

Photonic crystal fiber with novel dispersion properties

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Abstract Our recent research on designing microstructured fiber with novel dispersion properties is reported in this paper. Two kinds of photonic crystal fibers (PCFs) are introduced first. One is the highly nonlinear PCF with broadband nearly zero flattened dispersion. With introducing the germanium-doped (Ge-doped) core into highly nonlinear PCF and optimizing the diameters of the first two inner rings of air holes, a new structure of highly nonlinear PCF was designed with the nonlinear coefficient up to $47 \text{ W}^{-1} \cdot \text{km}^{-1}$ at the wavelength $1.55 \mu\text{m}$ and nearly zero flattened dispersion of $\pm 0.5 \text{ ps}/(\text{km} \cdot \text{nm})$ in telecommunication window (1460–1625 nm). Another is the highly negative PCF with a ring of fluorine-doped (F-doped) rods to form its outer ring core while pure silica rods to form its inner core. The peak dispersion $-1064 \text{ ps}/(\text{km} \cdot \text{nm})$ in 8 nm full width at half maximum (FWHM) wavelength range and $-365 \text{ ps}/(\text{km} \cdot \text{nm})$ in 20 nm (FWHM) wavelength range can be reached by adjusting the structure parameters. Then, our recent research on the fabrication of PCFs is reported. Effects of draw parameters such as drawing temperature, feed speed, and furnace temperature on the geometry of the final photonic crystal fiber are investigated.

Keywords photonic crystal fiber (PCF), nearly zero flattened dispersion, high nonlinear, high negative dispersion, fabrication technique

1 Introduction

Since the first working example was reported of so-called “endlessly single mode photonic crystal fiber” in 1996 [1], intensive researches have been promoted to develop photonic crystal fiber (PCF). PCF exhibits many unusual properties such as an endlessly single mode, highly tunable dispersion, highly controllable mode effective areas for

linear and nonlinear applications, and so on. Index-guiding PCF, also called holey fiber or microstructured fiber, is characterized by a periodic arrangement of air holes around a central high index core along the entire length of the fiber. Due to its special structure, PCFs offer more flexibility than conventional fibers do in the design of optical characteristics. Through changing the hole pitch Λ , the relative hole diameter d/Λ in different rings and the refractive index in the core, PCFs exhibit different chromatic dispersion properties such as flattened dispersion, large negative dispersion, nearly zero dispersion, and so on [2–4].

Highly nonlinear fiber with flattened dispersion over a wide wavelength range would be attractive candidates for application in the future high-capacity all-optical networks and development of highly nonlinear fiber based devices such as wavelength converters, parametric amplifiers, supercontinuum sources, and optical switches. It has attracted considerable attention in recent years. In order to get high nonlinearity and low confinement loss, conventional highly nonlinear PCF is usually designed with a small pitch of about $1 \mu\text{m}$ and a large ratio d/Λ of hole diameter to hole pitch. However, its chromatic dispersion is not flattened [5]. Several new structures had been proposed to improve its chromatic dispersion properties and to achieve nearly zero ultraflattened chromatic dispersion properties in telecommunication window wavelength range. However, this structure has the same diameter air holes in a regular triangular lattice [6] and small d/Λ that more than 20 rings of air holes are required in the cladding region to realize the nearly zero ultraflattened dispersion properties and significantly reduce the confinement loss. This increases the complexity of fabrication. Although a few new structure designs else were proposed with different air-hole diameters for each ring [7–9], the structure design of simple highly nonlinear PCF with nearly zero flattened chromatic dispersion properties and low confinement losses is still an ongoing challenge.

Dispersion compensation fiber (DCF) is one of the best

approaches to minimize the penalty of chromatic dispersion in the high-speed communication system. However, because of the limitation of doped concentration, it cannot realize the very large dispersion value in the commercial DCF, whose typical dispersion value is about -100 – -300 ps/(km·nm). To minimize losses and nonlinearity, DCFs should be as short as possible, and thus, the magnitude of negative dispersion should be as large as possible. PCF can realize larger refractive index modulation than the conventional DCF. In 2004, Gérôme et al. originally used the PCF technique to realize the equivalent dual-concentric-core structure that has been usually used in commercial DCFs [4]. Very high negative chromatic dispersion (-2200 ps/(km·nm)) is obtained. Subsequently, the dual-core PCFs with very large negative dispersion have been studied comprehensively. The most widely used method is to adopt some smaller air holes to form its outer ring core and realize the dual core asymmetry structure based on pure silica. This structure can exhibit very high negative chromatic dispersion, but some submicron air holes has been used and leads to high fabricating difficulties in controlling the dimension of the holes accurately. Recently, a new scheme was proposed and experimentally demonstrated by Yang et al. [10]. The structure consists of a germanium-doped (Ge-doped) inner core and pure silica outer core that eliminates the smaller holes. A peak dispersion of -666.2 ps/(km·nm) and mode field area of $40 \mu\text{m}^2$ were experimentally observed. Though this scheme is technically feasible and relatively easy to realize, there are several drawbacks. One major concern is that the traditional metal chemical vapor deposition (MCVD) process inevitably brings additional loss to the inner core when making the Ge-doped inner core perform. Whereas considering the dispersion slope of this kind of dual-core photonic crystal fiber (DCPCF), the operation wavelength always lies in the left side of the phase matching wavelength (PMW), within which region the mode field of supermode is concentrated in the inner core. Thus inner core loss is the dominant power cost and should be reduced as possible as we can. Therefore, a better scheme is needed, which can eliminate the above problem.

