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Numerical Simulation of Thulium Doped Fiber Laser with Dispersion Compensation Technology

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Abstract: When the laser transmits in the fiber, it will produce dispersion, and the dispersion is usually expressed by the time delay difference. The reason for dispersion is that the propagation speed of light with different frequencies in the fiber is different with the increasing transmission distance during the transmission of optical signals in the fiber. The light emitted by all light sources has a certain bandwidth, and the optical transmission delay at different frequencies is different, which leads to delay difference. Time delay difference is the time difference caused by different modes or different wavelength components transmitting the same distance in an optical pulse. Because of this time difference, the laser pulse will be broadened, which is a physical effect. For an optical communication system, dispersion will affect the transmission capacity of the system, and also adversely affect the relay distance. The existence of dispersion will also affect the confusion of optical signals at the receiver, cause mutual interference between optical signal numbers, and generate wrong signal codes. This increases the bit error rate of optical signal reception, which is extremely harmful to the optical communication system. We must find ways to eliminate this adverse effect. By analyzing the causes of dispersion, a thulium doped fiber laser based on dispersion compensation is designed, a method of laser dispersion compensation is proposed, and a scheme of laser dispersion compensation is presented. The experimental results show that the intracavity dispersion can be changed by introducing a dispersion compensation system, so that the optical pulse signal can basically restore the original pulse shape. The design scheme proposed in this paper can compensate the dispersion to some extent, and the proposed dispersion compensation method is effective.

Keywords: Fiber Laser, Laser Pulse, Dispersion Compensation, Optical Transmission

1. Introduction

The light wave transmitted in optical fiber is composed of light with different frequency components. Because light waves with different frequency components or different mode components transmit at different speeds in the same fiber, the optical signal in transmission will be distorted, which is the dispersion phenomenon in the fiber [1-3]. Optical fiber dispersion is one of the common phenomena in optical fiber transmission. As long as it is a dielectric material, dispersion will occur in the process of light transmission within it, which is inevitable, and it is also one of the physical properties of materials [4-6]. When the dispersion occurs in the fiber, the optical pulse in transmission will become wider, which will affect the normal reception of the target behind. In particular, when the dispersion becomes very large, the optical pulse signal will produce overlapping front and rear pulses, and the two pulses cannot be correctly distinguished [7-9]. This will cause interference between the two signal pulses, so that the correct optical signal cannot be received at the receiving end, which is very harmful [10-12]. For an optical fiber communication system, the light source is mainly fiber laser. Fiber laser has many advantages, such as very high energy conversion efficiency, good heat dissipation effect, and no need for a huge refrigeration system. The threshold value of the fiber laser is relatively low, which is very conducive to the startup and luminescence of the laser [13-15]. Only a small amount of energy is provided to the laser, and the fiber laser can produce laser [16-20]. In the resonant cavity of the fiber laser, there are no other optical lenses, which save a lot of trouble.

There is no need to adjust the optical elements. It is also very convenient for maintenance. In addition, the laser produced by fiber laser has high stability and good beam quality. The working life of the fiber laser is relatively long, which reduces the manufacturing cost of the laser. The emission wavelength of fiber laser is determined by the kind and weight of rare earth ions doped. The rare earth doped fiber laser can achieve laser output of specific wavelength according to the properties of doped ions and doping concentration, combined with different wavelength pump light sources. In recent years, Tm doped fiber lasers have been studied extensively. The Tm doped fiber laser can produce a laser of 2000nm wavelength, which is very harmless to human eyes and can be used in various medical surgical fields. In order to make the optical communication system work normally, we must find ways to eliminate the adverse effects of dispersion on the communication system. In this paper, the dispersion in optical fiber is deeply analyzed, the idea of dispersion compensation is proposed, and a dispersion compensation system is designed to reduce the adverse effects of dispersion.

2. Analysis on Laser Dispersion

Dispersion refers to the phenomenon that light waves of different frequencies propagate at different speeds in optical fiber media, which is a physical phenomenon. Dispersion causes the optical pulse to broaden in the process of propagation, which causes the front and rear pulses to overlap each other and affects the correct reception of optical signals. There are many kinds of dispersion, among which the most important one is material dispersion. The so-called material dispersion refers to a situation where the refractive index of the optical fiber changes with the wavelength, which will lead to different propagation speeds of light at different frequencies. After a certain distance of transmission, the transmitted optical pulse will become wider, as shown in figure 1.

