emitting device based on fiber, composed of fiber medium and excitation source. The main components include fiber medium, pump source, fiber grating, and output coupler.

The working principle of the fiber laser is based on the characteristics of the laser, that is, the atoms or molecules in the fiber medium are brought to an excited energy level through the stimulated radiation process. Under the guidance of the stimulated radiation, these atoms or molecules will spontaneously emit photons, thus forming a coherent laser beam.

In the fiber laser, the first need to provide a pump source through the absorption of external energy to excite the atoms or molecules in the fiber medium to transfer it to the excited energy level. Common pump sources include reflective semiconductor lasers, fiber laser diodes, etc.

The fiber medium is an important part of the fiber laser, and its role is to provide an optical gain medium to convert the pump light energy into a laser beam. Common fiber media include erbium-doped fiber, ytterbium-doped fiber, thulium-doped fiber, etc. Different dopants determine the working wavelength and performance characteristics of the laser.

In fiber lasers, fiber gratings are used to select the laser's output wavelength and enhance the laser mode. By changing the Bragg diffraction conditions of the FBG, the laser beam of a specific wavelength can be selectively enhanced.

Finally, the output coupler is the element used to separate the laser beam from the pump source. It can output the laser beam from the fiber laser and reflect the pump source

into the laser for recycling.

In summary, the structure and working principle of the fiber laser is to achieve efficient output of the laser beam by transferring the pump light energy to the fiber medium and through the selective enhancement of the fiber grating and the separation of the output coupler. This composition and working principle gives fiber lasers many application prospects in many application fields.

3. Classification of fiber lasers

Different structures of fiber lasers have different properties, and according to different classification standards, fiber lasers can be divided into the following.

Table 1 Classification of fiber lasers

Classification criteria	Fiber laser
The difference in the gain medium	Crystal fiber laser, plastic fiber laser, rare earth doped fiber laser, nonlinear optical fiber laser
Different structures of the resonator	Linear cavity, ring cavity, F-P cavity, “8” shape cavity, DFB fiber laser, DBR fiber laser
Different fiber structures	Special fiber lasers, photonic crystal fiber lasers, single cladding fiber lasers, double cladding fiber lasers
Different output laser characteristics	Pulse fiber laser, continuous fiber laser
Different numbers of laser output wavelengths	Multi-wavelength fiber laser, single-wavelength fiber laser
The tunable characteristics of the laser output wavelength are different	Tunable multi-wavelength laser, non-tunable single-wavelength laser
The laser output wavelength band is different	S-band (1460-1530 nm), C band (1530-1565 nm), L band (1565-1610 nm)
Mode-locked or not	Mode-locked laser, continuous-light laser
Different mode-locked devices	Active mode-locked laser, passive mode-locked laser

Classification criteria	Fiber laser
Different doping ions	15 kinds of doping ions, such as erbium, neodymium, fault, thulium, ytterbium, holmium, etc
Different working mechanisms	Upconversion fiber laser, down conversion fiber laser

4. Application fields of fiber lasers

Since the birth of fiber laser in the 1960s, due to the backward fiber preparation process, in the following decades, fiber laser did not have good application until 1980; with the application of double cladding optical fiber and cladding pump technology, fiber laser has been developed rapidly, and its influence has spread to communication, material preparation, medical treatment, measurement, military and other fields. Fiber lasers have higher power density, beam quality, and higher efficiency than traditional gas and solid-state lasers. As a result, the application of fiber lasers in various fields has been widely discussed.

4.1 Application in the military field

Fiber laser has strong adaptability, high-temperature, and high corrosion resistance, which is especially suitable for military fields. Fiber laser has obvious advantages in efficiency, beam quality, volume, quality, robustness, and cooling, so it will become one of the main light sources of tactical laser weapons^{[7][8]}. Modern warfare’s modernization and advancement of military communications, weapons, and equipment are all attributed to optical fiber technology.

4.2 The application in the field of communication

4.2.1 Optical fiber communication

Fiber laser is a key component in optical fiber communication systems^[8]. Optical fiber communication uses optical fiber as a transmission medium to transmit information in the form of light, which has the advantages of high bandwidth, large capacity, and low loss and is widely used in long-distance, high-speed, and large-capacity data transmission^[9].

Fiber lasers in fiber optic communication are mainly used as light sources. Because the fiber laser has the characteristics of high efficiency, stability, and good modulation performance, it can provide stable and high-quality optical signals. Hence, it plays a vital role in fiber communication. The commonly used fiber lasers in fiber communication include semiconductor and fiber Raman

lasers.

