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Investigation on the Dispersion Compensation Algorithm in Optical Fiber Communication with Large Capacity

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Abstract

Optical network faces increasing challenges with the development of telecommunication demand. The fiber must carry much more transmission channels with higher optical power and transmission rate and it causes higher dispersion. At present, people have proposed some technical solution for this problem, including the dispersion compensation fiber (DCF), midpoint spectral inversion, dispersion managed transmission, chirped fiber grating (FBG), and so on. But algorithm with higher compensating efficiency is still needed. In this paper, we propose a modified algorithm to compensate the dispersion. With the simulation method, we obtained the characteristics of dispersion and dispersion slope with the variation of wavelength λ, and some useful conclusion has been acquired. With the increasing of wavelength λ, dispersion and its slope coefficient have different variation disciplinarian. From the simulation results, we can verify the conclusion that it needs to optimize the design of the structure of optical fiber if we want to compensate the dispersion and dispersion slope simultaneously.

Keywords: *optical fiber, dispersion, compensation algorithm, photonic fiber*

1. Introduction

With the development of optical devices [1-3] and system technology, optical network is facing increasing challenges. The fiber will carry much more transmission channels, higher optical power, higher transmission rate, longer distance. At the same time, pulse becomes more and more narrow. Higher dispersion [4-6] will cause serious broadening and distortion and produce intersymbol interference. This will increase the bit error rate of the receiver and hindered the development of high-speed optical fiber systems. Dispersion of optical fiber has become the main obstacle in capacity upgrading for optical fiber system, and how to solve this problem has become a hot research topic.

In optical fiber transmission, signal transmission rates of different frequency are different, and there will be different time delay τ after the same transmission distance, which will lead to different $\Delta\tau$. The bigger time delay difference, the more seriously of the dispersion. The specific performance is that the optical pulse has been broadened in the transmission process in the optical fiber. So the dispersion is always measured with the group delay per unit length.

At present, people have proposed some technical solution for this problem, including the dispersion compensation fiber (DCF), midpoint spectral inversion [7], dispersion managed transmission [8-9], chirped fiber grating (FBG), and so on.

In this paper, a new compensation algorithm has been proposed. And the main contribution is the proposition of the new method to compensate for the optical fiber. The remainder of the paper is organized as the following: compensation methods are listed in section 2. Modified compensation method is shown in section 3. Simulation and analysis are given in section 4. And the conclusion is described in section 5.

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2 Dispersion and Compensation Methods

Figure 1 and figure 2 shows a kind of pulse and its broadening characteristics.