PCFs are usually drawn from a macroscopic preform typically a few centimeters to $125 \mu\text{m}$ in diameter with a conventional fiber-drawing tower. The general form of holes deformation is some air holes partially collapsing during the drawing process of PCF, and then, a discrepancy between experiment and theory exists as the practical structure distorts from the ideal structure. Therefore, the investigation on the fabrication process is very important for ensuring the dispersion properties of the practical PCF.

In this paper, we report our recent research on designing microstructured fiber with novel dispersion properties. In one hand, two kinds of novel PCFs, which are the highly nonlinear PCF with broadband nearly zero flatten

dispersion, and the highly negative PCF are proposed. On the other hand, effects of draw parameters such as drawing temperature and feed speed on the geometry of the final PCF are investigated.

2 Highly nonlinear PCF with broadband nearly zero flatten dispersion

2.1 Structure of highly nonlinear PCF with broadband nearly zero flatten dispersion

The novel structure of highly nonlinear PCF with broadband nearly zero flatten dispersion is shown in Fig. 1. The transverse section of the PCF proposed consists of a hexagonal lattice of air holes in pure silica and a Ge-doped core located at the center of the lattice. The number of rings of air holes is assumed to be seven. The air-hole diameter in the first and second inner rings and the other rings are denoted by d_1 , d_2 , and d , respectively. The diameter of Ge-doped core is selected as the same with the air-hole pitch Λ . Since small air-hole pitch is necessary for highly nonlinear fiber, a fixed hole pitch $\Lambda = 1 \mu\text{m}$ is chosen in view of the possibility of fabrication process. The Ge-doped concentration of the core is signed by C .

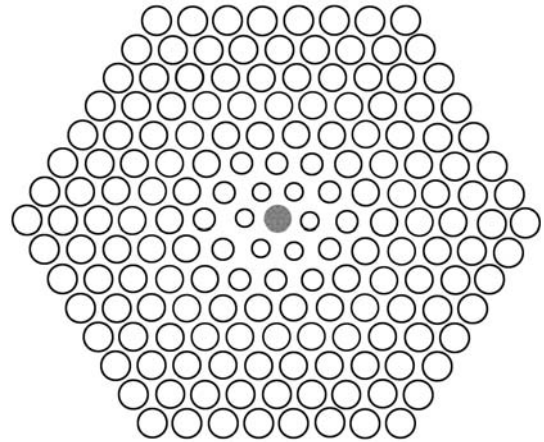


Fig. 1 Cross section of seven-ring triangular PCF considered

2.2 Effect of structure parameters on dispersion properties of highly nonlinear PCF

To make the fabrication process easy to control, we focus on discussing the effect of the first two inner rings of air hole and the doping concentration C of the core on the dispersion properties. Generally, the total dispersion coefficient D should be expressed as the sum of the waveguide dispersion D_w and the material dispersion D_m . Material dispersion D_m can be calculated by applying the Sellmeier law. Starting from the knowledge of the effective refractive index n_{eff} versus the wavelength λ obtained by the plane wave expansion method, the

waveguide dispersion D_w is derived using simple finite difference formulas, as shown below [11]:

$$D_w(\lambda) = -\frac{\lambda}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2}, \quad (1)$$

where c is velocity of light in the vacuum.

First, let us discuss the effect of air hole's diameter in the first inner ring on dispersion properties of the highly nonlinear PCF. Figure 2 shows the dispersion curves calculated for wavelength range from 1460 to 1625 nm for $d_2/\Lambda = 0.9$, $d/\Lambda = 0.9$, and the doped concentration $C = 0$, i.e., pure silica core. The normalized air-hole diameter d_1/Λ varies from 0.4 to 0.9. With a decrease in d_1/Λ from 0.9 to 0.4, the dispersion curve shift upwards, corresponding to an increase in the dispersion and a decrease in the dispersion slope in the wavelengths range from 1460 to 1625 nm, i.e., over the S, C, and L wavelength band. The shift is larger at longer wavelength than at shorter wavelength. Notice the case for the PCF with $d_1/\Lambda = 0.4$, the dispersion and dispersion slope becomes positive. With d_1/Λ decreasing, the dispersion slope varies from large negative value to positive value. This means that the diameter of air holes in the first inner ring have a strong influence on the dispersion properties of the highly nonlinear PCF. It is clearly seen that the dispersion becomes wavelength flattened at $d_1/\Lambda = 0.42$.

