Broadband Dispersion Compensation Technology in High Speed Optical Fiber Communication Systems

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***Abstract* — Dispersion can lead to broadening in the process of optical pulse transmission, which results in intersymbol interference that limits the development of fiber with high speed and large capacity. Conducting efficient compensation to the dispersion in an optical fiber communication system has become a significant research topic. This study adopts vector effective index method to conduct numerical simulation and analysis on the characteristics and nonlinear effects of photonic crystal fiber dispersion. The characteristics and nonlinear effects of photonic crystal fiber dispersion are analyzed by changing the structural parameters of photonic crystal fiber, such as the diameter of an air hole and the space between air holes. The numerical simulation shows that the dispersion coefficient, dispersion slope, and nonlinear coefficient of photonic crystal fiber dispersion change with structural parameters; therefore, broadband dispersion compensation can be achieved by changing the structural parameters. To achieve low-linearity and high-efficiency dispersion compensation of the conventional single-mode fiber, we have to optimize the structure of photonic crystal fibers. The results of this study have guiding significance for the structural design of photonic crystal fiber dispersion compensation.**

Keywords - photonic crystal fiber; dispersion coefficient; nonlinear coefficient; dispersion compensation

I. INTRODUCTION

Loss and dispersion are two main factors that limit the optical signal transmission of fiber. With the commercialization of erbium-doped fiber amplifier, loss is no longer the main factor that limits the performance of the system [1-3]. In an ultra-high-speed optical communication network, dispersion has become the bottleneck that limits the optical fiber transmission with more channels, larger optical power, higher rate, and longer distance. Therefore, research on dispersion compensation is necessary to realize long-distance, ultra-high-speed, and large-capacity transmission of optical fiber communication.

For single-mode optical fiber, the optical signal in the optical fiber transmission consists of many components with different frequencies. Various mode components with certain spectrum width, and different frequency components or energy signals disperse in the transmission process because of their different group velocities, thereby causing waveform distortion and pulse broadening in the transmitted signal. This physical phenomenon is known as dispersion, which includes waveguide dispersion and material dispersion. The former refers to the differences in the transmission coefficient β as a result of different effects of fiber boundary on optical waves with different frequencies, while the latter is caused by different refractive indexes of the fiber material on optical waves with different frequencies [4].

Fiber dispersion leads to the broadening of optical pulse in the communication process, causing an overlap in pulses and resulting in intersymbol interference between digital signals; thus, it is one of the major factors that constrain the further improvement in the velocity and capacity of optical communication [5]. In the second part of this paper, several methods of dispersion compensation are introduced and compared. A new method of broadband dispersion compensation is proposed in the third part. The fourth part presents an analysis of the simulation data, and the fifth part provides the conclusion.

II. STUDY ON MAJOR SCHEMS FOR DISPERSION COMPENSATION

The technologies for optical dispersion compensation have been widely studied. At present, dispersion compensating fiber (DCF), chirped fiber Bragg grating (CFBG), virtual image phased array, fiber soliton transmission, mid-span spectral inversion, dispersion supported transmission, planar optical circuit, pre-chirp compensation, and other methods of dispersion compensation have been formed in high-speed optical fiber transmission; each of these technologies has its own advantages and disadvantages. Fiber Bragg grating and dispersion compensation fiber are two of the most practical and mature methods [6].

(1) Chirped fiber Bragg grating [2] [4] [11]

When passing through the CFBG whose grating period shows periodic changes along the direction of the fiber, light with different frequencies are reflected in different locations and relative time differences increase; that is, CFBG has a wavelength dispersion feature. Therefore, it can be used for dispersion compensation. In general, we can measure the amount of dispersion compensation by using the chirp, reflected bandwidth, and dispersion value. For optical

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gratings with the same length, the smaller the amount of the chirp is, the narrower the reflection bandwidth and the higher the dispersion value becomes.

Results of studies on dispersion compensation using the CFBG method in many countries show that a conventional optical fiber communication network with a speed of 10 Gb/s uses single- or multiple-chirped gratings for dispersion compensation and the transmission distance reaches several hundred kilometers. The compensation method of the CFBG has the following characteristics: (1) gratings with small volume, which are easy to install and form an integration of all optical communications; (2) large amount of dispersion, high reflectivity, wide reflection bandwidth, low loss, and insensitivity to polarization, which make the method especially suitable for specific compensation to all channels of the DWDM high-speed transmission system; and (3) simple technology, low cost, and high reliability. The amount of compensation can be designed flexibly according to transmission distances.

