Principle and Design of Chirped Fiber Grating

Yan Mao¹,a, Xingpeng Yan ²,b, Weifeng Wang ³,c*

¹Academy of Army Armored Forces, Department of Information Communication, Beijing, China
²Academy of Army Armored Forces, Department of Information Communication, Beijing, China
³Academy of Army Armored Forces, Department of Information Communication, Beijing, China
aemail: 543555932@qq.com, bemail: yanxp@foxmail.com
cemail: wwfking@sohu.com

Abstract: At present, as a feasible solution to the dispersion problem in optical fiber communication, chirped fiber grating has been widely used and concerned. This paper analyzes the principles of linear chirped fiber gratings and nonlinear chirped fiber gratings, and on the basis of summarizing the current design of chirped fiber gratings, two implementation methods of chirped fiber gratings are proposed.

1. Introduction
With the development of optical fiber communications, network capacity is also expanding. At present, the loss and dispersion of optical fiber are the two main factors affecting the development of optical fiber communication to high speed and large capacity. Due to the emergence of erbium-doped fiber amplifier (EDFA), the difficulty of transmission loss in optical fiber communication has been overcome, and the nonlinear effect in optical fiber transmission can be controlled by changing the fiber input power. Therefore, dispersion is the main factor that limits the transmission distance in optical fiber communication systems nowº¹.

Dispersion means that the light of different colors (different frequencies) has different transmission delays in the optical fiber. The long-wavelength light transmits slowly, and the short-wavelength light transmits faster, so that they are separated from each other, so the light is expanded. In addition, this will also generate crosstalk between signals, affecting system performance. The influence of fiber dispersion on the performance of the communication system is also reflected in the limitation of the transmission rate. Dispersion will become more and more serious as the transmission distance increases, and the relay distance must also be reduced to ensure communication quality. The most important dispersion in a single-mode fiber is group delay dispersion. In addition, there are high-order dispersion and polarization mode dispersion. These dispersions will cause pulse broadening or deformation.

In addition, the transmission of light in the optical fiber will also have nonlinear distortion, which means that the optical fiber system needs to increase the light intensity for long-distance transmission. However, the light intensity will actually change the refractive index of the optical fiber, resulting in phase modulation when the optical signal is transmitted in the optical fiber. Moreover, the phase modulation will change the frequency component of the light pulse, causing pulse broadening.
Dispersion compensation technology is used to remedy dispersion and nonlinear distortion, so it is a very important technology for optical communication systems. The current schemes for realizing dispersion compensation mainly include the following: 1) All-pass filters (APFs-all-pass-filters) used as ring resonators. APFs can perform dispersion compensation without introducing amplitude changes, but they are far from practical. There is a considerable distance[2]; 2) Tunable dispersion compensation based on VIPA (virtually imaged phased array). VIPA is a kind of light structure whose output light angle depends on the wavelength of light; 3) Based on chirp Various tunable dispersion compensation schemes realized by fiber grating stress and temperature characteristics. Each of the above methods has its own advantages and disadvantages, and the chirped fiber grating is easy to integrate due to its all-fiber type, with small nonlinear effects, small insertion loss, small size, large compensation, independent of polarization, good compatibility, flexibility and convenience, etc. The advantages have attracted much attention and have been widely used. Moreover, the use of it for dispersion compensation has begun to be practical[3].

As shown in Figure 1, the stretched light pulse enters the chirped fiber grating through the circulator (its period linearly changes along the longitudinal direction of the grating). When a pulse is incident on the chirped fiber grating, different spectral components of the pulse are reflected by different parts of the grating. Long-wavelength (slow propagation speed) light is reflected first, and short-wavelength (fast propagation speed) light is reflected later, so that although long-wavelength light is delayed more by the dispersion fiber, it is delayed less in the chirped fiber grating, resulting the transmission time in the chirped fiber grating becomes shorter, while the short-wavelength light is delayed less by the dispersive fiber, but in the chirped fiber grating, the delay is much longer, resulting the transmission time in the chirped fiber grating becomes longer. So the dispersion generated by the signal pulse is largely compensated. After passing through the chirped fiber grating, the original broadened optical signal is compressed and matched to the same output time. Therefore, the chirped fiber grating can be used as a dispersion compensator. In practical applications, a 1cm chirped fiber grating can produce a delay of 0.1ns, that is, as long as there is a centimeter-level chirped fiber grating, a light pulse wavelength can be generated.