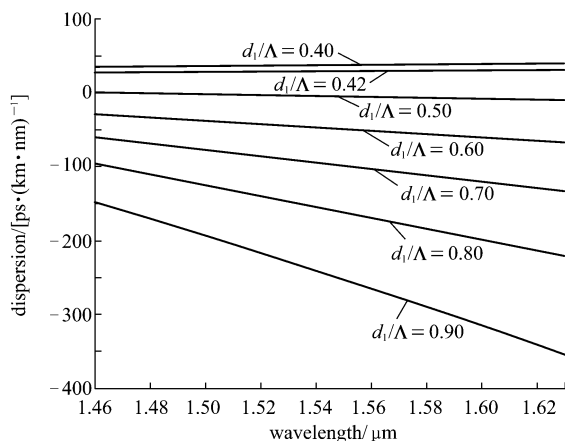


Fig. 2 Dispersion of PCF with $d_2/\Lambda = d/\Lambda = 0.9$ and $\Lambda = 1 \mu\text{m}$ at different d_1/Λ

Then, let us discussed the effect of the air hole's diameter in the second inner ring on dispersion behavior of the highly nonlinear PCF with $d_2/\Lambda = 0.9$, 0.87, 0.86, 0.85, and 0.8, respectively, for a fixed $d_1/\Lambda = 0.42$ and $\Lambda = 1 \mu\text{m}$ in Fig. 3. As d_2/Λ decrease from 0.9 to 0.86, the dispersion slope decreases, and the dispersion curve becomes more flat. As d_2/Λ decreases continuously from 0.86 to 0.8, the dispersion slope increases slightly. As $d_1/\Lambda = 0.42$ and $d_2/\Lambda = 0.86$, the dispersion curve becomes more flattened although the dispersion level is still not nearly zero. Although d_2/Λ also dominantly influences on the level of

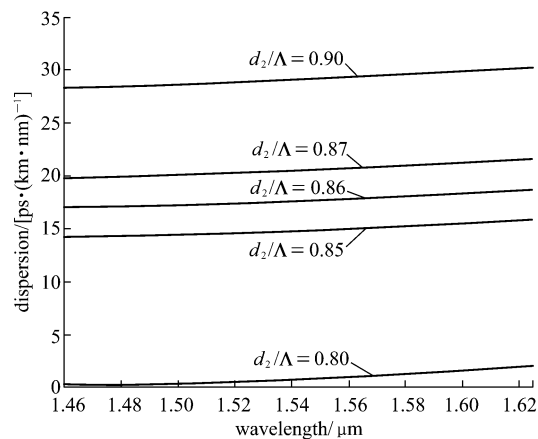


Fig. 3 Dispersion of PCF with $d_1/\Lambda = 0.42$, $d/\Lambda = 0.9$, and $\Lambda = 1 \mu\text{m}$ at different d_2/Λ

dispersion and dispersion slope, the variation of dispersion is smaller than in that case of changing d_1/Λ . This means that the chromatic dispersion properties are not affected significantly by the outer rings. Therefore, we choose a larger value of $d/\Lambda = 0.9$ for the outer ring in order to make good field confinement in the proposed structure.

Finally, let us discuss the effect of the Ge-doped concentration in the core on dispersion properties of the highly nonlinear PCF. When the core is doped with Ge instead of pure silica, the refractive index of doped core is calculated from doping concentration, and the dispersion of Ge-doped silica are taken into account by using the Sellmeier's formula [12]. According to Ref. [13], the core with suitable Ge-doped concentration is able to adjust slightly the dispersion curve. Furthermore, it can moderately increase the nonlinear index and thereby increase the nonlinear coefficient. The effect of the Ge-doped concentration C of the core on the dispersion curve is shown in Fig. 4 of the proposed highly nonlinear PCF with $d_1/\Lambda =$

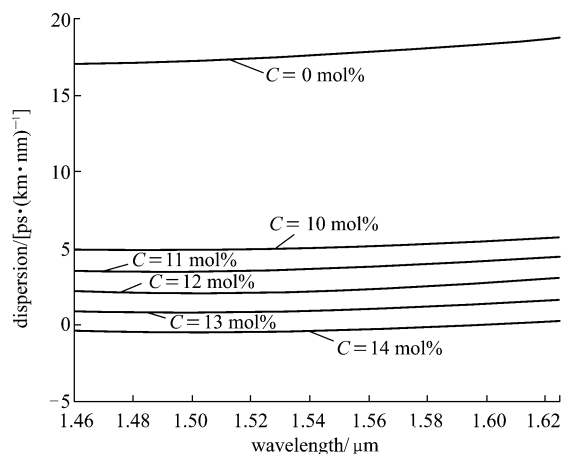


Fig. 4 Dispersion curves with various Ge doping concentration C from 10 mol% to 14 mol% for highly nonlinear microstructured fiber with $\Lambda = 1 \mu\text{m}$, $d_1/\Lambda = 0.42$, $d_2/\Lambda = 0.86$, and $d/\Lambda = 0.9$