(2) Dispersion compensating fiber [7-10]

DCF refers to dispersion compensating fiber, which is based on the principle of adding a fiber with negative dispersion onto ordinary G.652 fiber to control the total dispersion value of the circuit within the tolerance of the system and to reduce the influence of dispersion on the system. At present, a large amount of commercial DCF is applied in the dispersion compensation of C-band and L-band transmission in G.652 fiber.

Two types of DCF are available. One is single-mode fiber, which is designed on the basis of fundamental mode and whose relative refractive index difference in the fiber core is high. Furthermore, the cladding has multiple layers and the fundamental mode has large negative waveguide dispersion. A multi-cladding structure provides this type of DCF large negative dispersion and negative dispersion slope; therefore, the bending loss decreases in the process of usage, and the FOM, which is the absolute value ratio between dispersion coefficient and attenuation coefficient, is high.

The other type is the fiber designed on the basis of high-order mode, with a large effective area, high negative dispersion, and low nonlinearities, and can be transmitted in dual modes. However, because of the mismatch between the mode field distribution of fundamental mode and high-order mode, a mode converter should be appended in the application. Therefore, although the compensation efficiency of the fiber with this structure is high, it is complex in reality and the loss is large.

To ensure that the single-mode transmission has a large negative dispersion value, the fiber should have a high effective refractive index and small fiber core diameter. However, these conditions reduce the effective mode field area of the fiber core, resulting in a nonlinear effect. Increasing the effective refractive index through a combination of materials with a high refractive index causes difficulty in fabricating the optical fiber, thereby increasing the difficulty in achieving negative dispersion of the conventional DCF. At present, the negative dispersion of commercial DCF is in the range of 100 – 150 ps/nm/km.

The dispersion compensation module (DCM0, composed by DCF) is usually configured to each (or some) output end of remote optical transmission system to compensate the fiber transmission dispersion. However, the dispersion compensation technology only uses part of DCF, so certain defects occur in some aspects. This condition has prompted the emergence of new technologies such as controllable dispersion compensation module (M2DCM). When conducting dispersion compensation with DCF, we should consider low cost, small volume, light weight, compact structure, and reduction or elimination of the polarization correlation.

At the wavelength of 1550 nm, conventional single-mode fiber has positive dispersion whereas single-mode DCF has negative dispersion. Thus, DCF can be used in the dispersion compensation of conventional single-mode fiber communication systems. When DCF is used in dispersion compensation, the selection of DCF and the length of the fiber compensated should be in accordance with the requirements of the following formula:

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

In the preceding formula, $D(\lambda_S)$ and $D_C(\lambda_S)$ are the dispersion coefficient of conventional single-mode fiber and DCF, respectively, at the working wavelength ; L and LC are the communication length of conventional single-mode optical fiber and DCF, respectively.

When selecting DCF, the dispersion coefficient and attenuation coefficient have to be considered. The definition formula of F (FOM) is as follows:

$$F = \frac{|D_C|}{\alpha_C} \tag{2}$$

In the preceding formula, D_C and α_C are the negative dispersion coefficient and attenuation coefficient of DCF, respectively.

Formulas (1) and (2) show that the average attenuation coefficient of the circuit α ad is

$$\alpha_{ad} = \frac{\alpha L + \alpha_C L_C}{L} = \alpha + \frac{D}{F} \tag{3}$$

Formula (3) shows that when DCF is used in dispersion compensation, if we want to make the average attenuation coefficient of the circuit small after dispersion compensation, the FOM of DCF should be high. The FOM parameter can be used in the performance comparison of various types of DCF.

(3) Electronic dispersion compensation (EDC) [12-15]

EDC technology has attracted increasing attention because of its advantages in miniaturization as well as its low power consumption and low cost. EDC is a type of optical fiber dispersion compensation based on electronic filtering technology, which can effectively adjust the received signal waveform according to the sampling of electric field, software optimization, and signal recovery to achieve the goal of dispersion compensation. In practical applications, the most common usage is to obtain adaptive EDC by using a feed-forward equalizer and a decision feedback equalizer. Apart from being less costly than rotatory dispersion compensation technology, EDC can also use inexpensive laser. The EDC module is generally installed on the receiving end of a wireless transceiver and eliminates dispersion through the conversion between images and electricity.

III.FIBER WITH BROADBAND DISPERSION COMPENSATION

To meet the requirements of broadband and long-distance transmission, dispersion compensation, and dispersion slope compensation should be considered simultaneously. Aside from dispersion, the nonlinearity of the fiber is also a main factor that constrains the high-speed and long-distance transmission of fiber communication. In this case, we consider three aspects and propose a solution to the problem based on photonic crystal fiber. The nonlinearity of the fiber is inversely proportional to its effective mode field area, and the fiber parameters, such as the diameter of the mode field and the refractive index difference between the fiber core and the cladding, determine its effective mode field area. The study shows that the nonlinear coefficient of photonic crystal fiber is much larger than that of conventional fiber, which easily causes the nonlinear effects in optical fiber communication systems, such as four-wave mixing. Thus, when designing dispersion compensation photonic crystal fiber in reality, we should fully consider the nonlinear effect. This study differs from previous ones because it considers not only the impact of changes in the structural parameters of photonic crystal fiber on the dispersion compensation characteristics but also the impact of nonlinear coefficients.

