Development Trend of Active Optical Fiber

Abstract: In this paper, the working principle, application and future development trend of active optical fiber are briefly introduced, the demand of fiber laser for active optical fiber and the advantages and disadvantages of active optical fiber preparation technology solutions are analyzed, and the future development and further development of active optical fiber are prospected.

Keywords: laser; active optical fiber; ytterbium-doped fiber; double-clad fiber

Preface

The laser is one of the most important inventions of mankind since the 20th century, being the "fastest knife", the "most accurate ruler" and the "brightest light". The famous physicist Albert Einstein introduced the basic principle of laser in 1917 in his new theory "The interaction between light and matter" - stimulated radiation[1]. In the atoms composing matter, there are different numbers of electrons distributed in different energy levels, in which the particles in the high energy level will jump from the high energy level to the low energy level when excited by a certain photon, then will radiate the light of the same nature as the light that excites it, and in a certain state, the phenomenon of a weak light exciting a strong light can occur, which is called "light amplification by stimulated emission of radiation", referred to as "laser". In 1960, the American scientist Theodore Mayman made the first laser with ruby crystal [2] and obtained laser output. More than 60 years have passed since the invention of the first laser, and laser technology, as expected, has been applied in various industries and played a great role in leading the industrial revolution of the 21st century.

I. Development history and trends of fiber lasers

Fiber lasers are widely used in optical communication, spectroscopy, laser sensing, laser medicine, industrial processing, aerospace, and laser weapons with numerous advantages such as high efficiency, small size, fast heat dissipation, large tunable range, excellent beam quality, and good stability.

Fiber lasers first appeared in 1961 by the American scientist E. Snitzer, who used neodymium-doped (Nd^{3+}) rod glass to achieve laser output at a wavelength of 1.06 μm[3]. In the following decades, fiber lasers have been developed rapidly. Currently, the highest output power of single-mode fiber lasers from the fiber laser giant IPG, USA, has reached the order of 20 kW[4], while the output power of multimode fiber lasers has reached the order of 100 kW[5], leading the development of industrial fiber lasers.

The basic structure of a fiber laser is shown in Figure 1, where the pump light is first coupled into the doped fiber through a coupling system, and then the rare earth ions doped in the fiber core absorb the pump photon energy and undergo an energy level jump, thus revealing the laser output. Its key component is the gain medium, mainly composed of optical fiber doped with rare-earth elements, generally known as "active fiber". Rare-earth ions such as erbium (Er3+), praseodymium (Pr3+), thulium (Tm3+), neodymium (Nd3+) and ytterbium (Yb3+) can be used as dopants to make optical fibers, as shown in Figure 2. Different rare earth elements have their own unique energy levels, which can produce lasers with different working wavelengths, so each fiber manufacturer uses the corresponding doped elements to develop optical fiber according to the user's application scenario, and then use the doped fiber to make lasers for the corresponding scenario. For example, high-power lasers for laser cutting are used with ytterbium-doped fiber as the gain medium, featuring high power and energy density; lidar for intelligent driving is used with erbium-ytterbium co-doped active fiber as the gain medium, featuring excellent signal-to-noise ratio, strong anti-interference capability and high precision; and holmium-doped fiber with an emission wavelength of 2 μm is widely used in the laser medical field due to its safety to the human eye.

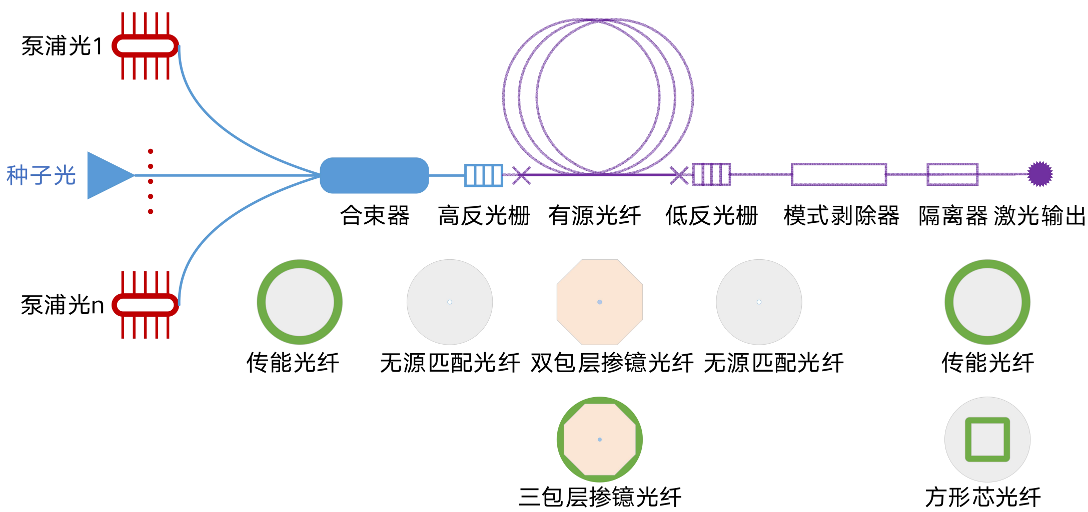

Figure 1 Schematic Diagram of a Typical Fiber Laser Structure and Related Laser Fiber