0.42, $d_2/\Lambda = 0.86$, $d/\Lambda = 0.9$, and $\Lambda = 1 \mu\text{m}$. An increase in the Ge-doped concentration C of the core causes the dispersion curves shift downward, corresponding to a decrease in dispersion. The reduction is more at longer wavelength than at shorter wavelength. As the doping concentration C increases to 12 mol%, the dispersion curves start to slightly shift upward at the short wavelength of $1.46 \mu\text{m}$. With a further increase in the doping concentration C up to 14 mol%, a nearly zero flattened dispersion curve can be achieved, and the fluctuation in the amplitude of dispersion is found to be less than $\pm 0.5 \text{ ps}/(\text{km} \cdot \text{nm})$ within the telecommunication wavelength window wavelength range from 1460 to 1625 nm.

2.3 Nonlinearity of highly nonlinear PCF proposed

Nonlinear coefficient is an important parameter for highly nonlinear fiber and defined by [14]

$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{\text{eff}}} \quad (2)$$

for fiber, where n_2 is the fiber nonlinear refractive index, and A_{eff} is the effective mode area.

It is clearly seen from Eq. (2) that nonlinear coefficient is determined by two factors. The first one is the nonlinear refractive index n_2 , which depends on the fiber material. For the Ge-doped silica, the nonlinear refractive index n_2 can be calculated by empirical relationships:

$$\begin{aligned} n_2 (10^{-20} \text{ m}^2/\text{W}) \\ = 2.867 \frac{68(n_D - 1)(n_D^2 + 2)^2}{\nu_D \left[1.517 + \frac{(n_D + 1)(n_D^2 + 2)}{6n_D} \nu_D \right]^{1/2}}, \end{aligned} \quad (3)$$

where $\nu_D = (n_D - 1)/(n_F - n_C)$, and n_F , n_D , and n_C denote the refractive index at 0.48613, 0.58756, and 0.65627 μm , respectively [15]. The second factor is the effective mode area A_{eff} , which can be calculated with

$$A_{\text{eff}} = \frac{\left(\iint |E|^2 dx dy \right)^2}{\iint |E|^4 dx dy}. \quad (4)$$

Figure 5 shows the effective mode area and the nonlinear coefficient as function of the wavelength for the proposed highly nonlinear PCF with pure silica core and Ge-doped core, respectively, where $d_1/\Lambda = 0.42$, $d_2/\Lambda = 0.86$, $d/\Lambda = 0.9$, $\Lambda = 1 \mu\text{m}$, and $C = 14 \text{ mol}\%$. It is obviously shown in Fig. 5 that Ge-doped core in highly nonlinear PCF efficiently decreases the effective mode area and thereby increase the nonlinear coefficient. On the other hand, Ge-doped core can moderately increase the nonlinear index and thereby increase the nonlinear coefficient. Nonlinear coefficient of $47 \text{ W}^{-1} \cdot \text{km}^{-1}$ is obtained at the wavelength $1.55 \mu\text{m}$ for the highly nonlinear PCF with Ge-doped core,

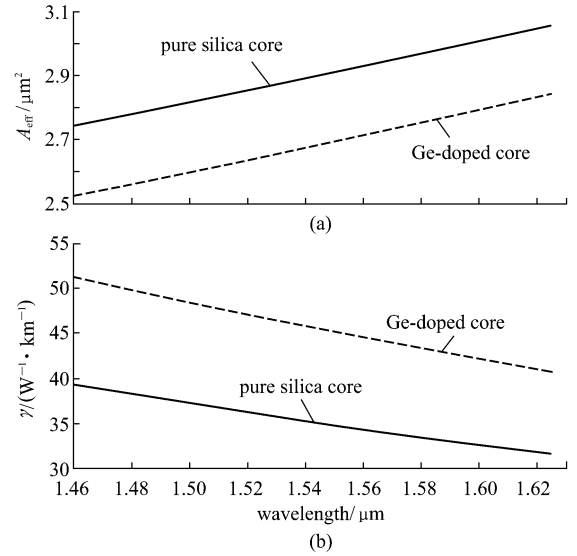


Fig. 5 Effective mode area (a) and nonlinear coefficient (b) of highly nonlinear PCF with $d_1/\Lambda = 0.42$, $d_2/\Lambda = 0.86$, $d/\Lambda = 0.9$, $\Lambda = 1 \mu\text{m}$, and Ge-doped concentration $C = 14 \text{ mol}\%$

whereas nonlinear coefficient only reaches a value of $34 \text{ W}^{-1} \cdot \text{km}^{-1}$ for the same structure with pure silica core. As Ge-doped core raises the refractive index of core, it makes the field tight confinement, and thus, the effective mode area decreases. This results in an improvement in the large magnitude for its nonlinear coefficient. By considering seven air-hole rings in the cross section of highly nonlinear PCF, the leakage losses at $1.55 \mu\text{m}$ is under the Rayleigh scattering limit and can be neglected [16].