Russell et al. [18] proposed the concept of photonic crystal fiber (PCF) in 1992 and Knight et al.[2] developed PCF in 1996. At present, PCF is still a new research field, which performs significantly better than other fibers. First of all, the extremely wide frequency range supports single-mode transmission; second, the nonlinear effect can be weakened or strengthened by changing the core region of the fiber; third, flexible and controllable dispersion and dispersion slope can provide broadband dispersion compensation; and finally, the core and cladding are made of the same material and can be completely matched mechanically and thermally. The refractive index of PCF is subject to the constraint of material compatibility and is able to transmit the wavelength under 1 um without dispersion. [1-5]

The structure of photonic crystal fiber in traditional hollow hexagonal periodic arrangement is shown in Figure 1[1]. In this figure, the filling diameter of air hole d, the radius r, the space between holes Λ, and the air filling rate can be represented with d/Λ, and the material used in the cladding is fused silica (refractive index n = 1.45).

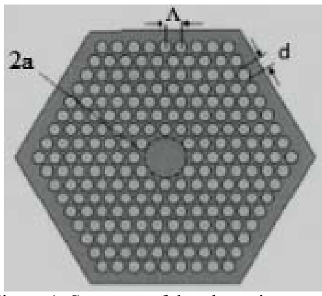

Figure 1. Structure of the photonic crystal fiber

Many numerical modeling techniques are available for the characteristics analysis of photonic crystal fiber. Common methods include effective index model, plane wave expansion, difference method, local basis function, finite element method, multi-pole method, and so on [16]. The comparison shows that vector effective index rate model has fast calculation speed and the same accuracy as the vector method. This paper has adopted the vector effective index rate model to obtain the equivalent refractive index n_{eff}, then emulated the dispersion value D, dispersion slope D_{slope}, kappa value k, and nonlinear coefficient γ in combination with the equivalent core radius $r_{eff} = 0.625 \times \Lambda$ [6] and the fiber theory.

The effective refractive index with changes of optical frequency in the cladding mode can be expressed as

$$n_{eff}(\omega) = \sqrt{\frac{n_2^2 - u^2(\omega)c^2}{\omega^2}} \tag{4}$$

The formula of waveguide mode and dispersion characteristics obtained with the vector method is

$$m^2\left[\frac{1}{U^2}+\frac{1}{W^2}\right]\left[\frac{n_0^2}{U^2}+\frac{n_2^2}{W^2}\right] = \left[\frac{1}{U}\frac{J_m(U)}{J_m(U)}+\frac{1}{W}\frac{K_m(W)}{K_m(W)}\right] \times \left[\frac{n_0^2 J_m(U)}{U \cdot J_m(U)}+\frac{n_2^2}{W}\frac{K_m(W)}{K_m(W)}\right] \tag{5}$$

Taking m=1, the characteristic function of the fiber under the basic mode is obtained as follows:

$$\frac{J_0(U)}{J_1(U)} = \frac{1}{U}+\frac{U}{2}\left(1+\frac{n_2^2}{n_0^2}\right)\left[\frac{1}{W^2}+\frac{K_0(W)}{W \cdot K_1(W)}\right] - \frac{U}{2}\sqrt{\left(1-\frac{n_2^2}{n_0^2}\right)^2 \cdot \left[\frac{1}{W^2}+\frac{K_0(W)}{W \cdot K_1(W)}\right]^2 + 4F(U,W)} \tag{6}$$

In Formulas (4) to (6), N0 stands for the refractive index of the air, which is usually 1.0; n2 is the refractive index of the quartz, which considers the material dispersion; and n2 is usually calculated with the Sellmeier formula.

$$F(U,W) = \left(\frac{1}{U^2}+\frac{1}{W^2}\right)\left(\frac{1}{U^2}+\frac{n_2^2}{n_1}\frac{1}{W^2}\right) \tag{7}$$

In Formula (7), the radial normalized phase constant U, the radial normalized attenuation constant W, and the normalized frequency V satisfy the following relation:

$$U = r_{eff}\sqrt{\left(k_0^2 n_1^2 - \beta^2\right)}$$

$$W = r_{eff}\sqrt{\left(\beta^2 - k_0^2 n_{eff}^2\right)}$$

$$V = \sqrt{W^2 + U^2} = k_0 r_{eff} \sqrt{\left(n_1^2 - n_{eff}^2\right)}$$

where β is the propagation constant, is the optical vector wave, n1 is the refractive index of the fiber core, and is the equivalent core radius of the photonic crystal fiber.