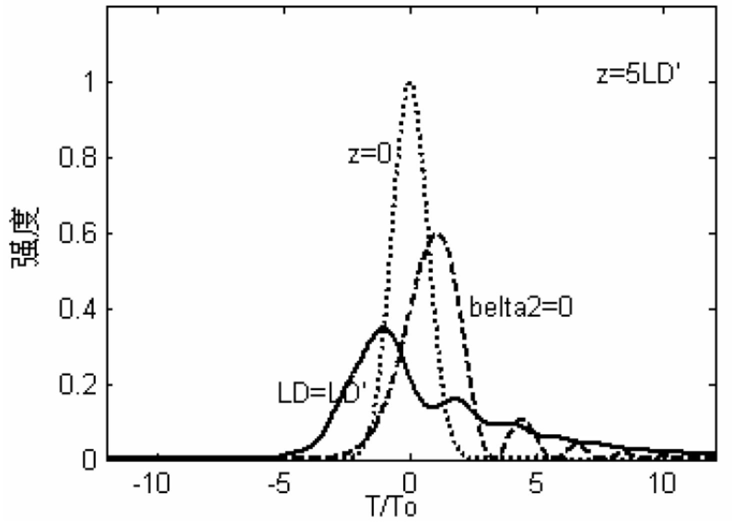

Figure 2. Gauss Pulse

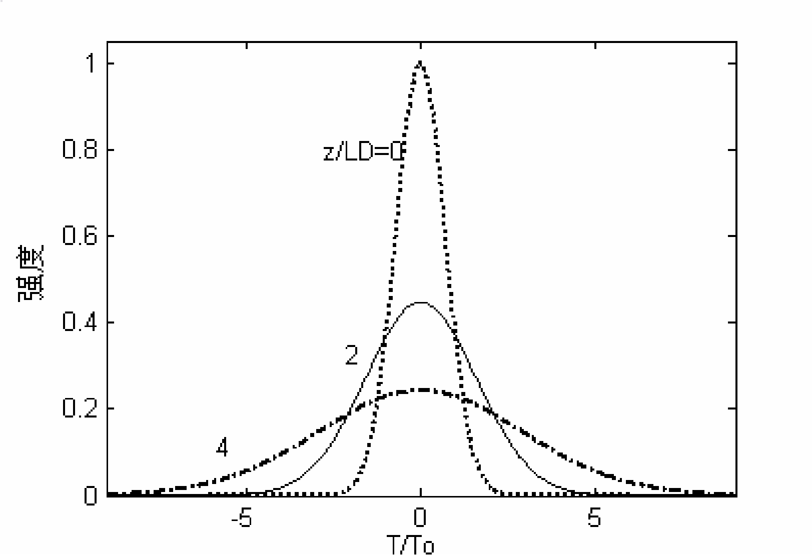

Figure1. Gauss Pulse Broadening Induced by Dispersion in Optical Fiber

The basic principle of dispersion compensation for optical fiber transmission is offset the dispersion by one or more large negative dispersion to compensate the accumulated dispersion, and then the total amount of dispersion of the system will be decreased. The most conventional methods of dispersion compensation are: dispersion compensation fiber (DCF), chirped fiber grating, electronic dispersion compensation technology, and so on.

(1) Dispersion compensation fiber (DCF) [10-13]

The conventional DCF is the most common technology used in the compensation of dispersion communication system, and the development is quite mature. DCF is a passive device with flexible and convenient installation, and it can realize the compensation for broadband dispersion, first order dispersion, the second order dispersion. It also can be compatible with standard single mode fiber at 1310nm. If proper control is given to its mode field diameter and improve welding technology, DCF can obtain small insertion loss. It is part of the focuses of current research.

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The concept of DCF was first proposed in 1980, successful application of EDFA (Erbium-doped Optical Fiber Amplifier) in communication system has accelerated the development of DCF. DCF is also from the matched clad type to multi cladding refractive index profile. Multi cladding structures can acquire high negative dispersion and negative dispersion slope. At the same time, it can reduce the bending loss. The quality factor DCF, which is defined as the ratio of absolute value of dispersion coefficient and attenuation coefficient, is higher and higher. In order to obtain DCF with large negative dispersion coefficient, waveguide dispersion must be controlled. There are now a large number of commercial DCF used in the compensation for dispersion of C band and L band transmission in G. 652 optical fibers.

In the long distance optical cable transmission system, Dispersion Compensation Modules (DCM0, which are made up of DCF, are usually configured at each (some) output end to offset the transmission fiber dispersion. Dispersion compensation technology, which almost just used a section of DCF, exists in certain aspects the flaw. So, it promotes some new technologies, such as manageable dispersion compensation module (M2DCM), and so on.

The basic compensation principle is described as follows. Dispersion and dispersion slope compensation of transmission fiber can be compensated according to select the appropriate length of DCF. It should meet the demand of the follows:

$$\mathrm{D}(\lambda_S)L + D_C(\lambda_S)L_C = 0 \tag{1}$$

Where, $\mathrm{D}(\lambda_S)$, and $D_C(\lambda_S)$ are dispersion coefficient of optical fiber and DCF at the working wavelength of λ_S; L and L_e are the corresponding length, respectively

Compensation ability of DCF on the transmission fiber dispersion slope can be expressed by relative dispersion slope, which can be defined as follows:

$$\mathrm{RDS} = \frac{S_\lambda}{D_\lambda} \tag{2}$$

Where, RDS is the relative dispersion slope; S_λ and D_λ are dispersion slope and dispersion coefficient of fiber at a wavelength, respectively. Ideally, when DCF and optical fiber RDS are equal, full compensation for fiber dispersion slope can be realized. This is to say that:

$$\mathrm{S/D} = |\mathrm{S_c}|/|\mathrm{D_c}| \tag{3}$$

Where, S and D are dispersion slope and dispersion coefficient of the optical fiber; $\mathrm{S_c}$ and $\mathrm{D_c}$ are dispersion slope and dispersion coefficient of DCF;