![Figure 1 Schematic diagram of the dispersion compensation principle of chirped grating](image)

2. The principle of chirped fiber grating
The chirped fiber grating can be regarded as a filter composed of resonant wavelengths distributed according to a certain law, and the reflected light wavelength selected by each filter changes regularly with the length of the chirped fiber grating. Chirped fiber grating is an important non-uniform grating, which is divided into linear chirp and nonlinear chirp. Linear chirped grating means that the grating period changes linearly along the axis, and nonlinear fiber grating is nonlinear.

The refractive index of the chirped fiber grating along the Z axis can be expressed as[4]:

\[
\Delta n = \Delta n \left[ 1 + \nu \cos \left( \frac{2\pi}{\Lambda} z + \varphi(z) \right) \right]
\]  
(1)
In formula (1), the DC component, $\Delta n$, is the average value of the effective refractive index change of the fiber grating core in each grating period, and the amplitude of the AC component, $\tilde{\Delta} n$, represents the effective refractive index change of the core, $\nu$ is the visibility of the refractive index change fringe. This visibility is generally a constant, usually taking a value of 0.5 or 1. $\Lambda$ is a constant, which represents the period of the center of the grating. $\varphi(z)$ is the phase of the refractive index change fringe, and is usually used to describe the amount of chirp of the grating. Different types of fiber gratings are mainly described and distinguished by $\Delta n$ or $\varphi(z)$.

Assume the spatial frequency at a certain point of the grating as $\omega(z)$, which can be calculated by the following formula:

$$\omega(z) = \frac{d\left(\frac{2\pi}{\Lambda} z + \varphi(z)\right)}{dz} = \frac{2\pi}{\Lambda} + \frac{d\varphi(z)}{dz}$$  \hspace{1cm} (2)

The period at a certain point of the grating is $T(z)$, which changes along the axial direction of the grating, resulting in the chirp of the grating. It can be calculated by the following formula:

$$T(z) = \frac{2\pi}{\omega(z)} = \left(\frac{1}{\Lambda} + \frac{d\varphi(z)}{2\pi dz}\right)^{-1}$$  \hspace{1cm} (3)

Expand $T(z)$, we can get

$$T(z) = \left(\frac{1}{\Lambda}\right)^{-1} \left(-1\right) \left(\frac{1}{\Lambda}\right)^{-2} \frac{d\varphi(z)}{2\pi dz} + \left(-1\right) \left(\frac{1}{2!}\right) \left(\frac{1}{\Lambda}\right)^{-3} \left(\frac{d\varphi(z)}{2\pi dz}\right)^2 + \cdots$$

i.e.

$$T(z) = \Lambda \left(-\frac{\Lambda^2}{2\pi} \frac{d\varphi(z)}{dz} + \frac{\Lambda^3}{4\pi^2} \left(\frac{d\varphi(z)}{dz}\right)^2\right) + \cdots$$  \hspace{1cm} (4)

$\Lambda$ is a constant, so formula (4) can be written as

$$T(z) = \Lambda \{1 - C_1 z - C_2 z^2 - \cdots\}$$  \hspace{1cm} (5)

The change of $\varphi(z)$ changes the period of the grating. In formula (5), the first term is a constant, which represents a uniform grating, the second term represents a linear chirped grating, which is a linear chirp coefficient, which can be used to compensate for the first-order dispersion, and the unit is $cm^{-1}$; $C_2$ is the second-order chirp coefficient, also called the first-order nonlinear chirp coefficient, which can be used to compensate the second-order dispersion (i.e. the dispersion slope), and the unit is $cm^{-2}$. The third term and later are all high-order nonlinear chirps. Because the coefficients of the three terms or more are small, they are generally ignored\cite{5}. For a uniform grating, $T(z)$ is a constant, $C_1 = C_2 = 0$; for a linear chirped grating, $T(z)$ changes linearly with $z$, $C_1 \neq 0, C_2 = 0$; and for a non-linear chirped grating, $T(z)$ changes nonlinearly with $z$, $C_2 \neq 0$\cite{6}.