According to optical principles of waveguide, the total dispersion coefficient of the optical fiber can be calculated as

$$D = \frac{d\tau}{d\lambda} = -\frac{\omega^2}{2\pi c}\frac{d^2\beta}{d\omega^2} \tag{8}$$

This function includes material dispersion, waveguide dispersion and polarization mode dispersion. The relationship between the dispersion slope D_{slope} and the wavelength of the fiber is as follows:

$$D_{slope} = \frac{dD}{d\lambda} = -\frac{1}{\lambda^2}\frac{dD}{d\omega} \tag{9}$$

The compensation condition of broadband dispersion is intended to compensate the dispersion and dispersion slope coefficient simultaneously. Therefore, the following conditions have to be met:

$$D_1 L_1 + D_2 L_2 = 0 \tag{10}$$

$$D_{slope_1} L_1 + D_{slope2} L_2 = 0 \tag{11}$$

In the Formula(10) to (11), L_1, D_1 , and D_{slope_1} are the length, dispersion coefficient, and dispersion slope coefficient of the fiber compensated, respectively; L_2, D_2 , and D_{slope_2} are the length, dispersion coefficient, and dispersion slope coefficient of the fiber for dispersion compensation, respectively.

Thus, the length of the fiber for dispersion compensation should meet $L_2 = -\frac{D_1 L_1}{D_2}$. Given the dispersion coefficient and the dispersion slope coefficient, a new parameter k is introduced as follows:

$$k = \frac{D_1}{D_{slope_1}} = -\frac{D_2}{D_{slope_2}} \tag{12}$$

The k parameter is used to characterize the ability of the device to compensate the dispersion and the dispersion slope. The closer the k value of the fiber for dispersion compensation to that of the fiber compensated, the higher the compensation efficiency is.

The nonlinear coefficient of photonic crystal fiber $\gamma(\lambda)$ depends on the effective mode area of the fiber A_{eff} . Thus, A_{eff} is also a highly important parameter. The nonlinear coefficient and effective mode field area of the photonic crystal fiber can be expressed as

$$\gamma(\lambda) = \frac{2\pi n_{2b}}{\lambda A_{eff}} \tag{13}$$

$$A_{eff} = \frac{\left(\iint |E|^2 dxdy\right)^2}{\iint |E|^4 dxdy} \tag{14}$$

In the Formula(13) to (14), $n_{2b} = 3.0\times10^{-20} m^2 \cdot W^{-1}$ is the nonlinear refractive index coefficient of the material, and $|E|^2$ stands for the intensity distribution of the cross-section area of the fiber. The calculation of the effective mode field area conducts integral transformation to the ends and faces of the entire fiber. The expression for the non-linear coefficient shows that the nonlinear coefficient is inversely proportional to the effective mode field area, i.e., the larger the effective mode field area, the smaller the nonlinear coefficient. Reducing the air filling ratio in the cladding of the photonic crystal fiber can reduce the refractive index difference between the fiber core and the cladding, while increasing the effective fiber core area can reduce the nonlinear coefficient of the photonic crystal fiber.

IV. Analysis of Numerical Simulation

By adjusting the air hole pitch Λ and the radius of the air hole in the cladding r, we have examined the main factors that affect the dispersion compensation characteristics of the photonic crystal fiber.