In long-distance fiber communication, fiber lasers can provide high-power laser sources to ensure signal transmission distance and quality. At the same time, the fiber laser has good modulation performance, which can realize the modulation of optical signals and improve the modulation rate to meet the high-speed data transmission needs.

In addition, fiber lasers can also be used as fiber amplifiers in fiber communication. By inputting the laser signal into the fiber laser, the signal can be amplified and enhanced to improve the transmission distance and quality of the signal.

Fiber lasers in fiber communication are used in traditional wired communication networks and widely used in wireless communication, fiber sensing, fiber radar, and other fields. In wireless communication, fiber lasers can be used as photoelectric converters of wireless signals to convert wireless signals into optical signals for transmission, improving transmission distance and data transmission rate. In fiber sensing, fiber lasers can be used as light sources for various sensors, such as temperature sensors, pressure sensors, etc., and play a key role in acquiring and transmitting sensing signals. In fiber optic radar, fiber lasers can be used as laser sources to provide high-power and high-stability laser signals for target detection and tracking^[10].

In short, fiber communication is one of fiber lasers' most important application fields. In long-distance, high-speed, and large-capacity data transmission, fiber lasers can provide stable and high-quality optical signals and play an important role. At the same time, fiber lasers also have a wide range of application prospects in wireless communication, fiber sensing, fiber radar, and other fields.

4.2.2 Optical fiber sensing

Fiber lasers are widely used in the field of fiber sensing, and their application prospects are very broad^[11]. The following is the specific content about fiber lasers in the field of fiber sensing:

Optical fiber sensing is the technology that uses optical fibers as sensors to sense, measure, and monitor changes in environmental parameters. Fiber lasers play a key role in fiber sensing as light sources. Fiber lasers are compact, stable, and high-power output, making them one of the most commonly used light sources in fiber sensing.

In fiber sensing, fiber lasers can be used in a variety of sensing applications, including but not limited to the following:

a. Fiber Bragg grating sensing: Fiber Bragg grating is a technology that uses the grating effect generated by periodic refractive index changes in the fiber to realize

fiber sensing. Fiber lasers can be combined with fiber gratings to measure and monitor parameters such as temperature, strain, and pressure by fiber grating sensors.

b. Fiber Raman sensing: Fiber Raman scattering is a kind of optical fiber as a sensor by measuring the Raman scattered light signal in the fiber to achieve the measurement and monitoring of temperature, pressure, strain, and other parameters. The narrow linewidth characteristics and laser power stability make it an ideal light source in fiber Raman sensing.

c. Optical fiber interference sensing: optical fiber interference sensing uses the interference effect in the optical fiber to realize the measurement and monitoring of environmental parameter changes. Fiber lasers can be combined with interferometric fiber sensors to achieve high-precision measurements of temperature, strain, pressure, and other parameters.

In summary, fiber lasers are widely used in fiber sensing, including fiber grating sensing, fiber Raman sensing, and fiber interference sensing. Fiber lasers' stability, high power output, and narrow linewidth characteristics make them one of the indispensable core components in fiber sensing.

4.3 Applications in the medical field

4.3.1 Laser therapy

Laser therapy is an important application of fiber laser in the medical field. With the continuous progress of science and technology, fiber lasers are increasingly widely used in laser therapy. Laser energy is mainly delivered through optical fibers to accurately treat diseased tissues.

In laser therapy, fiber lasers have the following advantages:

a. High energy density: Fiber lasers can provide laser beams with high power and energy density, allowing them to precisely act on diseased tissues for accurate and efficient treatment.

b. High orientation: the output beam of the fiber laser can be well oriented through the fiber guide, which can accurately target the area to be treated and reduce the damage to the surrounding healthy tissue.

c. Minimally invasive treatment: fiber laser can be treated by percutaneous or endoscopic methods without surgery, which can achieve minimally invasive treatment and reduce patients' pain and recovery time.

The application of fiber lasers in laser therapy in the medical field includes but is not limited to the following:

a. Laser beauty treatment: fiber laser can be used for skin beauty treatment, such as removing pigment spots, wrinkles, vascular diseases, etc., by selectively destroying the diseased tissue and stimulating skin

regeneration to achieve cosmetic effects.

