Design of broadband nearly-zero flattened dispersion highly nonlinear photonic crystal fiber

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Received May 4, 2008

We propose a new structure of broadband nearly-zero flattened dispersion highly nonlinear photonic crystal fiber (PCF). Through optimizing the diameters of the first two inner rings of air-holes and the GeO_2 doping concentration of the core, the nonlinear coefficient is up to 47 $W^{-1}\cdot km^{-1}$ at the wavelength of 1.55 μm and nearly-zero flattened dispersion of ± 0.5 ps/(nm·km) is achieved in the telecommunication window ($1460-1625$ nm). Due to the use of GeO_2-doped core, this innovative structure can offer not only a large nonlinear coefficient and broadband nearly-zero flattened dispersion but also low leakage losses.

OCIS codes: 060.2280, 060.2270, 060.4370.
doi: 10.3788/COL20080611.0821.

Highly nonlinear fiber based devices such as wavelength converters, parametric amplifiers, supercontinuum sources, and optical switches are attractive candidates for applications in future high-capacity all-optical networks. In order to reduce the physical length and/or required operating powers, and maximize the operating bandwidth of many such devices, considerable attention has been attracted to develop highly nonlinear fiber with flattened dispersion over a wide wavelength range in recent years.

Index-guiding photonic crystal fibers (PCFs), also called holey fibers or micro-structured fibers, are characterized by a periodic arrangement of air holes around a central high-index core along the entire length of the fiber. Due to their special structures, PCFs offer more flexibility than conventional fibers in design of optical characteristics. Through employing small hole pitch Λ and large ratio d/Λ of hole diameter to hole pitch to confine light tightly within the core, PCF exhibits a small mode area and extremely high nonlinearity. Moreover, its chromatic dispersion is also flexible to be controlled by manipulating the structure parameters.

In order to get high nonlinearity and low confinement loss, conventional highly nonlinear PCF is usually designed with small pitch of about 1 μm and the large ratio d/Λ of hole diameter to hole pitch. However, its chromatic dispersion is not flattened[1]. Several new structures have been proposed to improve the chromatic dispersion properties and achieve nearly-zero ultra-flattened chromatic dispersion properties in telecommunication window wavelength range. Since the designs arrange the same diameter air holes in a regular triangular lattice[2] and the d/Λ ratio is small, more than 20 rings of air holes are required in the cladding region to realize the nearly-zero ultra-flattened dispersion properties and significantly reduce the confinement loss in a cost of an increase in the effective area and a decrease in the nonlinear coefficient which make the fabrication complex. Although a few new structure designs else have been proposed with different air-hole diameters for each ring[3−5], the structure design of simple high nonlinear PCF with nearly-zero flattened chromatic dispersion properties and low confinement losses is still an ongoing challenge.

In this letter, we numerically investigate the influence of the structure parameters of highly nonlinear PCF on chromatic dispersion. Through optimizing the diameters of the first two inner rings of air-holes and the GeO_2 doping concentration of the core, a novel design of highly nonlinear PCF with nearly zero flattened dispersion, high nonlinear coefficient, and low confinement loss is proposed.

As shown in Fig. 1, the structure of PCF studied here has a transverse section consisting of a hexagonal lattice of air holes in pure silica whose refractive index is 1.444 and a GeO_2-doped core located at the center of the lattice. The number of rings of air-holes is assumed to be seven. According to the previous numerical results[6], the inner rings of air hole significantly affect the dispersion of PCF. The air-hole diameter is different in the first and second inner rings from that in the other rings. The air-hole diameter in the first, second inner rings, and the other rings are denoted by d_1, d_2, and d, respectively. The diameter of GeO_2-doped core is chosen to be same with the air-hole pitch Λ. Since small air-hole pitch is

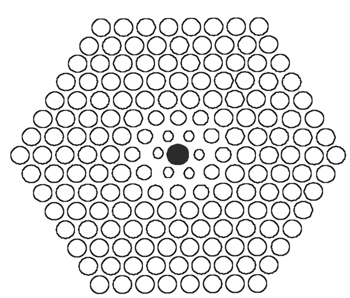

Fig. 1. Cross section of the seven-ring PCF considered: d_1, d_2 are air-hole diameters in the first and second rings, d is the air-hole diameter of the other rings.

necessary for highly nonlinear fiber, a fixed hole pitch $\Lambda = 1$ μm is chosen in view of the possibility of fabrication process. In order to make sure the fabrication process simple and realizable, we focus on the effects of the first two inner rings of air holes and the GeO_2 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

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

where c is the velocity of light in the vacuum.