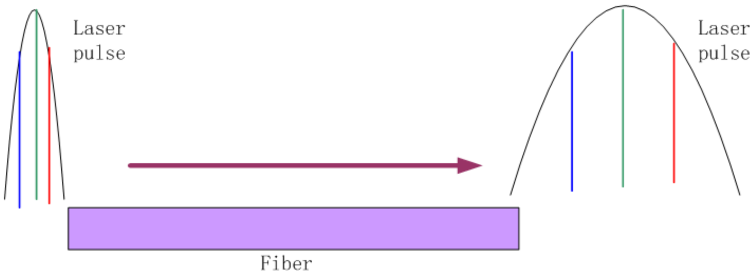

Figure 1. *Optical pulse broadening.*

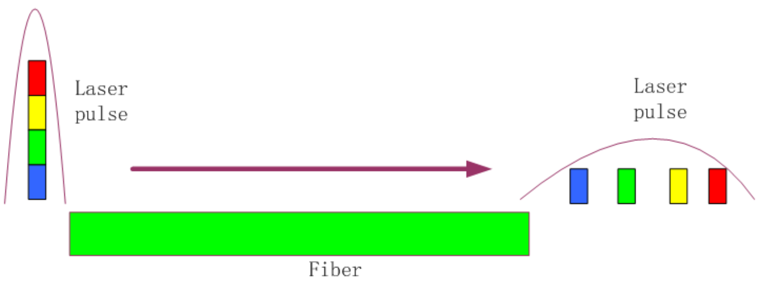

Figure 2. *Dispersion effect of materials.*

The reason of material dispersion is that the refractive index of optical fiber material changes with the frequency of light source. For light waves, light waves of different frequencies have different propagation speeds. Red light travels fast, while purple light travels slowly, which leads to the broadening effect of light pulses. The material dispersion is shown in figure 2.

Waveguide dispersion, which is due to the propagation constant of the mode, changes with the wavelength and is related to the structural parameters of the optical fiber waveguide. Both material dispersion and waveguide dispersion can occur in single-mode fiber and multimode fiber. Mode dispersion, because different conduction modes have different group velocities at the same light wave frequency, and different modes will lead to pulse broadening, as shown in figure 3. Mode dispersion mainly exists in multimode fibers.

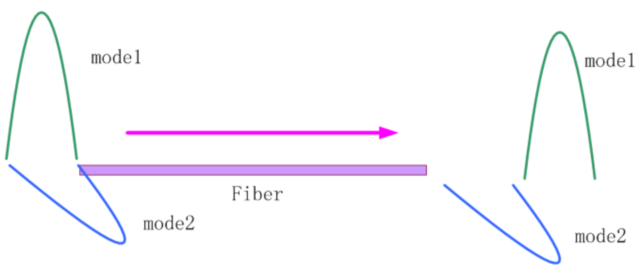

Figure 3. *Mode dispersion effect.*

When the optical signal wave is distorted, the transmitted optical pulse will be greatly changed. In the time domain, the light pulse at this time will be wider than the original pulse, but its intensity will decrease, as shown in figure 4.

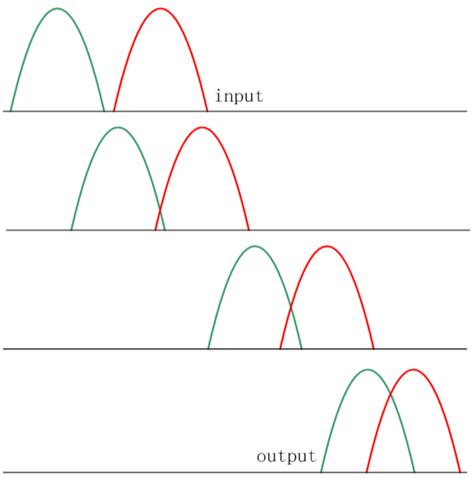

Figure 4. *Overlapping effect of two pulses.*

3. Compensation Design of Laser Dispersion

In the optical fiber communication system, in order to receive the optical pulse signal normally, the dispersion generated in the optical pulse transmission process must be compensated to eliminate the harm caused by dispersion, and the optical pulse signal must be correctly identified to maintain the normal operation of the optical communication system. In the field of dispersion compensation technology, dispersion compensation module (DCM) is sometimes called dispersion compensation unit (DCU). To sum up, there are three basic types of dispersion compensation methods. The first is pre compensation, the second is rear compensation, and the third is simultaneous compensation. The dispersion compensation method is shown in figure 5.