When DCF is selected, both dispersion coefficient and attenuation coefficient must be taken into consideration. The Figure of Merit can be defined as follows:

$$\mathrm{FOM} = \frac{|\mathrm{D_c}|}{\alpha_\mathrm{c}} \tag{4}$$

Where, $\mathrm{D_c}$ and α_c are negative dispersion coefficient and attenuation coefficient of DCF.

(2) Fiber Bragg grating (FBG) dispersion compensation [14-17]

Fiber Bragg grating (FB G) dispersion compensation is proposed in 1982 by F. Ouellette. The chirped Bragg gratings are used as reflective filter to compensate dispersion. However, further application is in the development of the manufacturing process. An advantage of chirped fiber grating compensation method is the device with miniaturization, compactable structure, low insertion loss and nonlinear effects, insensitive to the polarization, and so on. It also can be dynamically adjusted by stress or temperature. Chirped fiber grating is one of the devices to effectively compensate the dispersion. The principle is as follows: when the pulse cross through the linear chirped

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fiber grating, time delay of light with a short wavelength is longer than that of light with longer wavelength, and this just plays the role of dispersion equalization to realize the dispersion compensation. Predominant FBG dispersion compensation module is used in multi-channel FBG technology. With the development of the new technology, the more vitality products have been developed with strong adaptability.

Here, we give the basic principle of the FBG. The refractive index can be described as follows:

$$n(z) = n_o + \Delta n(z)\cos(\omega z + \Phi(z)) \quad (5)$$

Where, n_0 is the refractive index of core region with no disturbance; $\Delta n(z)$ represents the refractive index perturbation; $\omega = 2\pi / \Lambda_0$ is a spatial frequency of FBG; Λ_0 is the period of FBG at the midpoint.

For linear FBG,

$$\int_0^z B(z') = 2\delta\beta z - \Phi(z) \quad (6)$$

Where, βz is the detuning of propagation constant. Define the local reflective constant of FBG as follows:

$$\gamma(z) = \frac{R(z)}{T(z)}\exp(j\Phi) \quad (7)$$

Then we can get Riccati differential equation:

$$\gamma' = K(z)(1-\gamma^2) + j[2\Delta\beta - \Phi'(z)]\gamma \quad (8)$$

Combined with the response of reflectance spectrum, we can get the reflectance spectrum characteristics and delay characteristics of linear FBG.

(3) Photonic crystal DCF [18-21]

Photonic crystal fiber (PCF) is a new research field, and it has 3 advantages. Firstly, single mode transmission can be supported over a wide range of frequencies; Secondly, area of fiber core can be changed in order to weaken or strengthen the fiber nonlinear effects; Thirdly, dispersion and dispersion slope can be flexibly designed to provide broadband dispersion compensation. PCF can bring the wavelength with no dispersion below 1 μm. This is because the PCF is made of the same material, and refractive index of the core and cladding will not be restricted to the material incompatibility. Besides, the mechanical and thermal properties of the core and cladding can be completely matched. Mode characteristics of PCF changed rapidly with the variation of wavelength. It can get a larger dispersion in a wide wavelength range and realize the anomalous dispersion.

(4) EDC [22-25]

EDC technology has gradually attracted more attention due to its advantages of miniaturization, low power and low cost. EDC is based on electronic filter technology for fiber dispersion compensation. It can effectively adjust the received signal waveform according to sample in an electric field, software optimization and signal recovering to achieve the effect of dispersion compensation. In actual application, the most common use is the feed forward equalizer (FFE) and decision feedback equalizer (DFE) in order to realize the adaptive EDC. EDC is not only cheaper than the optical dispersion compensation technique, but also used with cheap laser. The EDC modules are generally located at the receiver of the transceiver and eliminate dispersion according to the conversion between photo and electric.