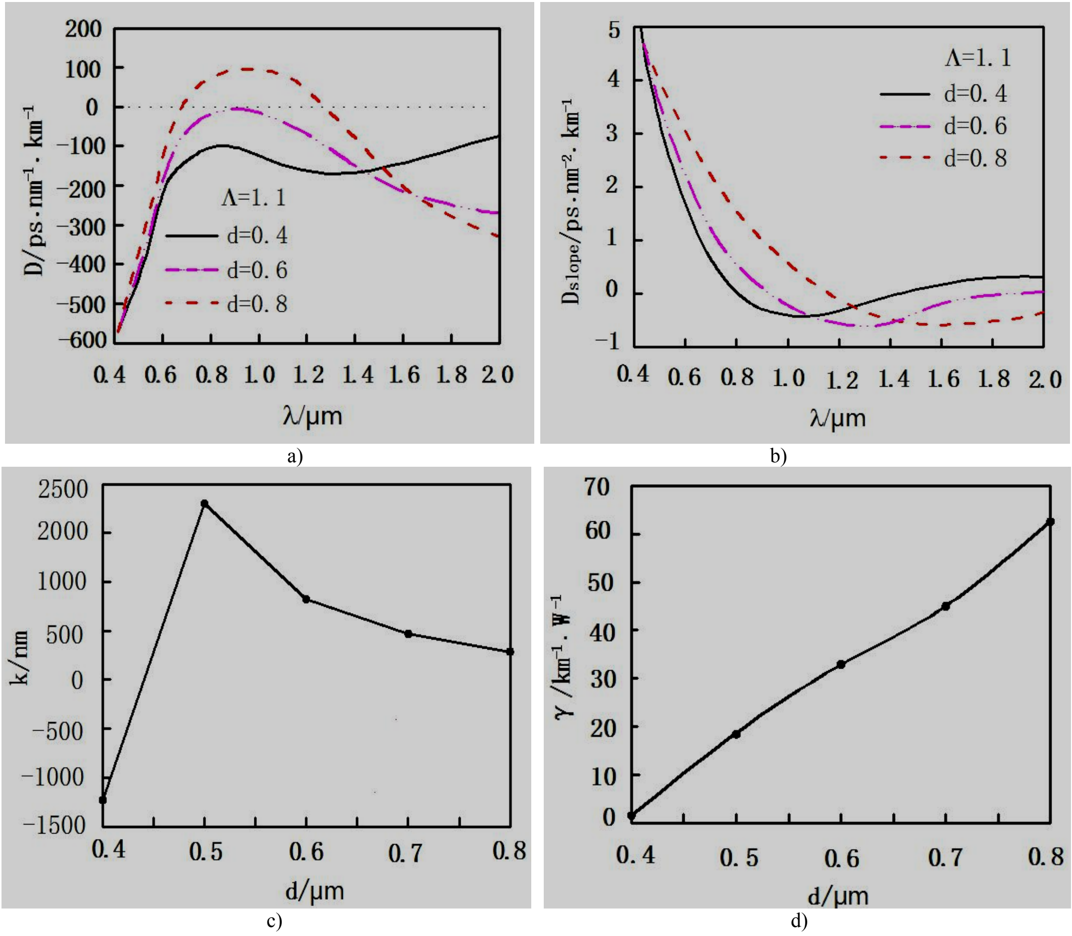

Figure 2. When Λ = 1.1 μm and d is variable, a) Variation curve of dispersion value D with the wavelength λ, b) Variation curve of dispersion slope D_{slope} with the wavelength λ, c) Variation curve of kappa value κ with the air hole diameter d, d) Variation curve of nonlinear γ with the air hole diameter d.

TABLE 1. DISPERSION CHARACTERISTICS AND NONLINEAR COEFFICIENTS WHEN Λ=1.1 MM AND WHEN D IS VARIABLE

Diameter of air hole d/μm	Dispersion value D/ ps•nm^{-1}•km^{-1}	Dispersion slope D_{slope}/ps•nm^{-2}•km^{-1}	Kappa value k/nm	Nonlinear γ/ km^{-1}•W^{-1}
0.4	-145.09	0.118	-1229.58	1.49
0.6	-222.01	-0.269	825.32	33.01
0.8	-144.58	-0.501	288.58	62.61

Table 1 shows the dispersion values of PCF when the wavelength is at 1550 nm, Λ = 1.1 μ m and remains unchanged, and d is changing.

Figure 2 and Table 1 show that when the air hole pitch remains constant, the dispersion coefficient and dispersion slopes vary with changes in the wavelengths of input light, and the K values may be different. When the wavelength is 1550 nm, the dispersion coefficient first decreases and then increases with the increase of the air hole diameter. When d = 0.6 is m, the dispersion coefficient is the smallest, which means that the compensation efficiency is at maximum. When d = 0.4 μ m, the dispersion slope is positive, which is unsuitable for compensating the dispersion of the conventional single-mode optical fiber. The nonlinear coefficient increases with the increase of the air hole diameter.