- b. Laser eye therapy: Fiber laser has a wide range of applications in the field of ophthalmology, such as laser keratoplasty (LASIK), cataract surgery, retinal disease treatment, etc., which can achieve high precision and low-damage eye surgery.
- c. Laser tumor therapy: fiber lasers can be used for photothermal therapy of tumors. By focusing laser energy on tumor tissues, it can produce local tissue thermal damage to kill tumors.
- d. Laser endoscopic therapy: fiber laser can be used for endoscopic treatment, such as endoscopic mucosal resection (EMR), endoscopic mucosal dissection (ESD), etc., which can achieve accurate treatment of pathological tissues such as the digestive tract and respiratory tract.

In summary, fiber laser has a wide application prospect in laser therapy. With technology's continuous innovation and development, fiber lasers will play an increasingly important role in the medical field, providing patients with more accurate, safe, and effective treatment methods.

4.3.2 Laser Diagnosis

Laser diagnosis is a method that uses laser technology for medical diagnosis, industrial testing, and scientific research. As a laser source with high stability and high power output, fiber lasers have the potential to play an important role in laser diagnosis. The high resolution and high sensitivity of fiber lasers can be used to realize the microscopic observation of tissues and early diagnosis of lesions ^[12].

In the medical field, fiber lasers can be used in laser surgery, ophthalmic treatment, skin cosmetology, and medical imaging. The high power output and tunability of lasers make them ideal for accurate and non-invasive diagnosis and treatment. For example, by performing laser surgery using fiber lasers, minimally invasive surgery can reduce postoperative pain and recover time.

4.4 Applications in industry

4.4.1 Material processing

The application of fiber lasers in the field of material processing mainly includes laser cutting, laser welding, and laser marking. Fiber lasers have high power and high beam quality, which can achieve high-speed and high-precision material processing. In addition, the fiber laser can also realize the surface modification and micro/nano processing of materials by adjusting the laser parameters ^[13].

4.4.2 Applications in the field of measurement

Applications of fiber lasers in scientific research include

spectroscopic analysis, optical microscopy, and optical imaging. Fiber lasers can generate multiple wavelengths of light, which can be used for spectroscopic analysis and optical microscopy research. In addition, the fiber laser can also realize non-contact imaging of the sample by adjusting the laser parameters.

5. The development direction of fiber laser

5.1 Development trend of micro and nanomanufacturing technology of fiber laser

With the continuous progress of science and technology and the growth of application demand, the micro and nanomanufacturing technology of fiber lasers is also developing and breaking through, which provides new solutions for the performance improvement and application expansion of fiber lasers ^[14]. The following is the specific content of the development trend of the micro/nano manufacturing technology of fiber lasers:

- a. Micro/nano preparation technology of optical fiber materials: The development of micro/nano manufacturing technology makes the preparation of optical fiber materials more precise and efficient. For example, ultrafine fibers with an outer diameter of only a few microns can be fabricated by active fiber stretching technology, improving fiber lasers' beam quality and power density.
- b. Micro/Nanostructure design of fiber laser: The introduction of micro/nanostructure can change the optical characteristics of fiber laser and enhance the interaction between light and matter ^[15]. For example, using micro/nano processing technology to manufacture microporous fiber can realize efficient interaction between laser and gas or liquid and expand the application of fiber laser in gas sensing, biomedicine, and environmental monitoring.
- c. Fabrication of micro/nano optical components for fiber lasers: The development of micro/nano manufacturing technology has made the micro/nano optical components required for fiber lasers more precise and efficient ^[16]. For example, using electron beam exposure ion beam etching and other technologies, micrometer-level optical components such as fiber couplers, gratings, and microlenses can be fabricated, improving the coupling efficiency and tuning performance of fiber lasers.
- d. Micro/nano packaging technology of fiber lasers: The micro/nano packaging technology of fiber lasers can improve the thermal stability and optical performance of fiber lasers. For example, micro and nanomanufacturing technology can be used to prepare micro-cooling devices and microchannel heat sinks,

effectively reducing the working temperature of fiber lasers and improving their long-term stability.

In summary, the development trend of micro/nano manufacturing technology for fiber lasers involves the micro/nano preparation of fiber materials, micro/nanostructure design, micro/nano optical component manufacturing, and micro/nano packaging technology. The development of these technologies will provide strong support for the performance improvement and application expansion of fiber lasers and is expected to promote the development and application of fiber lasers in various fields.