3. Compensation Methods

In order to meet the demands of broadband transmission, compensation for dispersion slope should be also considered when compensation for dispersion is given. One of the

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methods for dispersion compensation is the dispersion compensation fiber. We will give a modified method based on the PCF.

We can get the characteristic equation of cladding space filling mode as follows:

$$\frac{I_2(\mathrm{wr})}{I_1(\mathrm{wr})}+\frac{1}{wr}+\frac{wr}{2}\left(1+\frac{n_2^2}{n_1^2}\right)g(u)+wr\left[\frac{1}{4}\left(1-\frac{n_2^2}{n_1^2}\right)^2 g^2(u)+\frac{f(w,u)}{n_1^2}\right]^{1/2}=0 \quad (9)$$

Where,

$$g(u)=\frac{1}{wr}\frac{J_0(ur)Y_1(uR)-Y_0(ur)J_1(uR)}{J_1(ur)Y_1(uR)-Y_1(ur)J_1(uR)}-\frac{1}{u^2r^2} \quad (10)$$

$$f(w,u)=\frac{1}{r^4}\left(\frac{1}{u^2}+\frac{1}{w^2}\right)\left(\frac{n_2^2}{u^2}+\frac{n_1^2}{w^2}\right) \quad (11)$$

Where, n_1 and n_2 are refracted index of air and quartz medium. Generally n_1 is often set with a value of 1.0. Take the material dispersion into consideration, n_2 is often calculated by Sellmeier formula. R is determined by the equal area method, and R is set with the value of 0.525A. The parameters of w and u meet the demand of conditions described as follows:

$$w^2+u^2=\frac{\omega^2\left(n_2^2-n_1^2\right)}{c^2} \quad (12)$$

$$w^2=\frac{\omega^2\left(n_{eff}^2-n_1^2\right)}{c^2} \quad (13)$$

$$u^2=\frac{\omega^2\left(n_2^2-n_{eff}^2\right)}{c^2} \quad (14)$$

And then, we can get the principle of effective refractive index with the variation of optical frequency for cladding mode according to the numerical solution.

$$n_{eff}(\omega)=\sqrt{\frac{n_2^2-u^2(\omega)c^2}{\omega^2}} \quad (15)$$

Vector method is used to solve the waveguide mode and dispersion characteristics. Characteristic equation can be obtained as follows:

$$m^2\left[\frac{1}{U^2}+\frac{1}{W^2}\right]\left[\frac{n_1^2}{U^2}+\frac{n_2^2}{W^2}\right]=\left[\frac{1}{U}\frac{J_m(U)}{J_m(U)}+\frac{1}{W}\frac{K_m(W)}{K_m(W)}\right]\times\left[\frac{n_1^2 J_m(U)}{U\cdot J_m(U)}+\frac{n_2^2}{W}\frac{K_m(W)}{K_m(W)}\right] \quad (16)$$

If set $m=1$, then we can get the characteristics function followed by base mode in the optical fiber.

$$\frac{J_0(U)}{J_1(U)}=\frac{1}{U}+\frac{U}{2}\left(1+\frac{n_2^2}{n_1^2}\right)\left[\frac{1}{W^2}+\frac{K_0(W)}{W\cdot K_1(W)}\right]-\frac{U}{2}\sqrt{\left(1-\frac{n_2^2}{n_1^2}\right)^2\cdot\left[\frac{1}{W^2}+\frac{K_0(W)}{W\cdot K_1(W)}\right]^2+4F(U,W)} \quad (17)$$

According to the optics principle of waveguide, coefficient of fiber group velocity dispersion can be calculated by:

$$D=\frac{d\tau}{d\lambda}=-\frac{\omega^2}{2\pi c}\frac{d^2\beta_c}{d\omega^2} \quad (18)$$

This function includes the material dispersion, waveguide dispersion and profile dispersion. And then we can get the relationship between fiber dispersion slope D_{slop} with wavelength variation as follows:

$$D_{slop} = \frac{dD}{d\lambda} = -\frac{1}{\lambda^2}\frac{dD}{d\omega} \tag{19}$$