3 Novel Structure of highly negative PCF

3.1 Structure of highly negative PCF

Novel structure of highly negative PCF proposed is shown in Fig. 6. The cladding is formed by a triangular lattice of air holes with a diameter of d and pitch of Λ . To form an

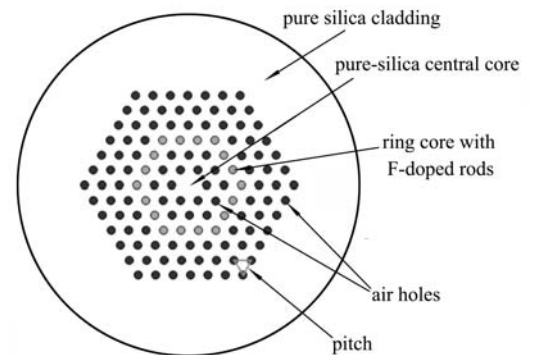


Fig. 6 Cross section of proposed structure of DCPCF adopting 18 F-rods to form its outer ring core

outer ring core with lower index than that of inner core, the air holes within the third ring are replaced by 18 fluorin-doped (F-doped) rods. Moreover, we assume that these F-doped rods have the same diameter as other air holes.

3.2 Dispersion of highly negative PCF proposed

First, a reference configuration is chosen in which the pitch is $\Lambda = 6 \mu\text{m}$, the relative diameter of air holes, and F-doped rods is $d/\Lambda = 0.5$, and relative index difference between the F-doped rods (refractive index of n_F) and pure silica (refractive index of n_{silica}) is $\Delta n_F = (n_F - n_{\text{silica}})/n_{\text{silica}} = -0.674\%$. The mode coupling process and the dispersion curve versus the wavelength is shown in Fig. 7, in which the brightness represents the mode field intensity in the region with different radius (left y-axis) versus wavelength (x-axis). The white curve shows dispersion parameter (right y-axis) versus wavelength (x-axis). In this structure, the radius of inner core is about $4.5 \mu\text{m}$, while the inner and outer radius of outer ring core is about 13.5 and $22.5 \mu\text{m}$, respectively. The power of the mode is only concentrated in the inner core when the wavelength is relative low, when the wavelength approaches $1.55 \mu\text{m}$, some power appears in the outer ring core. When further increasing the wavelength, the power is depressed in the inner core, while it is gradually enhanced in the outer ring core, which means that the mode field is coupling from the inner core into the outer ring core. In addition, the phase-matching wavelength (PMW) is just $1.55 \mu\text{m}$. The peak dispersion of $-1064 \text{ ps}/(\text{km} \cdot \text{nm})$ is obtained at wavelength $\lambda = 1.55 \mu\text{m}$, and the full width at half maximum (FWHM) is about 8 nm .

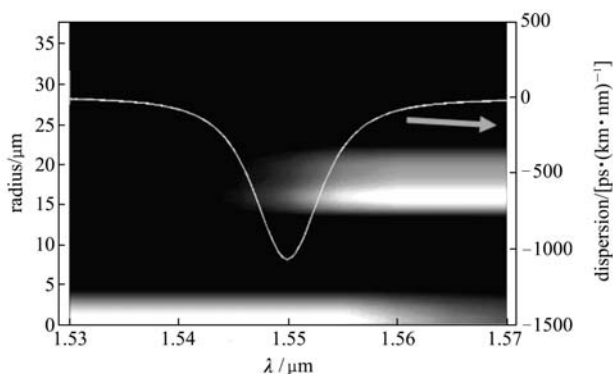


Fig. 7 Mode coupling process and dispersion curve of proposed DCPCF

Also, we can change the structure parameter such as hole pitch, the relative hole diameter, and the doped concentration of F-doped rod to tailor the dispersion and the full width at half maximum. For example, we change the structural parameter d/Λ from 0.5 to 0.45 and Δn_F from -0.673% to -0.83% while keeping the other parameters unchanged. Decreasing d/Λ is intended for a wider

dispersion compensation bandwidth while it has the side-effect of shifting the dispersion peak toward shorter wavelength. Therefore, increasing the index difference is used as a counteraction to guarantee the dispersion peak at the expected wavelength. Its corresponding dispersion curve is shown in Fig. 8 compared with the reference configuration. The FWHM of this fiber is widened to 20 nm , but the cost is that the peak dispersion is decreased to $-365 \text{ ps}/(\text{km} \cdot \text{nm})$.