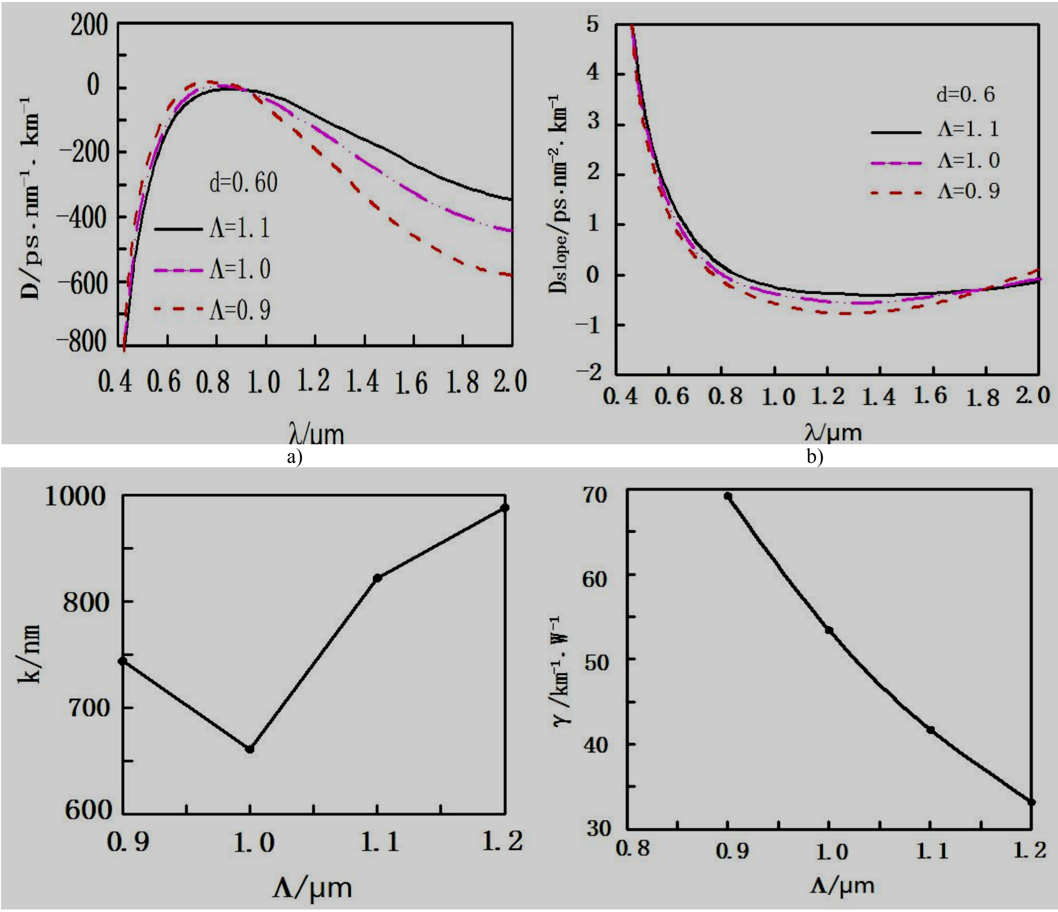

Figure 3. When d = 0.6 μm and Λ is variable, a) Variation curve of dispersion value D with the wavelength λ, b) Variation curve of dispersion slope D_{slope} with the wavelength λ, c) Variation curve of kappa value κ with the air hole pitch Λ, d) Variation curve of nonlinear γ with the air hole pitch Λ.

TABLE 2. DISPERSION CHARACTERISTICS AND NONLINEAR COEFFICIENTS OF PCF WHEN D=0.6 MM AND WHEN Λ IS VARIABLE

Air hole pitch Λ/μm	Dispersion value D/ ps•nm^{-1}•km^{-1}	Dispersion slope D_{slope}/ps•nm^{-2}•km^{-1}	Kappa value k/nm	Nonlinear γ/ km^{-1}•W^{-1}
0.9	-431.78	-0.580	744.45	69.18
1.0	-304.40	-0.461	661.74	53.41
1.1	-221.16	-0.269	822.16	41.68

Table 2 shows the dispersion characteristic parameters and nonlinear coefficients of PCF when the wavelength is at 1550 nm, d = 0.6 μm and remains unchanged, and Λ is changing.

Figure 3 and Table 2 show that when the air hole diameter is constant, the dispersion coefficient and dispersion slope vary with changes in the wavelengths of input light, and the K values may be different. When the wavelength is 1550 nm, the dispersion coefficient and dispersion slope increase with the increase of the air hole pitch. The nonlinear coefficient decreases with the increase of the air hole diameter.