3. **The design of chirped fiber grating**

Generally, the input light of the chirped fiber grating is not single, and the working environment changes
dynamically, so the chirped fiber grating that can adjust the dispersion parameter has become the consensus of the developers. As a new type of optical fiber device, the chirped fiber grating has sensitive optical frequency selection characteristics. Due to the elasto-optical and thermo-optical effects of chirped fiber gratings\(^7\), its refractive index modulation is very sensitive to environmental factors such as temperature and stress, so it can be precisely adjusted by applying stress or temperature field to the chirped fiber grating dispersion parameters of chirped fiber gratings. The advantages of the stress tuning of the chirped fiber grating over the temperature tuning are: the adjustment range is large, the response speed is fast, and the ambient temperature within a certain range will not cause significant changes to the pulse. In addition, the fiber grating can be coupled with the fiber structure system, and its loss is small compared with other coupling methods.

Linear chirped fiber grating (LCFG) is an important dispersion compensation method in optical communication systems. It realizes the function of broadening or compressing the light pulse because the period of the grating is distributed in a linear law along the fiber axis. Someone designed a cascaded chirped fiber grating\(^8\), and used it as a dispersion compensation device in an eight-channel high-speed transmission system. Experiments show that the cascaded chirped grating can perform better dispersion compensation; someone use nonlinear double exposure method to make chirped grating\(^9\). Because the photosensitive fiber refractive index increment and the exposure amount have a nonlinear change law, before writing the grating, scan exposure according to the designed exposure distribution, a fiber grating with linear change of effective refractive index and uniform distribution of grating refractive index modulation will be obtained; someone proposed to apply a continuous linear temperature gradient field\(^7\). By adjusting the gradient of the continuous temperature gradient field, precise modulation of the dispersion of linear chirped fiber grating can be achieved.

Although linearly chirped fiber gratings have a series of advantages such as large and stable dispersion, adjustable bandwidth, and easy control. However, for a certain wavelength channel, dispersion accumulation is a process that changes with time. Due to the complexity of the network, the wavelength channels in the network may be transmitted from endpoints at different distances, that is, the amount of dispersion compensation required for a signal of a certain wavelength at a specific location varies, and the system will be interfered by many external factors to produce dynamically changing dispersion. For example, changes in the operating environment of the transmission system (such as lasers and modulators) may also cause the dispersion effect in a single channel to change over time. In addition, the certain sensitivity to temperature that optical fiber and other communication devices have, the change of signal power causes the influence of fiber nonlinearity, the influence of the gain flatness of erbium-doped fiber amplifier, and the change of optical power caused by the undesirable gain balance, each will lead to additional nonlinear phase shift, thereby changing the dispersion distribution of the system.

If only LCFG is used for compensation, the effect is not ideal, and the nonlinear chirped grating (NLCFG) can provide larger spectral width and time delay of nonlinear variation. Therefore, as long as the grating chirped parameters are accurately controlled, it can be used for the compensation of dispersion and dispersion slope to realize the tunable dispersion, meeting the needs of high-rate, long-distance Dense Wavelength Division Multiplexing (DWDM) systems, dynamically tracking and compensating the dispersion accumulation of the channel. It can be seen that the use of nonlinear chirped fiber gratings is an effective means to dynamically compensate high-order dispersion in high-speed optical fiber communication systems.