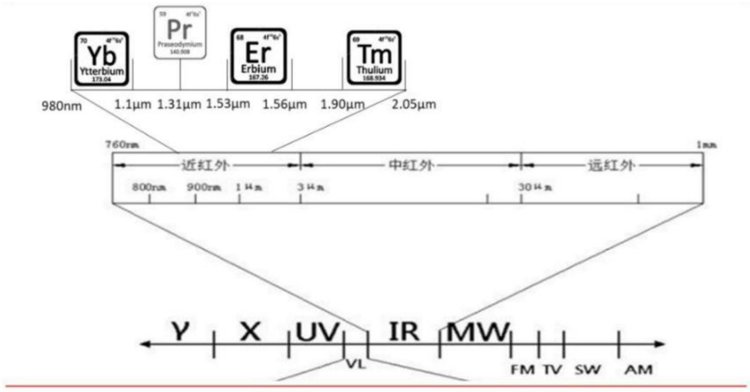

Figure 2 Radiation Bands of Fiber Optic Elements of Various Rare Earth Elements of Ytterbium, Praseodymium, Erbium and Thulium

As one of the core components of fiber lasers, the active fiber plays a key role in their performance. Many research institutions in Europe and the United States have carried out a lot of R&D work on it, such as Nufern and IPG in the United States, SPI in the United Kingdom, LIEKKI in Finland, and CorActive in Canada, among which the products of IPG in the United States and SPI in the United Kingdom are self-produced and not sold to the public. High power laser fibers with core diameter greater than 25 μm were included in the list of 20 products under U.S. high-tech export control to China in 2014 and 2015, which seriously restrict the development of China's laser industry.

China's Wuhan Rexin, Changjin laser, Changfei fiber, Fiber Optics, National University of Defense Technology, China Academy of Engineering Physics, Shanghai Institute of Optics, China Electronics Technology Group 23, 46, etc. have carried out research work, of which, Wuhan Raycus, Changjin laser, Changfei fiber and Fiber Optics have partially achieved the mass production and commercialization of a variety of models of active fiber, making bulk supply to the domestic mainstream fiber laser manufacturers. In the future, China's active fiber will achieve domestic substitution, and high, medium and low power, as well as the full model coverage from ultraviolet to mid-infrared.

II. Development trend of ytterbium-doped optical fiber

Ytterbium-doped (Yb^{3+}) fiber lasers have been developed relatively quickly with their high stability, good beam quality, and high slope efficiency. Ytterbium-doped fiber has many advantages over other rare-earth ion-doped fibers (Yb^{3+} ion absorption bands are shown in Figure 3). For example, it can effectively couple with the emission spectrum of the ZnLnAs semiconductor pump source in the range of 800~1100nm, while its absorption band is wide and the absorption cross section changes more slowly at short wavelengths (less than 970nm), which is very advantageous for pumping semiconductor lasers whose output wavelength is affected by ambient temperature and narrow emission band, i.e., there is no need to strictly control the ambient temperature to obtain matching wavelength of semiconductor laser output. Yb^{3+} energy level structure is relatively simple, containing only two multiplet states, so there is no excited absorption at the pump wavelength and signal wavelength. Yb^{3+} has a high photoconversion efficiency with a large energy level spacing, which can exclude the occurrence of non-radiative relaxation and concentration quenching. Meanwhile, the Yb^{3+} material generates a low thermal load and has a long fluorescence lifetime, which is conducive to energy storage.