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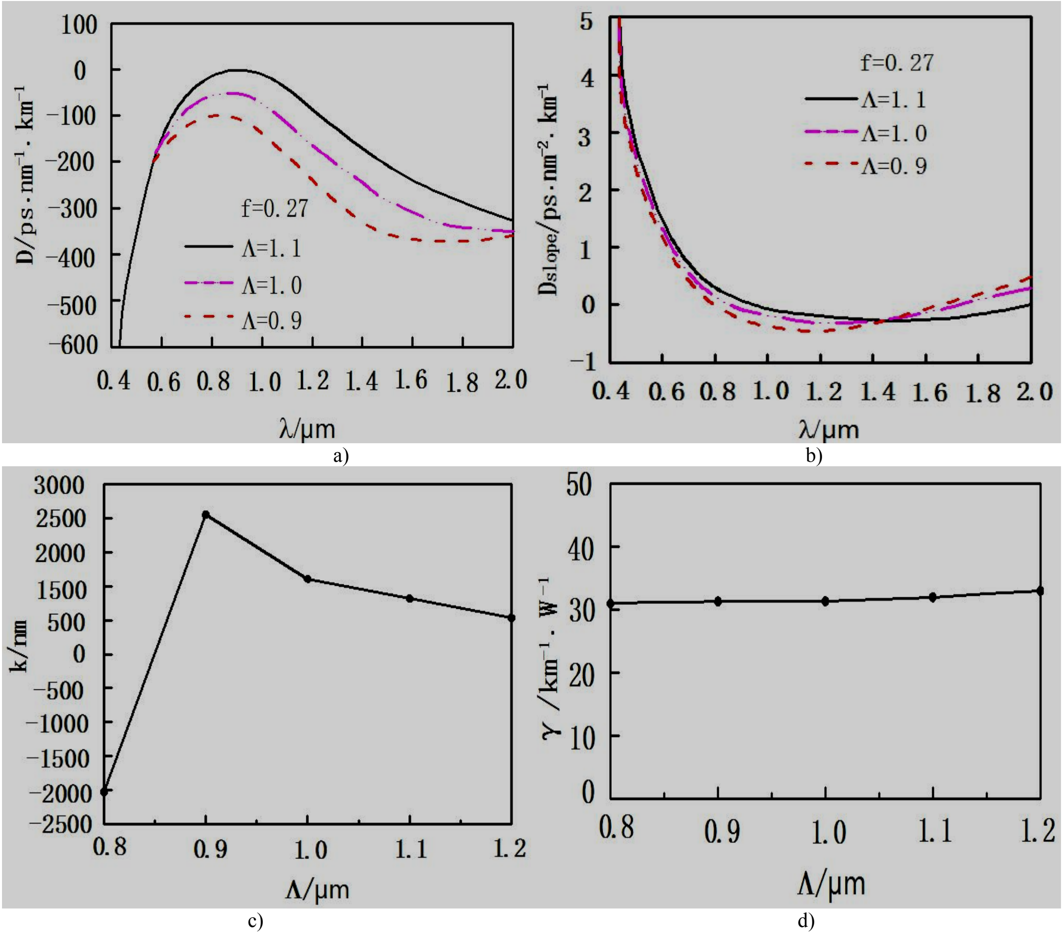

Figure 4. When f = 27% and Λ is variable, a) Variation curve of dispersion value D with the wavelength λ, b) Variation curve of dispersion slope D_{slope} with the wavelength λ, c) Variation curve of kappa value κ with the air hole pitch Λ, d) Variation curve of nonlinear γ with the air hole pitch Λ.

TABLE 3 DISPERSION CHARACTERISTICS AND NONLINEAR COEFFICIENTS OF PCF WHEN F = 27% AND WHEN Λ IS VARIABLE

Air hole pitch Λ/μm	Dispersion value D/ ps•nm^{-1}•km^{-1}	Dispersion slope D_{slope}/ps•nm^{-2}•km^{-1}	Kappa value k/nm	Nonlinear γ/ km^{-1}•W^{-1}
0.9	-362.01	-0.142	2549.37	31.30
1.0	-293.43	-0.183	1603.44	31.36
1.1	-222.01	-0.272	816.21	32.01

Table 3 shows the dispersion characteristic parameters and nonlinear coefficients of PCF when the wavelength is at 1550 nm, the air filling rate f = 27% and remains unchanged, and Λ is changing.

As shown in Figure 4 and Table 3, when f = 27% and remains unchanged, the dispersion coefficient and dispersion slope vary with changes in the wavelengths of input light, and the K values may be different. When the wavelength is 1550 nm, the dispersion coefficient increases with the increase of the air hole pitch, and the dispersion slope decreases with the increase of the air hole pitch. When the air filling rate f is constant, the nonlinear coefficient is also almost constant.

V. Conclusions

Through theoretical analysis and numerical simulation, this study finds that the dispersion compensation efficiency of PCF is related to certain structural parameters, such as the air hole diameter d, the air hole pitch Λ, the air filling rate, and so on. Therefore, by adjusting the structural parameters of PCF, we can realize the dispersion compensation of fibers with different dispersion characteristics within the scope of fiber broadband. When the wavelength of input light changes, the dispersion coefficient and dispersion slope of PCF also change, which shows that the photonic crystal fiber can be used in broadband dispersion compensation. The nonlinear coefficient of PCF changes with the changes in the structural parameters of fiber. When PCF is used in dispersion compensation, its nonlinear coefficient should be considered to ensure high-speed, large-capacity, and long-distance transmission of the fiber. We hope that the analysis presented in this study can serve as a reference for the structural design of photonic crystal fiber.