The reflection wavelength of the grating is

\[
\lambda_n = 2\Delta n\Lambda
\]  

From equation (6), it can be seen that different wavelengths are reflected at different grid periods. To make a nonlinear chirped grating, only \(\lambda_n\), the local center reflection wavelength of the grating, needs to be nonlinearily changed along the z direction. There are many manufacturing methods for nonlinear chirped fiber gratings. Such as: using a nonlinear chirp mask; using a linear mask, but the exposure time is changed along the length of the grating; applying a nonlinear stress gradient in the direction of the
fiber axis, and releasing the stress after the production is completed, the uniform grating can generate modulation period \( T(z) \) along the axis of the grating, which has an axial nonlinear distribution, so as to realize nonlinear chirp and achieve the purpose of tuning.

Specifically, some people use a smaller voltage amplitude to PZT the linear chirped fiber grating to introduce an approximate second-order chirp\(^{(5)}\), and turn it into a nonlinear chirped fiber grating, or use a larger voltage amplitude to make a uniform grating into an approximate nonlinear chirped fiber grating; some people use high birefringence fiber to make a nonlinear chirped grating, and it has been studied to compensate for polarization mode dispersion. Such a nonlinear chirped grating works at high speeds. It plays an important role in optical communication systems; some people have improved the geometry of the chirped fiber grating itself\(^{(10)}\), that is, by designing the cross-sectional area of the chirped fiber grating to change nonlinearly in the direction of the grating axis, such as using a uniform mask to illuminate the photosensitive fiber during the production process, so as to realize the tuning of nonlinear chirped fiber grating; some people propose bending nonlinear strain chirp\(^{(11)}\), as shown in Figure 2, that is, the grating is fixed to the deflection plate, and one end of the deflection plate is fixed and is called the "fixed end", and the other end is not fixed and is called the "free end". When the “free end” of the deflection plate is tilted upwards, the upper surface of the deflection plate produces nonlinear strain, thereby completing the dispersion compensation for the input light; some people use the magnetostrictive effect to make nonlinear strain chirp\(^{(12)}\), as shown in Figure 3. When a material with magnetostrictive properties is placed in a magnetic field, the length and volume of the material will change. The change in the length direction is called linear magnetostriction, the change in volume are called volume magnetostriction. Generally, volume magnetostriction is much weaker than linear magnetostriction. This effect can be used to make nonlinear strain chirp, which can be implemented in two forms, namely, bonding a uniform fiber grating on the bulk magnetostrictive material, coating or plating a uniform film of magnetostrictive material on the surface of the uniform fiber grating.
However, the manufacturing cost of the chirped fiber grating is relatively high, and once the existing chirped fiber grating is produced, the reticle is fixed, and the dispersion compensation characteristic is determined accordingly. Therefore, improving the adaptability and reproducibility of chirped fiber gratings has become a research focus. Here, two designs of chirped fiber grating are proposed.

(1) The prism has different refraction characteristics of light, which can cause dispersion. Similarly, we can look for special materials and structures, and use the different reflection characteristics of light that special materials and structures themselves have at different wavelengths, so as to achieve compensation for input light dispersion. This approach seeks to realize the adaptability of the fiber grating from the material and structure. It can be predicted that this method has a complicated manufacturing process and high requirements for materials and structures.

(2) When knowing the composition of the input light (for example, a spectrometer can be added in front of the system), use a computer program to engrave and erase the lines on the chirped fiber grating, so as to realize the dispersion compensation of the input light. The advantage is that it can be reused. As long as the composition of the incident light can be analyzed, the corresponding chirped grating can be generated. This method requires the system to quickly respond to changes of the input light, but once it is implemented, it can be widely used in the field of scientific research and experimentation. For incident light with simple components, the effect is more obvious.

4. summary
This article starts from dispersion, the main factor that affects the development of optical fiber communication to high-speed and large-capacity, and analyzes the solution to the dispersion, that is, the principle of chirped fiber grating, and then summarizes the existing chirped fiber grating design method. Based on this, for the purpose of improving the adaptability and reproducibility of chirped fiber gratings, two designs of chirped fiber gratings are proposed, which provide possible ideas for the next research of scientific researchers.

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