Research on dispersion control technology of thulium-doped fiber laser

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Abstract. Rare earth doped optical fibers have important applications in fiber lasers, amplifiers and sensors. The Tm-doped fiber laser made with Tm-doped fiber as gain medium can be used in optical communication system. Because the fiber itself has a cylindrical waveguide structure and the core diameter of the fiber is very small, it is easy to achieve high energy density pumping in the fiber. Fiber laser has low laser threshold and good heat dissipation performance, and its core diameter matches well with the communication fiber, forming the integration of transmission fiber and active fiber, which can be an important basis for all-optical communication. However, due to the dispersion of Tm-doped fiber laser, it will lead to the broadening of laser pulse and the degradation of laser quality, which seriously affects the quality of laser communication. In this paper, the causes of dispersion are analyzed, and a dispersion adaptive control system is designed. The experimental results show that the proposed dispersion compensation system can compensate the dispersion produced in the optical fiber laser to a certain extent, so that the laser pulse can return to normal state. This is of great significance for optical communication systems.

1. Introduction
Fiber laser is one of the most active and potential fields in laser technology. Optical fiber communication is a communication mode that uses optical fibers to transmit optical signals to achieve information transmission. Compared with wireless communication, optical communication is a wired communication mode. As a transmission medium, optical fibers are composed of inner core and cladding. The inner core of optical fibers, usually tens of microns to several microns, is thinner than a hair. The outer layer of the optical fiber is called the cladding layer. Because the diameter of the optical fibers are very small and very fragile, therefore, the optical fibers have a cladding, the role of this cladding is to protect the optical fibers. In fact, in order to improve the transmission efficiency of optical fiber communication, for an optical fiber communication system, not a single fiber is used, but many optical fibers are assembled together to form the optical cable. In terms of carrying data services, the traditional optical network is designed for transmitting voice services, and the connection carrying voice services seldom changes after being established. Therefore, the traditional optical network usually adopts centralized control mode to configure the optical channels statically through the network management system, with a period of several days or even weeks. Obviously, this is unacceptable for data services with strong burst characteristics. In order to effectively carry data
services, optical networks must be able to dynamically create, dismantle and modify connections according to the real-time needs of users, and the acceptable time constraints are usually only a few seconds to a few minutes. In addition, the traditional optical network based on ring network will encounter the problem of scalability while coping with the high-speed growth of data services. Firstly, the construction cycle of the ring network is long, which makes the best investment opportunity often lost in the competitive market; secondly, when the network expands, some nodes may not need too much capacity, but the construction of the ring network usually requires that all adjacent nodes should allocate the same resources, which will inevitably cause the idle of some resources of the ring network. Macroscopically, optical fiber communication mainly includes three parts: optical fiber cable, optoelectronic device and optical communication system equipment. From the aspect of laser quality, the fiber laser has many output spectra, good monochromaticity and wide tunable range. The optical fiber has a wide incineration spectrum, many tunable parameters of the optical fiber and a wide range of choices, so it can generate more laser spectra and have a wide tuning range [1-3]. Traditional optical network achieves all-optical among nodes, but still uses electrical devices at network nodes, which limits the improvement of the total capacity of the trunk line of the current communication network, so the real all-optical network becomes a very important topic. All-optical network replaces electrical nodes with optical nodes, and the nodes are also all-optical. Information is always transmitted and exchanged in the form of light. Switches no longer process user information in bits, but determine routing according to its wavelength. All-optical network has good transparency, openness, compatibility, reliability, scalability, and can provide huge bandwidth, ultra-large capacity, extremely high processing speed, low bit error rate. As far as optical fiber communication technology itself is concerned, it should include the following main parts: optical fiber cable technology, transmission technology, optical active devices, optical passive devices and optical network technology. When optical signals are transmitted in optical fibers, dispersion phenomenon will occur, which will seriously affect the quality of optical signal transmission, and the transmission of optical signals is the most important part of optical communication system [4-6]. Therefore, it is necessary to study the dispersion phenomenon.

2. Thulium-doped fiber laser

Fiber laser, is the use of rare earth doped material in the fiber, causing gain, realize optical amplification. According to Einstein's radiation theory, for the energy level structure of an atom, the condition for optical amplification is that the rare earth ions in the active fiber can realize the population inversion. The process of population inversion is shown in figure 1.