REFERENCES

[1] JU Xiao-dan, LIU Zhao-lun, NI Zheng-hua, GAO Yan-dong, LI Shu-guang, HOU Lan-tian, LIU Xiao-dong, "Application of Dispersion Compensation of Photonic Crystal Fiber for Modern communication Systems". Optical Communication Technology, No. 7, pp.26-28, 2004.

[2] in Ru, Ni Yan Rong, "Investigation on the Dispersion Compensation Algorithm in Optical Fiber Communication with Large Capacity". International Journal of Future Generation Communication and Networking, Vol. 8, No. 3, pp. 235-246, 2015.

[3] WANG Xu-de, LUO Ai-ping, XU Wen-cheng, DENG Li-qiong, ZHU Ri-dan, LIU Song-hao. "Design of photonic crystal fiber for broadband dispersion compensation". Optical Technique, Vol. 33, No. 6, pp.899-902, 2007.

[4] Yanfeng Li, Bowen Liu, Qingyue Wang, "Influence on photonic crystal fiber dispersion of the size of air holes in different rings within the cladding". Chin Opt Lett, Vol. 2, No. 2, pp.75-77, 2004.

[5] Maji Partha Sona, P. R. Chaudhuri, "Design of ultra large negative dispersion PCF with selectively tunable liquid infiltration for dispersion compensation". Optics Communications, Vol. 325, No. 5, pp.134-143, 2014.

[6] Lin Hsiu-Sheng, Lai Po-Chou, "High raman gain of dispersion compensation fiber using RZ-DPSK format for long-haul DWDM transmission system". Microwave and Optical Technology Letters, Vol. 52,No.11, pp.2548-2551, 2010

[7] Mazzoni Annalisa, Angeloni Valeria, Apolonio Fabianni M., Scotti Nicola, Tjäderhane Leo, Tezvergil-Mutluay Arzu, Di Lenarda Roberto, Tay Franklin R., Pashley David H., Breschi Lorenzo, "Effect of carbodiimide (EDC) on the bond stability of etch-and-rinse adhesive systems". Dental Materials, Vol. 29, No.10, pp.1040-1047, 2013.

[8] Rong Liu, Jinfa Ming, Huanxiang Zhang, Baoqi Zuo, "EDC/NHS crosslinked electrospun regenerated tussah silk fibroin nanofiber mats". Fibers and Polymers, Vol. 13, No. 5, pp.613-617, 2012.

[9] Brodsky M., George E. C., Antonelli C., Shtaif M., "Loss of polarization entanglement in a fiber-optic system with polarization mode dispersion in one optical path". Optics letters, Vol. 36,No. 1,pp.43-45, 2011.

[10] Rogers H. L., Holmes C., Gates J. C., smith P. G. R., "Analysis of Dispersion Dharacteristics of Planar Waveguides via Multi-order Interrogation of Integrated Bragg Gratings". IEEE Photonics Journal, Vol. 4,No. 2, pp.310-316, 2012.

[11] Haque M. M., Rahman M. S., Habib M. S., Razzak S. M. A., "Design and characterization of single mode circular photonic crystal fiber for broadband dispersion compensation". Optik-International Journal for Light and Electron Optics, Vol. 125, No. 11, pp.2608-2611, 2014.

[12] Zhang Yani. "Design and optimization of low-loss low-nonlinear high negative-dispersion photonic crystal fiber". Acta Phys Sin., Vol. 61, No. 8, pp.084213, 2012.

[13] Wang Dan, Zheng Yi, "Numerical Investigation of a Ultra-Broadband Low-Dispersion Holey Fiber". Acta Optica Sinica, Vol. 33, No. 8, pp.0806005, 2013.

[14] Saitoh K., Koshiba M., "Numerical modeling of photonic crystal fibers. Lightwave Technology". Vol. 23, No.11, pp.3580-3590, 2005.

[15] Philip Russell. "Photonic crystal fibers". Science, No. 299, pp.358-362, 2003.

[16] Velimir Graorkoski, Ana Madevska-Bogdanova, "Instantiation in Partial Learning. International Journal of Informatics and Communication Technology". Vol. 3, No. 1, pp.59-66, 2014.

[17] Rahul Yadav, VinitKumar Jayprakash Dongre, "Demonstration of Helical Antenna Stability beyond C-Band Frequency". International Journal of Informatics and Communication Technology, Vol. 2, No. 3, pp. 166-174, 2013.

[18] Wang Bing, Ma Xiaojun, Yang Huajun, Jiang Ping, "Study on dispersion characteristics of photonic crystal fiber". Laser and Infrared, Vol. 44, No. 3, pp.302-305, 2014.