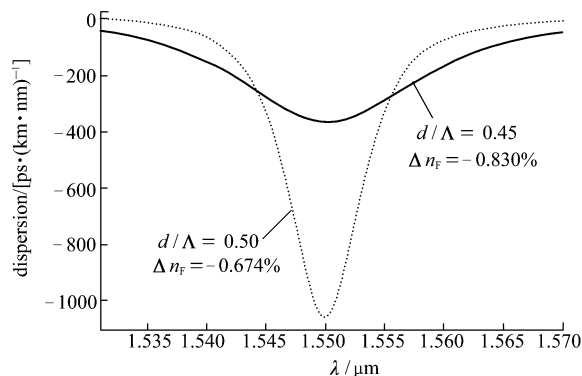


Fig. 8 Dispersion curves of proposed DCPCF with same pitch $\Lambda = 6 \mu\text{m}$

4 Fabrication of PCF

4.1 Modeling fabrication of PCF

PCFs are manufactured by heating a macroscopic structured preform (a few centimeters in diameter) and drawing it down to the required dimension (typically 125 micrometers in diameter). The geometry of the final fiber can be modified significantly by controlling the parameters used in the drawing process, i.e., the temperature of the furnace, the speed at which the preform is fed into this furnace, and the draw speed. However, it is difficult to keep air holes free of collapse. In order to avoid the closure of holes, inert gas pressurization is introduced in the preform during the fiber drawing process to finely control the geometry of PCF that good uniform in transversal and longitudinal of the final PCF is realized.

For the optical fiber drawing process shown in Fig. 9, the inner and outer radii of the initial capillary A and that of final air hole in PCF are defined as R_h and R_i , $R_i(z)$ and $R_o(z)$, respectively, during the fabrication process of PCF; the inert pressure is denoted by p , and the flow speed of the wall is given by $\mathbf{v} = u\mathbf{e}_z + w\mathbf{e}_r$, where u , w are axial velocity and radial velocity, respectively. Assuming that the heating and the flow are axisymmetric. Momentum and energy equations can be written for both the glass preform and fiber in cylindrical coordinates, which is assumed to be incompressible at the typical low flow rates employed in practice [17–20]:

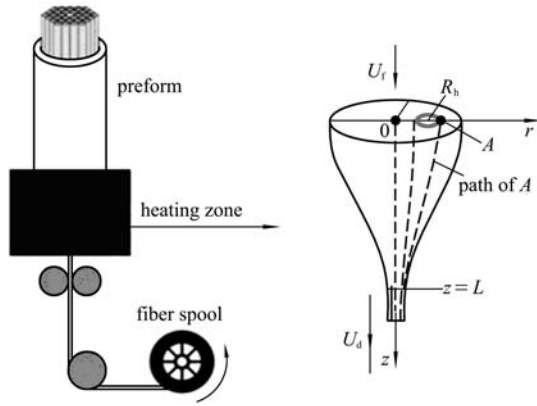


Fig. 9 Schematic diagram of drawing process of PCF

$$\begin{aligned} \rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial z} + w \frac{\partial u}{\partial r} \right) \\ = -\frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} \left(\mu r \frac{\partial u}{\partial r} \right) \\ + \frac{\partial}{\partial z} \left(2\mu \frac{\partial u}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\mu r \frac{\partial w}{\partial z} \right), \end{aligned} \quad (5)$$

$$\begin{aligned} \rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial z} + w \frac{\partial w}{\partial r} \right) \\ = -\frac{\partial p}{\partial r} + \mu \frac{\partial}{\partial r} \left[\frac{1}{r} \frac{\partial}{\partial r} (rw) \right] + \frac{\partial}{\partial z} \left(\mu \frac{\partial w}{\partial z} \right) \\ + \frac{\partial \mu}{\partial z} \frac{\partial u}{\partial r} + 2 \frac{\partial \mu}{\partial r} \frac{\partial w}{\partial r}, \end{aligned} \quad (6)$$

$$\frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} + \frac{w}{r} = 0, \quad (7)$$

where ρ is the density of silica, t is the time, and μ is dynamic viscosity. According to the initial condition and boundary conditions, the $R_i(z)$ and the $R_o(z)$ can be obtained. For describing the relative changes of A in the drawing process, S is defined as

$$S = \frac{R_i(L)/R_o(L)}{R_h/R_i}. \quad (8)$$

The viscosity coefficient can be represented by the following equation:

$$\mu = 5.8 \times 10^{-8} \exp \left(\frac{515400}{8.3145T + 2271.10567} \right) pS, \quad 1400^\circ\text{C} \leq T \leq 2500^\circ\text{C}. \quad (9)$$

4.2 Effect of structure parameter on fabrication of PCF

Assuming that the capillary with the initial inner radius is $R_h = 0.3$ mm and outer radius is $R_i = 0.45$ mm for the triangular lattice perform of PCF, and the length of furnace is $L = 161.6$ mm. Effects of draw parameters such as furnace temperature, feed speed, and drawing speed on the geometry of the final PCF are investigated. The curves between S and p are depicted in Fig. 10.