Firstly, let's discuss the effect of air holes' 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 $C = 0$, 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 shifts upwards, corresponding to an increase in the dispersion and a decrease in the dispersion slope in the wavelength range from 1460 to 1625 nm, i.e., over the S, C, and L wavelength bands. The shift is larger at longer wavelength than at lower wavelength. Notice the case for the PCF with $d_1/\Lambda = 0.4$, the dispersion and dispersion slope become 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 has a strong influence on the dispersion properties. It is clearly seen that the dispersion becomes wavelength-flattened at $d_1/\Lambda = 0.42$.

Then let's discuss 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, and 0.8, respectively, for fixed $d_1/\Lambda = 0.42$ and $\Lambda = 1$ μm. The results are shown in Fig. 3. As d_2/Λ decreases from 0.9 to 0.86, the dispersion slope decreases and the dispersion curve becomes flatter. As d_2/Λ decreases continuously from 0.86 to 0.8, the dispersion slope increases slightly. When $d_1/\Lambda = 0.42$ 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 affects the level of dispersion and dispersion slope, the variation of dispersion is smaller than that in 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 rings in order to make good field confinement in the proposed structure.

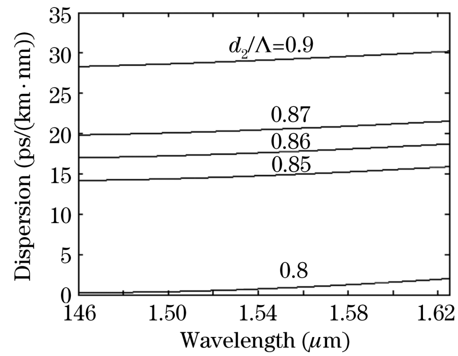

Fig. 3. Dispersion of the PCF with $d_1/\Lambda = 0.42$, $d/\Lambda = 0.9$, and $\Lambda = 1$ μm at different d_2/Λ.

Finally, let's discuss the effect of the GeO_2 doping concentration in the core on dispersion properties of the highly nonlinear PCF. When the core is doped with GeO_2 instead of pure silica, the refractive index of doped core is calculated from doping concentration and the dispersion of GeO_2-doped silica is taken into account by using the Sellmeier's formula[7]. According to Ref. [8], the core with suitable GeO_2 doping concentration is able to slightly adjust the dispersion curve. Furthermore, it can moderately increase the nonlinear index and thereby increase the nonlinear coefficient. The effect of the GeO_2 doping concentration C of the core on the dispersion curve is shown in Fig. 4 with $d_1/\Lambda = 0.42$, $d_2/\Lambda = 0.86$, $d/\Lambda = 0.9$, and $\Lambda = 1$ μm. An increase in C causes the dispersion curves to shift downwards, corresponding to a decrease in dispersion. The reduction is more at longer wavelength than at shorter wavelength. As C increases to 12 mol%, the dispersion curves start to slightly shift upwards at the short wavelength of 1.46 μm. With C further increased 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 ± 0.5 ps/(km·nm) within the telecommunication wavelength window (1460 – 1625 nm).

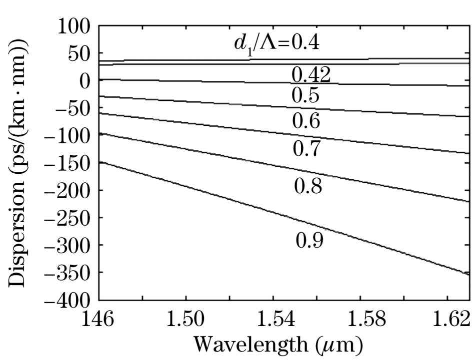

Fig. 2. Dispersion of the PCF with $d_2/\Lambda = d/\Lambda = 0.9$ and $\Lambda = 1$ μm at different d_1/Λ.

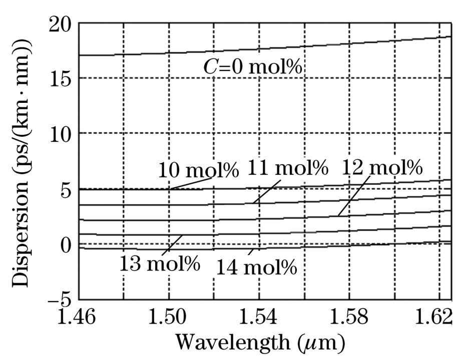

Fig. 4. Dispersion curves with various GeO_2 doping concentration C from 10 to 14 mol% for highly nonlinear PCF with $\Lambda = 1$ μm, $d_1/\Lambda = 0.42$, $d_2/\Lambda = 0.86$, and $d/\Lambda = 0.9$.