5.2 Research on high power and high energy output technology of fiber lasers

Fiber lasers are widely used in various fields with the rapid development of science and technology. For specific application requirements, such as laser cutting, laser marking, and laser radar, fiber lasers' high power and high energy output technology has put forward higher requirements. Therefore, it is of great significance to study the high power and high energy output technology of fiber lasers to meet the needs of practical applications.

In the research of high power and high energy output technology of fiber laser, the following aspects are worth paying attention to:

a. Optimization of fiber materials

Fiber material is an important factor in determining a laser's output power and energy. At present, the commonly used fiber materials are mainly erbium-doped fiber, ytterbium-doped fiber, terbium-doped fiber, etc. ^[17]^[18]. Researchers can improve the absorption and radiation characteristics of fiber materials by optimizing the composition, purity, and preparation process to achieve higher power and energy output.

b. Pump technology of fiber lasers

Pumping technology is the key to achieving fiber lasers' high power and energy output. Currently, the commonly used pump technology mainly includes laser diode pump, fiber pump, fiber beam combination pump, etc. Researchers can improve the pump efficiency and fiber absorption efficiency by improving the pump technology and then improving the output power and energy of the fiber laser.

c. Optical design of fiber lasers

Optical design is also very important to improve fiber lasers' power and energy output. Optical design involves the optimization of the resonator structure of the laser, the length and diameter of the fiber, and other parameters. The optical loss and nonlinear effects of the laser can be reduced through reasonable optical design, and then the output power and energy of the laser can be improved.

d. Temperature management and heat dissipation technology

High power and energy output will cause the temperature rise of the fiber laser, which will affect the performance and life of the laser. Therefore, researchers need to pay attention to fiber lasers' temperature management and heat dissipation technology. Effective heat dissipation materials, heat dissipation structure design, and temperature monitoring and control technology can be used to achieve high power and high energy output of fiber lasers ^[19].

In short, the research on high power and high energy output technology of fiber lasers is an important direction for the future development of fiber lasers. Through the optimization of fiber materials, the improvement of pump technology, the optimization of optical design, and the application of temperature management and heat dissipation technology, higher power and energy output of fiber lasers can be achieved, and more powerful and reliable technology can be provided for various fields of application.

5.3 Research on wavelength Extension and Frequency Conversion Technology of Fiber lasers

Wavelength extension and frequency conversion technology is one of the important directions for the future development of fiber lasers. By realizing wavelength extension and frequency conversion, more optical frequency output can be realized in fiber lasers, and the application field of fiber lasers can be expanded.

The following is the research content of wavelength extension and frequency conversion technology of fiber lasers:

a. Research on the nonlinear effect of fiber: The wavelength extension and frequency conversion of fiber lasers mainly depend on the nonlinear effect of fiber. Researchers can study and understand the nonlinear effects in fiber, such as Self Phase Modulation (SPM), Four-Wave Mixing (FWM), etc., to achieve wavelength extension and frequency conversion.

b. Wavelength extension technology of fiber lasers: Current fiber lasers mainly work in a few specific wavelength ranges, while wavelength extension technology can allow fiber lasers to work in a wider range of wavelengths. One of the commonly used wavelength extension techniques is the use of Fiber Bragg Grating (FBG) to achieve wavelength selective reflection, to achieve wavelength extension.

c. Frequency conversion technology of fiber lasers: The frequency conversion of fiber lasers can achieve different frequencies of light output. Optical Parametric

Amplification (OPA) technology is a common frequency conversion technology based on nonlinear optical effects. The frequency conversion of fiber lasers can be achieved by using nonlinear optical crystals and specific pump light sources.

- d. Frequency mixing technology for fiber lasers: Frequency mixing technology is a technology that mixes two or more optical signals of different frequencies together to produce new frequencies. The mixing technology of fiber lasers can achieve frequency conversion and wavelength expansion and, at the same time, can generate new frequencies. This technology can be applied to optical communication, spectral analysis, and other fields.

In a word, the research on wavelength extension and frequency conversion technology of fiber lasers is of great significance for the future development. The continuous development and improvement of these technologies will effectively promote the application of fiber lasers in a wider range of application fields.

6. Summary

This paper introduces the classification and application of fiber lasers, and the future development direction of fiber lasers is prospected. As an important optical device, fiber laser has many application prospects. Reviewing the development history, technical characteristics, and future development trends of fiber lasers shows that the application prospect of fiber lasers in communication, medical treatment, material processing, and other fields is very broad. Future research should focus on improving the power output, efficiency, versatility, and integration of fiber lasers to meet the growing application needs.

7. References

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