Numerical results demonstrate that the variation of draw parameters would affect the final ratio of inner radius and outer radius of air hole in PCF, i.e., the final geometry of PCF. When the furnace temperature T and drawing speed U_d are fixed, the variation of feed speed U_f would affect the slope of the curve of S versus p . The smaller the feed speed is, the larger the curve slope is. This means that the final geometry of PCF is more sensitive to pressure p at the small feed speed than at the large feed speed. When the furnace temperature T and feed speed U_f are fixed, the variation of drawing speed U_d would also affect the slope of the curve of S versus p . However, the effect of drawing speed on the final geometry of PCF is less than the feed speed does. Furthermore, the furnace temperature T also has a large effect on the final geometry of PCF. With the increase from 1800°C to 1900°C in the furnace temperature, the curve slope of S versus p increase rapidly. When the furnace temperature reaches to 1900°C , the geometry of the final PCF is very sensitive to the inert pressure p . A little change in the pressure p would result in a large magnitude of variation in the value of S .

When $S = 1$, air holes in the final geometry of PCF will keep the ratio of the inner diameter to outer diameter of the

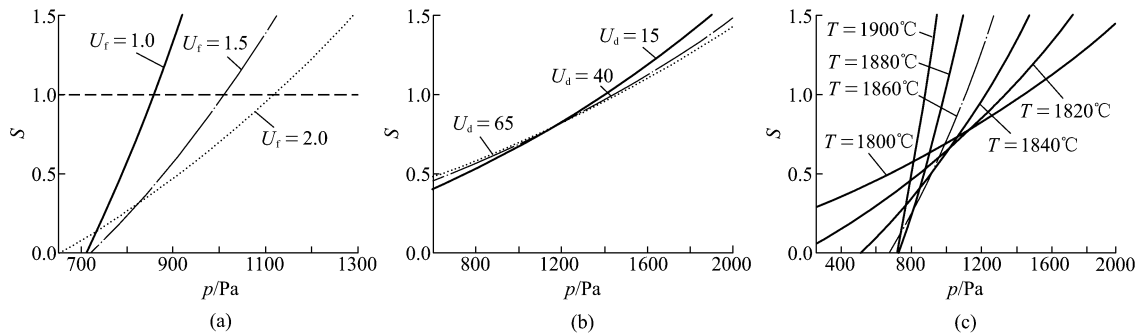


Fig. 10 Curves of S versus p . (a) $T = 1850^\circ\text{C}$, $U_d = 15$ m/min; (b) $T = 1800^\circ\text{C}$, $U_f = 2$ mm/min; (c) $U_f = 2$ mm/min, $U_d = 40$ m/min

initial capillary. When $S < 1$, the air holes have some degree of collapse. When $S > 1$, the air holes have some degree expansion. In fact, inert pressure introduced into the fabrication process of PCF can improve the flexibility of fabricating PCF. With the same preform of PCF, the different geometry of PCF can be drawn by using different parameter assignment. For example, the different draw parameters can be chosen from Fig. 10 if we want to fabricate the PCF with $d/\Lambda < 0.45$, i.e., $S < 0.675$ or with $d/\Lambda > 0.8$, i.e., $S > 1.2$. Figure 11 shows two kinds of different geometry of PCF drawn from the same preform of PCF.

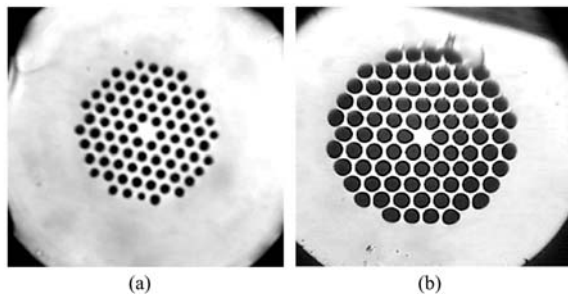


Fig. 11 Two kinds of final geometry of PCF drawn from same preform with initial ratio of inner radius to outer radius 2/3. (a) $d/\Lambda = 0.45$; (b) $d/\Lambda = 0.8$

Furnace temperature and inert pressure should be controlled reasonably during the fabrication process of PCF. However, when the temperature is too low or U_f is too high to make the silica melt fully, it will results in the gap appearing between the holes, and the properties of the final PCF has a large distort from the initial design. The strength of PCF will be lowered. Based on the above analysis, although lowering temperature and increasing U_f can make the tunable range of pressure broad, the temperature should not be too low, and feed speed should not be too high so that the design structure of PCF can be kept, and the strength of PCF can satisfy the need for application. The recommending temperature should not be less than 1800°C.