Since the dispersion coefficient of fiber D varies with the variation of wavelength. In order to meet the needs of broadband dispersion compensation, compensation for both dispersion and dispersion slope coefficients should be process at the same time. Then, the compensation condition for broadband dispersion can be described as follows:

$$D_1 L_1 + D_2 L_2 = 0 \tag{20}$$

$$D_{slope_1} L_1 + D_{slope2}\ L_2 = 0 \tag{21}$$

Where L_1 D_1 and D_{slope_1} are optical fiber length, dispersion coefficient and dispersion slope coefficient L_2 D_2, and D_{slope_2} are compensated optical fiber length, dispersion coefficient and dispersion slope coefficient. Then, length of compensating fiber for dispersion should meet the demand of $L_2 = -\frac{D_1 L_1}{D_2}$. Consider the dispersion coefficient and dispersion slope coefficient, we can get the follows:

$$\frac{D_1}{D_{slope_1}} = -\frac{D_2}{D_{slope_2}} \tag{22}$$

In order to describe the relationship between D and D_{slope}, a new parameter has been defined as follows:

$$\kappa = \frac{D}{D_{slope}} \tag{23}$$

It is used to represent the ability of device to compensate for the dispersion and dispersion slope. Generally, requirements for dispersion compensation fiber have the same or close value of κ with that of optical fiber needed compensation.

4 Simulation and Analysis

Three different ways are used to investigate the main factors influencing the dispersion compensation characteristics of photonic crystal fiber. Parameters of air hole pitch Λ and cladding air hole radius r are adjusted to get the aim.

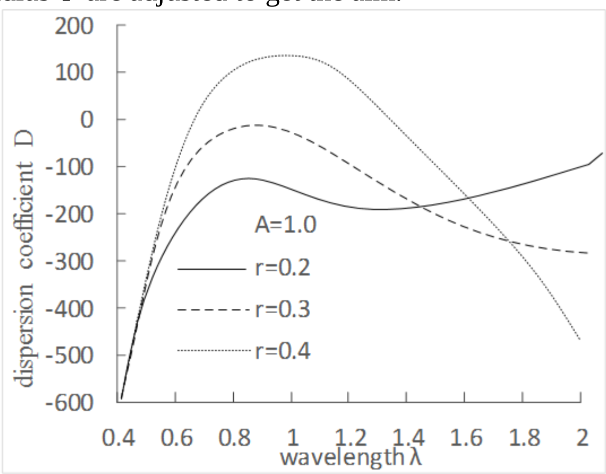

Figure3. Variation Curve of Dispersion Value D with the Wavelength λ

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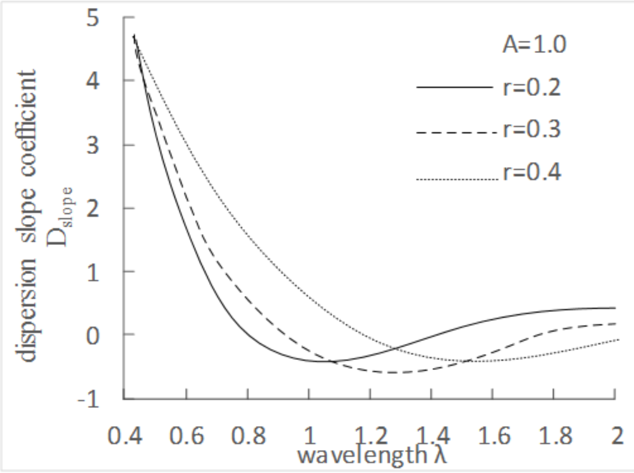