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

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{\mathrm{eff}}}, \tag{2}$$

where n_2 is the fiber nonlinear refractive index, and A_{eff} is the effective mode area. The nonlinear refractive index n_2 depends on the fiber material. For the GeO_2-doped silica, n_2 can be calculated by

$$n_2(\times 10^{-20}\ \mathrm{m}^2/\mathrm{W}) = 2.867 \cdot \frac{68(n_{\mathrm{D}}-1)(n_{\mathrm{D}}^2+2)^2}{\nu_{\mathrm{D}}\left[1.517+\frac{(n_{\mathrm{D}}+1)(n_{\mathrm{D}}^2+2)}{6n_{\mathrm{D}}}\cdot\nu_{\mathrm{D}}\right]^{1/2}}. \tag{3}$$

ν_{D} represents Abbé number defined as $\nu_{\mathrm{D}} = (n_{\mathrm{D}}-1)/(n_{\mathrm{F}}-n_{\mathrm{C}})$, where n_{F}, n_{D}, and n_{C} denote the refractive index at 0.48613, 0.58756, and 0.65627 μm, respectively[9]. The effective mode area A_{eff} can be calculated with

$$A_{\mathrm{eff}} = \frac{(\iint |E|^2 \mathrm{d}x\mathrm{d}y)^2}{\iint |E|^4 \mathrm{d}x\mathrm{d}y}. \tag{4}$$

Figure 5 shows the effective mode area and the nonlinear coefficient as functions of the wavelength for the proposed highly nonlinear PCF with pure silica core and GeO_2-doped core respectively. It is obvious that GeO_2-doped core in highly nonlinear PCF efficiently decreases the effective mode area and thereby increases nonlinear coefficient. On the other hand, GeO_2-doped core can moderately increase the nonlinear index and thereby increase the nonlinear coefficient. Nonlinear coefficient of 47 $\mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$ is obtained at 1.55 μm for the highly nonlinear PCF with GeO_2-doped core, whereas nonlinear coefficient only reaches a value of 34 $\mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$ for the same structure with pure silica core. As GeO_2-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 loss at 1.55 μm is under the Rayleigh scattering limit and can be neglected[10].

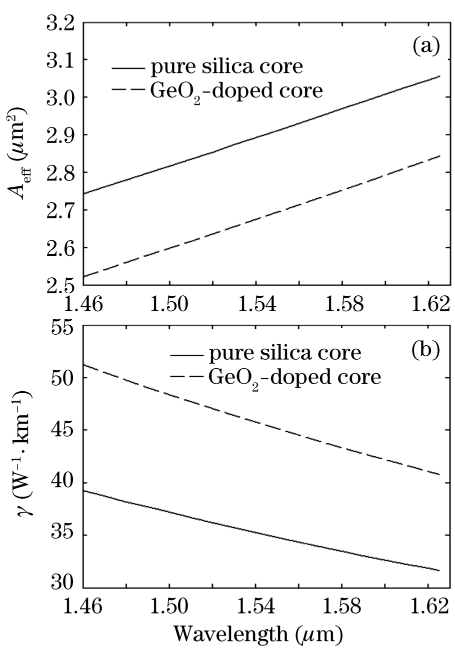

Fig. 5. (a) Effective mode area A_{eff} and (b) nonlinear coefficient γ of highly nonlinear PCF with $d_1/\Lambda = 0.42$, $d_2/\Lambda = 0.86$, $d/\Lambda = 0.9$, $\Lambda = 1$ μm, and $C = 14$ mol%.

Based on the effect of the structure parameter and GeO_2 doping concentration in the core region on dispersion properties, a new structure of nearly-zero flattened dispersion highly nonlinear PCF is proposed. Through optimizing the air-holes' diameter in the first two inner rings of air-holes and GeO_2 doping concentration of the core, broadband nearly-zero flattened dispersion highly nonlinear PCF is designed. Nonlinear coefficient of 47 $\mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$ at the wavelength 1.55 μm and the nearly-zero flattened dispersion of ± 0.5 ps/(nm·km) over S, C, L wavelength bands are obtained for the proposed PCF as $d_1/\Lambda = 0.42$, $d_2/\Lambda = 0.86$, $d/\Lambda = 0.9$, $\Lambda = 1$ μm, and GeO_2 doping concentration $C = 14$ mol%. Due to the use of GeO_2-doped core, this innovative structure can offer not only a large nonlinear coefficient and broadband nearly-zero flattened dispersion properities but also low leakage loss. The highly nonlinear PCF with broadband nearly-zero flattened dispersion will be useful for many applications, such as supercontinuum generation, soliton pulse transmission, and so on[11,12]. Fabrication of such PCF is now under consideration.

This work was supported by the National Natural Science Foundation of China (No. 60777033) and the Key Project of Ministry of Education of China (No. 308002). S. Lou's e-mail address is shqlou@bjtu.edu.cn.

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