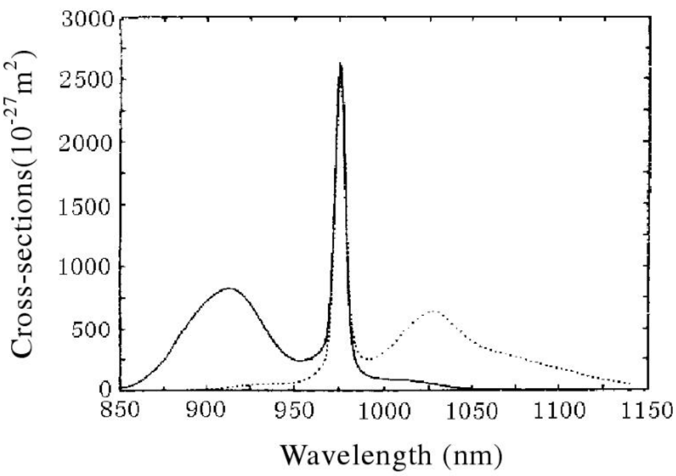

Figure 3 Absorption (solid line) and Radiation Spectrum (dashed line) of Double Cladding Ytterbium Doped Fiber

Fiber laser developed with ytterbium-doped fiber has a high slope efficiency and optical conversion efficiency, and can obtain high power laser output in the 1.06μm band, so it has received widespread attention and rapid development, becoming the dominant force in the laser industry, with excellent application prospects in industrial processing, medical and defense fields.

At present, most of the laser products produced by domestic manufacturers, such as Raycus, Hanslaser, Max, are mostly made of ytterbium-doped fiber.

Fiber lasers essentially convert low brightness multimode semiconductor pump light into a high beam quality, high power laser output through a rare earth doped gain fiber. Evidently, high quality gain fiber has a critical impact on fiber laser output power, beam quality, laser performance and reliability. The development of fiber materials has contributed to the improvement of fiber laser output power, while the renewal of fiber lasers has also traction the development direction of fiber materials. When fiber lasers were introduced in 1961, the output power was low due to the single cladding single-mode fiber, which made it difficult to effectively couple the pump light into the fiber core area. By the mid to late 1980s, with the rapid development of optical communications and the introduction and application of rare earth doped fiber and cladding pumping technology, the output power and efficiency of fiber lasers have been greatly improved.

The double-cladding technique was first proposed by Snitzer et al[6]. Due to the small diameter of single-mode fiber core, the pump light power with high NA value is more difficult to be coupled into the core effectively, while the special structure of double-clad fiber solves the problem that the pump light is difficult to be coupled into the core of single-mode fiber by directly coupling the pump light into the cladding, which significantly enhances the coupling efficiency and pump power. The double-clad fiber consists of core, inner cladding, outer cladding and coating, and its structure is illustrated in Figure 4. The fiber core consists of ytterbium-doped SiO_2 glass, which is used as a laser medium in fiber lasers and as a waveguide for single-mode lasers. The inner cladding consists of pure SiO_2, which can effectively increase the incident area of the pump light due to its much larger area and numerical aperture than the fiber core, and therefore multiple pump sources can be used. The current double-clad inner cladding has a conventional diameter of 400 μm (edge-to-edge distance) or more, and the outer cladding consists of a low-fold coating. As high power lasers generate high temperature in operation, some fiber manufacturers, in order to improve the stability of the fiber, will add another layer of fluorine doped layer outside the inner cladding, forming a three-clad fiber, and Figure 5 shows a typical three-clad ytterbium-doped fiber end-face diagram.