Figure4. Variation curve of dispersion slope Dslope with the wavelength λ

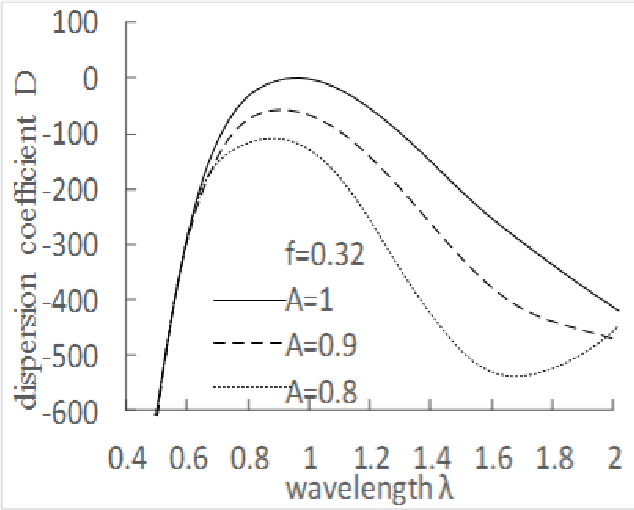

Figure 5. Variation Curve of Dispersion value D with the Wavelength λ

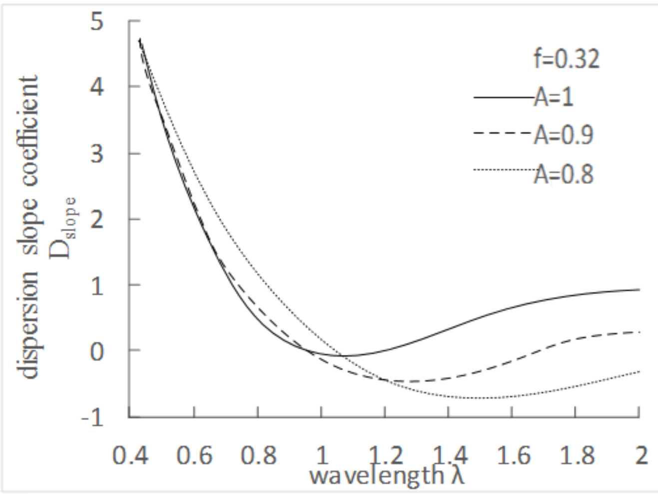

Figure6. Variation Curve of Dispersion Slope Dslope with the Wavelength λ

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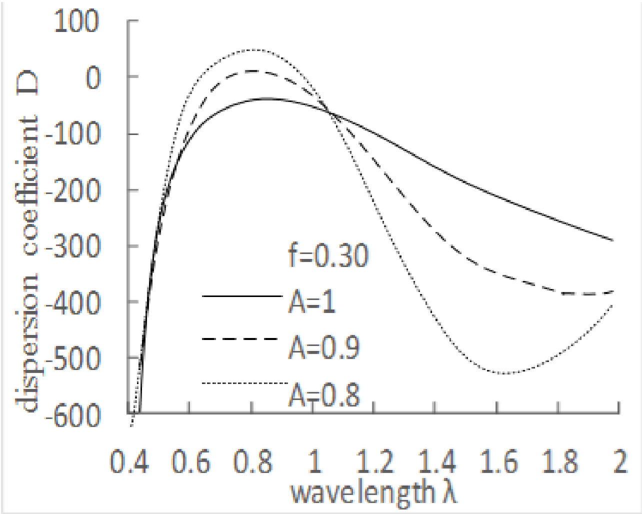