![Population inversion process](image)

Figure 1. The process of population inversion.

As for the problem of particle number inversion, when the matter is in the thermal equilibrium state, the particle number of each energy level of rare earth ions obeys Boltzmann statistical distribution, and there is no such phenomenon at this time. For matter, under the condition of thermal equilibrium, the number of particles in high energy level is always less than that in low energy level. When the pump
light which provides energy passes through the gain fiber doped with rare earth ions, the number of stimulated absorption photons of ions is greater than that of stimulated radiation. At this time, the gain fiber is in the state of absorbing external energy, and the ions in the gain fiber can only absorb photons. As the gain fiber continuously absorbs external energy, the number of particles in the high-energy level of ions in the gain fiber will be more and more. Finally, the number of particles in the high-energy level will exceed the number of particles at the low-energy level, thus realizing the population inversion.

In general, the output power of fiber laser is relatively small, which brings some difficulties to practical application. In order to improve the output power of fiber laser, we must first find a way to improve the power of pump light to provide more energy for fiber laser. Therefore, the coupling technology can be used to combine multiple pump sources to provide energy to the fiber laser, so as to improve the output power of the fiber laser. The effective coupling of pump light is the key to develop high power TM doped fiber laser. The pump source of cladding pumped fiber laser is usually high power semiconductor laser (LD) or LD array with output tail fiber. The LD array coupled pump structure of the fiber laser is shown in figure 2.

![Figure 2. LD array coupled pumping structure of fiber laser.](image)

It is a good way to lock the laser if the laser wants to get high power. Only when the mode-locked laser is realized can the stable sequential pulse be obtained and the laser output with higher power can be obtained. The high power laser output device is shown in figure 3. Therefore, it is very important to lock the laser mode.

![Figure 3. High power laser output device.](image)

According to the working mechanism of mode locking, the main methods to realize the mode locking can be divided into active mode locking, passive mode locking, self-locking and so on. The basic principle of active mode locking is to insert a modulator into the laser cavity, and realize the phase locking of each longitudinal mode of the laser by the modulation of periodic external signals, so as to achieve the goal of mode locking. In frequency domain, active mode-locked technology uses
modulator to modulate laser amplitude or phase periodically, resulting in a series of modulation side frequencies. When the modulation frequency is equal to the longitudinal mode interval frequency, the interaction and synchronization between the modulation side frequency and its adjacent longitudinal modes can be achieved, so that the laser can form a stable mode-locked pulse output. In the time domain, the introduction of modulator is equivalent to introducing a periodic loss to the fiber laser, and the periodic output of laser pulse is realized by the periodic change of cavity loss. Passive mode-locked technology is a kind of nonlinear technology. Passive mode-locked technology can realize ultrashort pulse output without using any active device such as modulator in laser cavity, and obtain short optical pulse. The basic principle of passive mode locking is to use the nonlinear optical effect in optical fiber or other optical elements to depend on the intensity of the input pulse, so that the laser mode locking can be carried out, and the laser mode-locked pulse narrower than the input pulse can be obtained. Compared with the active mode-locked fiber laser, the passive mode-locked fiber laser is not only simple in structure and has no electronic components, but is completely integrated by all fibers, which is very beneficial to all-optical communication system. In addition, with the narrowing of the pulse, the peak intensity of the pulse increases, the interaction with the saturable absorber is further strengthened, and the pulse width is further narrowed, which can produce shorter pulses than the active mode locking technology. However, in passive mode-locked fiber laser, there are also some shortcomings. The output frequency of passive mode-locked fiber laser is limited by the length of laser cavity. Because the cavity length is too small, it is difficult to obtain high repetition rate mode-locked pulse output, which needs to be improved. At present, the main passive mode locking technologies include saturable absorber mode locking, nonlinear fiber loop mirror and other mode locking methods.