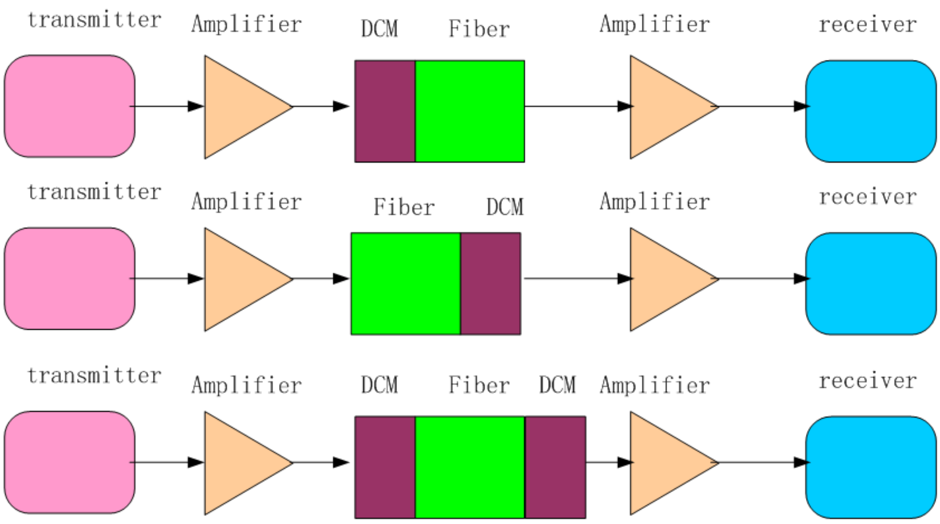

Figure 5. *Three dispersion compensation methods.*

In order to better compensate the dispersion generated during the transmission of optical signals in the fiber, a multi-level compensation scheme is designed, as shown in figure 6.

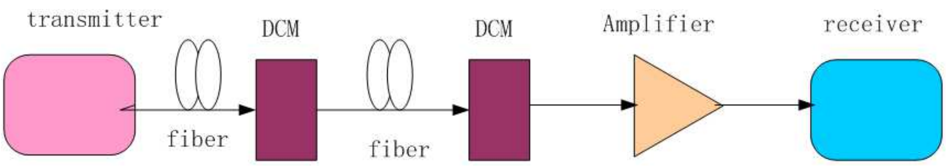

Figure 6. *Multilevel compensation scheme for dispersion.*

The dispersion problem is analyzed from a mathematical perspective. When at the starting position, the propagation equation of the optical signal is

$$U(0,\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty}U(0,T)\exp(-j\omega T)dT \qquad (1)$$

After a certain propagation distance, the equation is

$$U(z,t)=\int_{-\infty}^{\infty}U(z,\omega)\exp(-j\frac{1}{2}\beta_2\omega^2 z+j\omega T)d\omega \qquad (2)$$

If v_g is the group velocity, then the group velocity can be expressed as

$$v_g=\frac{\mathrm{d}\omega}{\mathrm{d}\beta} \qquad (3)$$

Where ω is the angular frequency of the light wave, β represents the phase propagation constant.

Use τ to indicate the group delay. The meaning of group delay is the time required for optical signal to travel a unit distance in optical fiber.

$$\tau = \frac{d\beta}{d\omega} = \frac{1}{v_g} \tag{4}$$

According to the relationship among wavelength, group delay, optical velocity and phase propagation constant, the group delay can be expressed as

$$\tau = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \tag{5}$$

As can be seen from (5), τ is the function of wavelength λ. For different λ, it will definitely lead to different τ. From the perspective of physics, its physical significance is very clear. It means that when the components of different frequencies in the optical signal propagate at different speeds, although at the input end of the optical signal, the optical signals of these components of different frequencies start at the same time, when they reach the destination, the arrival time is different for different wavelengths. The result is the broadening of the light pulse. If the transmission delay of the frequency component with the slowest propagation speed in the optical signal is allowed, the difference between the transmission delay of the frequency component with the fastest propagation speed is recorded as $\Delta\tau$. In this way, the degree of broadening of the optical pulse signal can be fully expressed by the parameter of delay difference $\Delta\tau$.

$$\Delta\tau = \frac{d\tau}{d\lambda}\Delta\lambda = -\frac{1}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)\Delta\lambda \tag{6}$$

When the optical signal propagates in the optical fiber for a certain distance, the optical pulse broadening caused by dispersion is shown in figure 7.