5 Conclusion

In this paper, we propose the highly nonlinear PCF with broadband nearly zero flatten dispersion and the highly negative PCF. While introducing the Ge-doped core into highly nonlinear PCF and optimizing the diameters of the first two inner rings of air-holes, a new structure of highly nonlinear PCF was invented with the nonlinear coefficient up to $47 \text{ W}^{-1} \cdot \text{km}^{-1}$ at the wavelength $1.55 \mu\text{m}$ and nearly zero flattened dispersion of $\pm 0.5 \text{ ps}/(\text{km} \cdot \text{nm})$ in telecommunication window (1460–1625 nm). While introducing a ring of F-doped rods into the third

ring of air holes in PCF to form its outer ring core, a new structure of highly negative PCF has been proposed. The peak dispersion $-1064 \text{ ps}/(\text{km} \cdot \text{nm})$ in 8 nm (FWHM) wavelength range, and $-365 \text{ ps}/(\text{km} \cdot \text{nm})$ in 20 nm (FWHM) wavelength range can be reached by adjusting the structure parameters. We also set up the theoretical model to investigate the effects of draw parameters such as drawing temperature and feed speed on the geometry of the final photonic crystal fiber. Through choosing the different drawing parameter, the final PCFs with different geometry have been drawn from the same preform.

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References

1. Knight J C, Birks T A, Russell P St J, Atkin D M. All-silica single-mode optical fiber with photonic crystal cladding. *Optics Letters*, 1996, 21(19): 1547–1549
2. Ferrando A, Silvestre E, Miret J, Andrés P. Nearly zero ultraflattened dispersion in photonic crystal fibers. *Optics Letters*, 2000, 25(11): 790–792
3. Reeves W H, Skryabin D V, Biancalana F, Knight J C, Russell P. Demonstration of ultra-flattened dispersion in photonic crystal fibers. *Optics Express*, 2002, 10(14): 609–613
4. Gérôme F, Auguste J L, Blondy J M. Design of dispersion-compensating fibers based on a dual-concentric-core photonic crystal fiber. *Optics Letters*, 2004, 29(23): 2725–2727
5. Gander M J, McBride R, Jones J D C, Mogilevtsev D, Birks T A, Knight J C, Russell P. Experimental measurement of group velocity dispersion in photonic crystal fibre. *IEEE Electronics Letters*, 1999, 35(1): 63–64
6. Wu T L, Chao C H. A novel ultraflattened dispersion photonic crystal fiber. *IEEE Photonics Technology Letters*, 2005, 17(1): 67–69
7. Kunimasa S, Masanori K. Highly nonlinear dispersion-flattened photonic crystal fibers for super-continuum generation in a telecommunication window. *Optics Express*, 2004, 12(10): 2027–2032
8. Ferrando A, Silvestre E, Andres P, Miret J J, Andres M V. Designing the properties of dispersion-flattened photonic crystal fibers. *Optics Express*, 2001, 9(13): 687–697
9. Saitoh K, Koshiba M, Hasegawa T, Sasaoka E. Chromatic dispersion control in photonic crystal fibers: application to ultra-flattened dispersion. *Optics Express*, 2003, 11(8): 843–852
10. Yang S G, Zhang Y J, Peng X Z, Lu Y, Xie S Z. Theoretical study and experimental fabrication of high negative dispersion photonic crystal fiber with large area mode field. *Optics Express*, 2006, 14(7): 3015–3023
11. Ren G B, Lou S Q, Wang Z, Jian S S. Study on dispersion properties of photonic crystal fiber by effective-index model. *Acta Optica Sinica*, 2004, 24(3): 319–323 (in Chinese)

12. Boling N, Glass A, Owyong A. Empirical relationships for predicting nonlinear refractive index changes in optical solids. *IEEE Journal of Quantum Electronics*, 1978, 14(8): 601–608
13. Hoo Y L, Jin W, Ju J, Ho H L, Wang D N. Design of photonic crystal fibers with ultra-low, ultra-flattened chromatic dispersion. *Optics Communications*, 2004, 242(4–6): 327–332
14. Linn F M. Nonlinear optics in fibers. *Science*, 2003, 302(5647): 996–997
15. Nakajima K, Ohashi M. Dopant dependence of effective nonlinear refractive index in GeO₂- and F-doped core single-mode fibers. *IEEE Photonics Technology Letters*, 2002, 14(4): 492–494
16. Ferrarini D, Vincetti L, Zoboli M, Cucinotta A, Poli F, Selleri S. Leakage losses in photonic crystal fibers. In: *Proceedings of Optical Fiber Communication Conference*, 2003, 2: 699–700
17. Lee S H K, Jaluria Y. The effects of variable viscosity and viscous dissipation on the flow and thermal transport during optical fiber drawing. In: *Proceedings of 10th International Heat Transfer Conference*, 1994, 7: 303–308
18. Lee S H K, Jaluria Y. The effects of geometry and temperature variations on the radiative transport during optical fiber drawing. *Journal of Material Processing and Manufacturing Science*, 1995, 3 (4): 317–331
19. Myers M R. A model for unsteady analysis of preform drawing. *Journal for the American Institute of Chemical Engineers*, 1989, 35 (4): 592–602
20. Falkenstein P, Merritt C D, Justus B L. Fused performs for the fabrication of photonic crystal fibers. *Optics Letters*, 2004, 29(16): 1858–1860