3. Dispersion control
When a pulse passes through a dispersive medium, the response of the medium is related to the frequency of the light wave, which is called dispersion. It shows the dependence of refractive index on frequency. Experiments have proved that the dispersion degree of light waves with different frequencies is different. High frequency light wave, the dispersion phenomenon is larger, and lower frequency light wave, the dispersion is smaller. Because light wave is essentially an electromagnetic wave, the analysis of light wave can be described by Maxwell equation system.

\[ \nabla \times E = -\frac{\partial B}{\partial t} \quad (1) \]
\[ \nabla \times H = J + \frac{\partial D}{\partial t} \quad (2) \]
\[ \nabla \cdot D = \rho \quad (3) \]
\[ \nabla \cdot B = 0 \quad (4) \]

Where, \( E \) represents the electric field intensity vector, \( H \) represents the magnetic field intensity vector, \( D \) represents the potential shift vector, \( B \) represents the magnetic induction intensity vector, \( J \) represents the current density vector, and \( \rho \) represents the source of the electromagnetic field.

For laser pulses, the analysis tool is the nonlinear Schrödinger equation (NLSE). Using NLSE to describe the transmission process of optical pulse in ordinary optical fiber is as follows:

\[ \frac{\partial A}{\partial z} + i\beta_2 \frac{\partial^2 A}{\partial T^2} + \alpha A - i\gamma |A|^2 A = 0 \quad (5) \]

In formula (5), \( A \) represents the slowly varying envelope of the optical field, \( \alpha \) represents the fiber loss, \( \beta_2 \) represents the group velocity dispersion coefficient of the optical fiber, and \( \gamma \) represents the nonlinear coefficient of the optical fiber.
Mathematically, the dispersion effect of an optical fiber can be solved by spreading the Taylor series at the center frequency as a transmission constant.

\[
\beta(\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2} \beta_2(\omega - \omega_0)^2 + \cdots 
\]

(6)

\[
\beta_m = \left( \frac{d^n \beta}{d\omega^n} \right)_{\omega = \omega_0} \quad (m = 0,1,2,3,\ldots) \quad (7)
\]

Where \( \beta_1 \) is the first-order dispersion coefficient and \( \beta_2 \) is the second-order dispersion coefficient.

Due to the effect of dispersion, different frequency components in the optical pulse propagate at different speeds in the media, which results in the broadening of the pulse width during the propagation of the optical pulse. In order to eliminate the effect of dispersion on the laser pulse, a part of the laser system must be designed to compensate for the dispersion. For this reason, according to the characteristics of the laser transmission process, a dispersion compensation system is set up after the laser dispersion occurs, as shown in figure 4.

![Dispersion Compensation Structure](image)

**Figure 4.** Design of dispersion compensation structure.

In this process, the dispersion compensator can compensate the dispersion in the laser to some extent. Experiments show that the pulse waveform after laser pulse compensation is shown in figure 5.

![Pulse Waveform with Different Dispersion Compensation](image)

**Figure 5.** Waveform width of light pulse with different dispersion compensation.
In figure 5, (a) the original laser pulse, (b) the laser pulse which is affected by the dispersion, (c) the laser pulse which is widened by the dispersion, (d) the laser pulse which is given a certain amount of dispersion compensation, (e) the laser pulse which is increased by the dispersion compensation, (f) the laser pulse which is basically recovered by the increase of the dispersion compensation.

As can be seen from figure 5, the laser pulse is continuously broadened due to the effect of dispersion, and the waveform of the laser pulse is gradually recovered after the action of the dispersion compensator.

4. Conclusion
Rare earth doped optical fiber lasers are widely used. In recent years, optical fiber laser has been one of the hot areas of research. Tm-doped fiber laser has important applications in medicine because its wavelength is safe for human eyes. Fiber laser is simple in composition, and its basic components include gain fiber, pump light, WDM/optical coupler, etc. Gain fiber is a special optical fiber formed by doping some rare earth elements into the core of the quartz fiber. It is the core part of the doped optical amplifier. Pumped light is used to provide energy to rare-earth elements, through the energy provided by the outside world, to reverse the number of rare-earth ions in the gain optical fiber, and then generate photoradiation to form the laser output. The function of a WDM or an optical coupler is to combine the signal light with the pump light. An adaptive compensation system based on dispersion control is designed for the dispersion generated in a fiber laser. It can better compensate the dispersion generated in a fiber laser, restore the shape of the light pulse, and ensure high quality laser output.

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