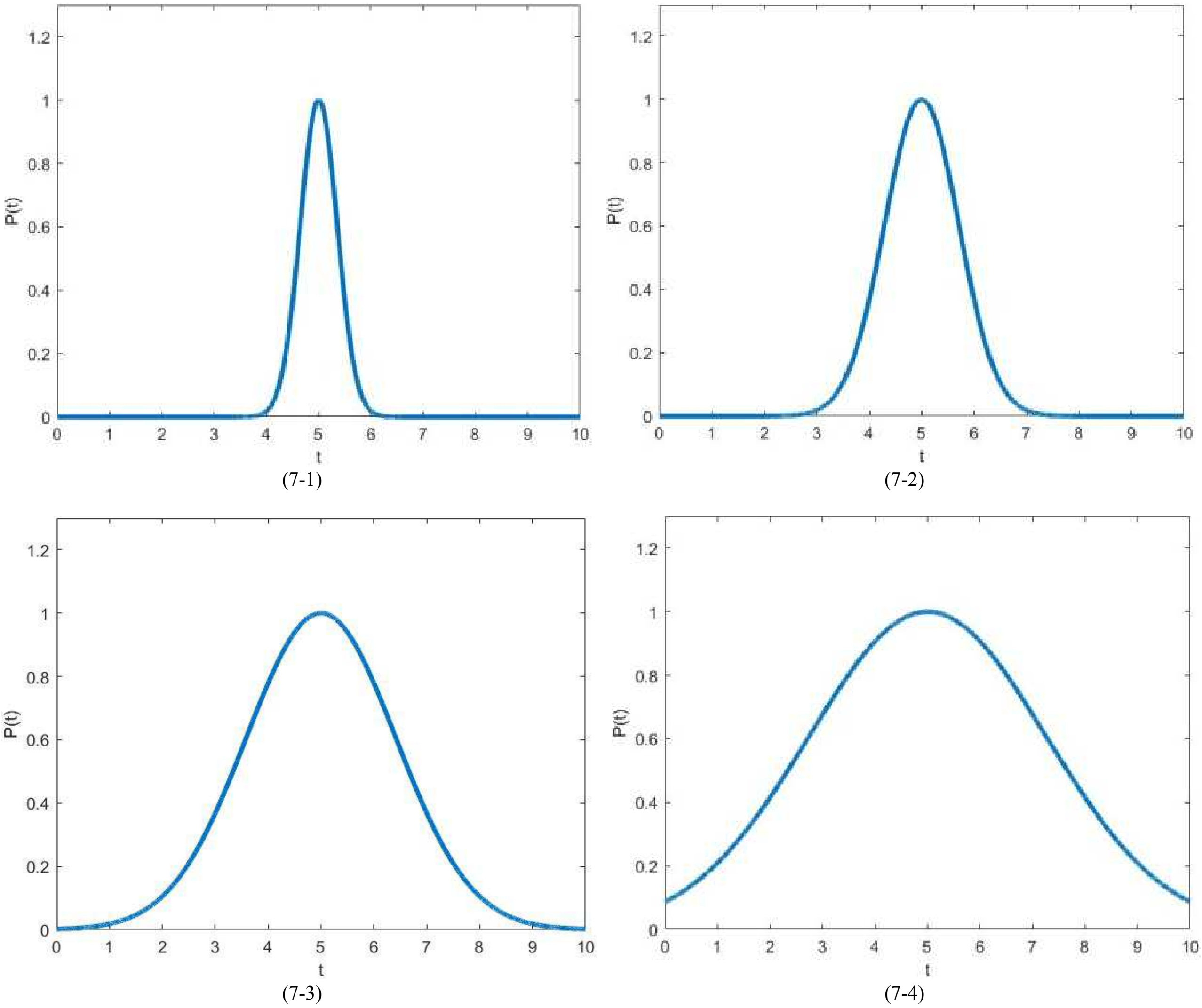

Figure 7. *Dispersion increases the width of optical pulse.*

When the dispersion compensation module is added, the width of the optical pulse decreases with the continuous dispersion compensation, as shown in figure 8.