Figure7. Variation Curve of Dispersion Value D with the Wavelength λ

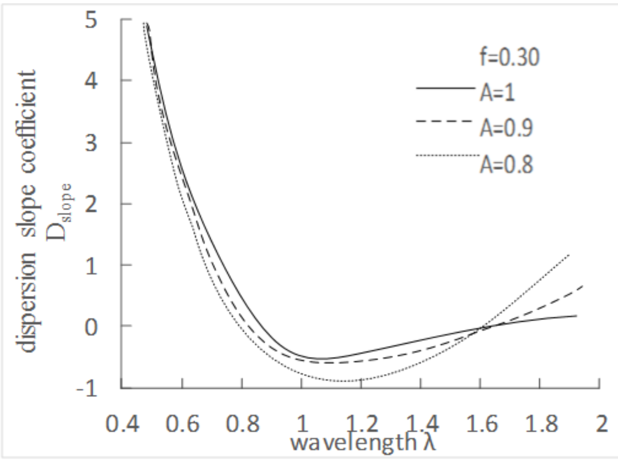

Figure 8. Variation Curve of Dispersion Slope Dslope with the Wavelength λ

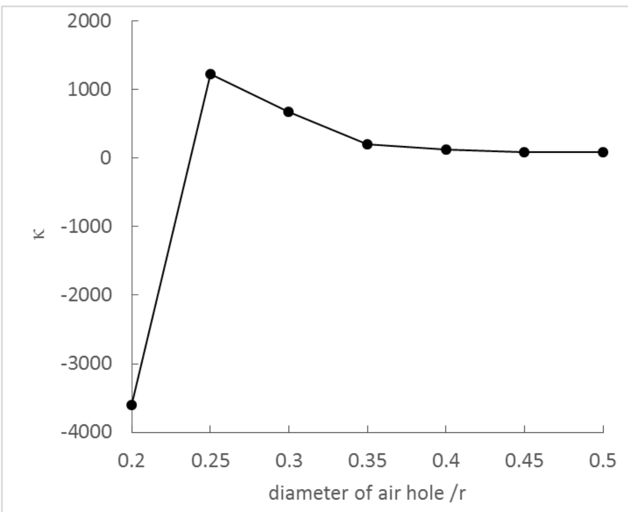

Figure9. Variation Curve of κ with Variation of Air Hole Radius

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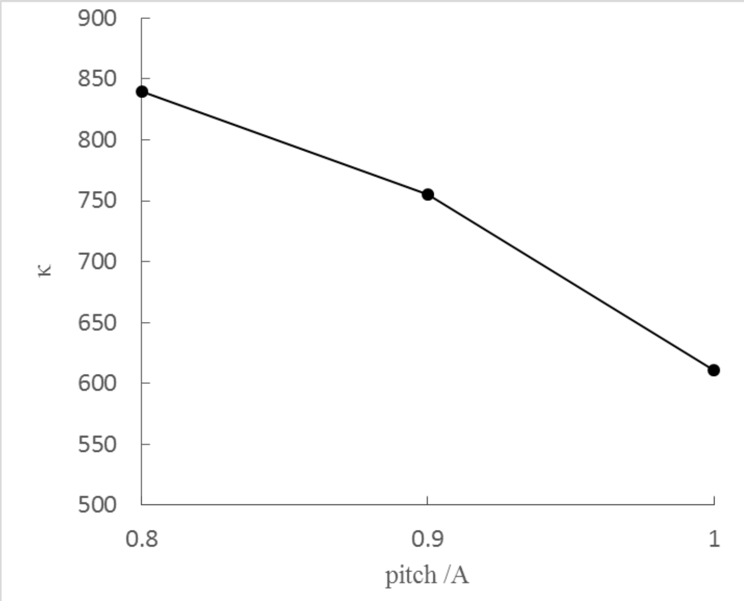

Figure 10. Variation Curve of κ with Variation Cavitation Pitch A

From the figure 3 and 4, we can see that dispersion coefficient first decreases and then increases with the increasing wavelength λ. D_{slope} decreases with the increasing of the wavelength λ.

Figure 5 and 6 gives the characteristics of dispersion when keep the cladding air dispersion rate as constant. With the increasing of the wavelength λ, dispersion D and dispersion slope D_{slope} decrease gradually.

Figure 7 and 8 shows the characteristics of dispersion when keep the air hole radius as constant. With the increasing of the wavelength λ, dispersion coefficient increases firstly and then decrease and variation of dispersion slope coefficient has just the contrary trend.

Figure 9 and 10 shows variation of κ. We can change the structure of the photonic crystal fiber to change the value of κ in a large range.

5. Conclusion

Optical network faces increasing challenges with the development of telecommunication technology optical devices and system. The fiber will carry much more transmission channels with higher optical power and transmission rate. Higher dispersion causes serious broadening and distortion to lead to bit error. Dispersion of optical fiber has become the main obstacle.

In this paper, we propose a modified algorithm to compensate for the dispersion. With the simulation method, we obtained the characteristics of dispersion and dispersion slope with the variation of wavelength λ, and some useful conclusion has been acquired. From our simulation results, we can verify the conclusion that it needs to optimize the design of the structure of optical fiber if we want to compensate for the dispersion and dispersion slope simultaneously.

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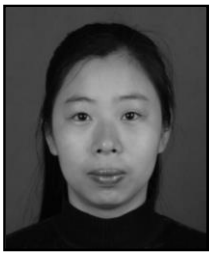

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