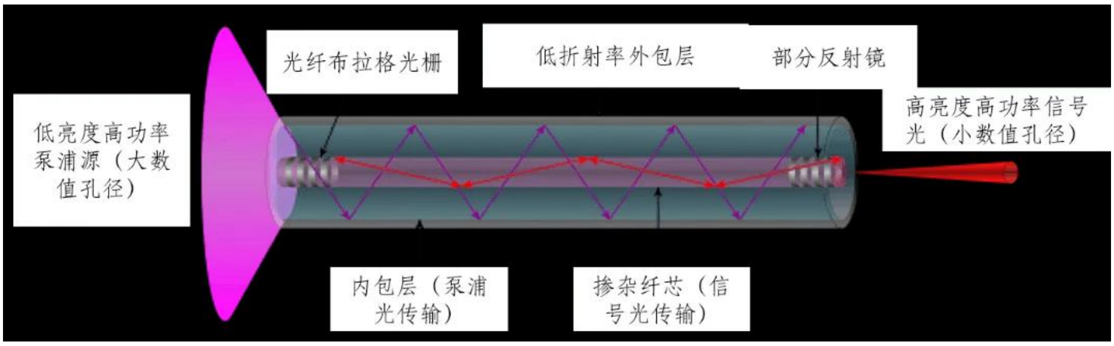

Figure 4　　Double Cladding Active Fiber Gain Effect

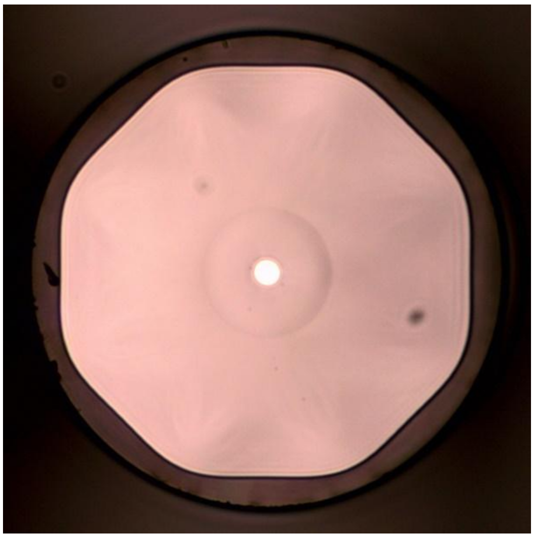

Figure 5　　Micrograph of the Endface of Triple Cladding Fiber

III. Active fiber preparation process

Active optical fiber preparation technology is not only a key determinant of active optical fiber performance, but also the core technology of each special optical fiber manufacturer, making it extremely difficult to develop. The conventional preparation processes include vapor phase, fusion, SOL-GEL and liquid phase methods.

The vapor phase method, also known as "vapor phase deposition", is generally realized by MCVD or PCVD. High-purity oxygen is selected as the carrier gas, and the chelated gas after gasification is brought into the reaction zone for deposition, and then the purity of the reactants is purified to achieve strict control of transition metal ions and hydroxyl groups, which can produce high-quality optical fibers with higher production efficiency and better fiber quality. However, the current process also has shortcomings, such as expensive raw materials, large investment in equipment, difficult gas transport, narrow range of glass composition, low doping concentration, and small refractive index adjustment range.

The process of melting method is as follows: a variety of high-purity glass powder materials and rare earth element powder are mixed, melted at high temperature and then cooled to produce doped glass prefabricated rods, which are then drawn into optical fibers. Although the doping concentration of rare earth ions in the optical fiber prepared by this method is high, there are problems such as large losses and uneven doping, which prevent commercial production.

The sol-gel method[7] means that ester compounds or metal alcohol salts are dissolved in organic solvents to form a homogeneous solution, and then other component materials are added, and hydrolysis and condensation reactions occur at a certain temperature to form a gel, which is then dried, heat treated, sintered, and other processes to make doped glass preforms, and finally drawn into optical fibers. The optical fiber prepared by this method is uniformly doped with rare earth elements and has a low reaction temperature, but there are problems such as high losses and poor mechanical strength, leading to the non-commercialization of this method.

The liquid-phase method[8] can be divided into online and offline modes, which generally involves depositing an undoped cladding layer inside a high-purity quartz tube for MCVD, then lowering the temperature to deposit a sparse core layer to ensure a good porosity of the core layer, and then placing it into a solution containing rare earth ions for immersion and then sintering. When using the in-line method, instead of taking off the liner tube from MCVD, a small diameter glass tube is placed at one end of the high-purity quartz tube, with one end of the small glass tube leading to the sparse core layer and the other end connected to the pump and the rare earth doping solution, and the doping solution delivered to the sparse core layer by the pump. Once the sparse core layer is immersed throughout, the transfer glass tube is immediately withdrawn and the quartz tube is filled with an inert gas stream, keeping the quartz tube rotating throughout the process. After completing drying, the sintered doped sparse core layers are glass layer, sintered quartz tube, cladding layer and core layer, i.e., solid prefabricated rods are obtained. In off-line mode, the liner tube with the deposited sparse body is removed by flame or cutting knife and placed in the configured doping solution, and the doping is controlled by controlling the temperature, solution concentration, soaking time, etc. Finally, after drying by drying device, the liner tube is reattached to the MCVD and fused and compacted into a solid doped mandrel. The optical fiber made by this method has low loss, higher doping concentration of rare earth ions than that made by the conventional MCVD method, and can be further increased by multiple immersions, with better doping uniformity and flexibility, and can be doped with nanoparticles containing rare earth elements, which gives the fiber more outstanding spectral properties, and thus is widely used in the fabrication of experimental and commercial rare earth doped fibers.

IV. Prospects

At present, double cladding ytterbium-doped fiber is mainly used on fiber lasers, while the upgraded triple cladding ytterbium-doped fiber is used on some high-power lasers. The triple cladding ytterbium-doped fiber can effectively improve the slope efficiency of fiber lasers, reduce the heat of the laser and improve the fluorescence life of the laser. The multi-component Yb-doped fiber prepared by the liquid-phase method features low loss, uniform doping, excellent photodarkening performance, etc., which has a certain guiding significance for the development of active optical fiber in our company.

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