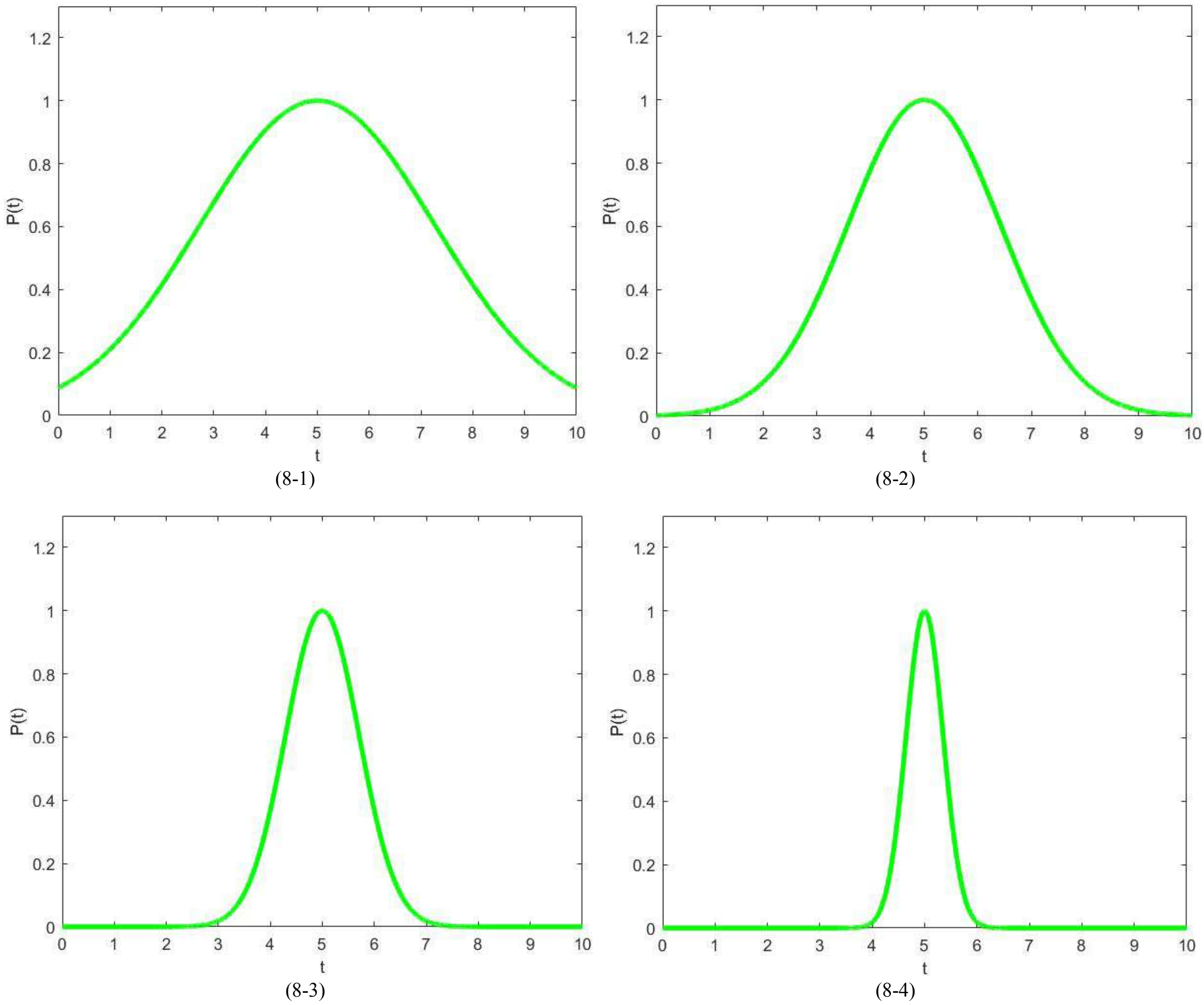

Figure 8. *The width of optical pulse decreases continuously after dispersion compensation.*

For the laser transmitted in the resonant cavity of the fiber laser, because the optical pulses with different frequencies have different group velocities in the fiber, when the laser with different frequencies transmits the same distance in the fiber, the light with different frequencies will produce a small time delay difference, leading to dispersion. If the laser pulse in the laser goes through multiple cycles in the laser cavity, the laser transmission distance will be longer. At this time, the laser has accumulated a large time delay difference, which means that the dispersion is getting larger and larger. If the dispersion is larger, the optical pulse in the fiber will be broadened to a greater extent. At this time, the optical pulse directly output from the laser will be greatly broadened. A dispersion compensation mechanism is adopted to manage the dispersion in the laser cavity. By dispersion compensation, the time delay difference of the laser will be reduced. Some researchers use a section of fiber with negative dispersion coefficient in the laser cavity, which has a certain effect on dispersion compensation. Now, the most common method for dispersion compensation is to use a medium with negative dispersion value and put it on the optical transmission path of the laser to play the role of dispersion compensation. If the dispersion compensation is good, the pulse width becomes smaller. If the dispersion is completely compensated, theoretically, the time delay difference can become zero, and then the laser pulse will completely return to its original shape.

4. Conclusion

Optical pulses transmitted in optical fibers have different frequency components, different frequencies, and different propagation speeds, which leads to dispersion. The existence of dispersion is harmful to an optical communication system. It will lead to the broadening of optical pulse, produce signal distortion, and affect the work of the receiver of the communication system. In order to avoid the bad influence of dispersion on optical communication system, a dispersion compensation scheme is designed. The numerical simulation results show that the proposed design scheme compensates the dispersion and basically restores the shape of the optical pulse, which shows that the designed dispersion compensation scheme is effective.

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