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高双折射 $80PbO \cdot 20Ga_2O_3$ 中心填充光子晶体光纤特性

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摘　要:提出一种高折射率材料 $80PbO \cdot 20Ga_2O_3$(PG 玻璃)中心填充椭圆芯光子晶体光纤.基于有限元法对光子晶体光纤的双折射特性和模场面积进行数值模拟,并研究了椭圆芯尺寸、椭圆率和孔间距等光纤几何参量对双折射特性的影响.数值研究表明:在 1 550 nm 波长处,双折射高达 1.256×10^{-1},x 偏振和 y 偏振模场面积分别为 0.43 μm^2 和 0.68 μm^2;在 910 nm～1931 nm 的宽波段范围内,双折射始终保持 10^{-1} 量级.该光纤可以作为保偏光纤应用于偏振控制、相干通信和光纤传感系统.

关键词:光子晶体光纤;双折射;中心填充;有限元法;PG 玻璃;模场面积;偏振控制
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Ultra-high Birefringence Photonic Crystal Fiber with Elliptical $80PbO \cdot 20Ga_2O_3$ Doped Defected Core

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Abstract: An ultra-high birefringence photonic crystal fiber was designed, which is composed of an elliptical all-solid hole doped with $80PbO \cdot 20Ga_2O_3$ in the core and a cladding with periodic hexagonal-lattice air holes. The performance of the modal birefringence and the contribution of different factors were investigated by the full-vector finite-element-method. Numerical results indicate that the modal birefringence has a magnitude of order of 10^{-1} in the range of wavelength from 910 nm to 1 931 nm. At the wavelength of 1 550 nm, we acquired an extremely high birefringence of 1.256×10^{-1} and the small effective areas of both orthogonal polarizations (<0.7 μm^2). The design of the fiber will be highly meaningful for the development of interferential fiber optic sensors, nonlinear optic and polarization-preserving devices.

Key words: Photonic crystal fiber; Modal birefringence; Doped core; Finite-element-method; PG glass; Mode area; Polarization control
OCIS Codes: 060.2420; 060.5295; 060.2310

0 Introduction

Photonic Crystal Fibers (PCFs), also known as microstructures fibers, have attracted more and more attention and intensive study in recent years due to their outstanding optical properties that are difficult to realize in conventional single-mode fibers, such as endless single-mode guiding, high birefringence, nonlinear properties, flattened dispersion and so on[1-4]. According to the waveguide mechanism, PCFs are

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classified into two different types of PCFs: one type of PCFs guides light by a principle of total internal reflection, and those PCFs are also known as index-guiding PCFs. The other type of PCFs, which is called photonic band-gap PCFs, is based on photonic band-gap effect, leading to mode field spread in the core.

The modal birefringence of PCFs are usually one or two order of magnitude higher than that of conventional fibers[5]. Photonic Crystal Fibers with High Birefringence (HB-PCFs) have demonstrated widespread application prospects in the optical fiber communication systems, optical sensors and fiber lasers[6-8]. The refractive index distribution of cross section of the PCFs determines the light propagation and the generation of the modal birefringence in this circular waveguide. The birefringence of conventional PCFs is always in the order of 10^{-3}[9]. The higher modal birefringence up to a magnitude of order of 10^{-2} was obtained by the formation of squeezed lattices of air holes[10-11], twin grapefruit air holes near the core[12], soft glass with liquid core[13], or substrate material based on Schott glass[14]. Recently a high birefringence fiber with the modal birefringence of 10^{-1} had been reported. However, the fiber had complex and difficult manufacture processes because of the complicated cladding with spirally arranged and gradually enlarged air holes[15].

The power distribution of the fundamental mode field is mainly in the core region of the index-guiding PCFs and the asymmetry of the core will increase the impaction on the modal propagation. The PG glass ($80PbO \cdot 20Ga_2O_3$) is widely used in the optical fiber owing to their better glass forming ability, thermal stability, high refractive index and the zero material-dispersion[16]. In this paper, we propose an Ultra-High Birefringence Photonic Crystal Fiber (UHB-PCF) with small mode area. The proposed UHB-PCF is composed of an elliptical defected core doped with PG glass and a cladding with periodic hexagonal-lattice air holes. The modal birefringence properties are simulated numerically by full-vector Finite-Element-Method (FEM)[17]. The modal birefringence of such an UHB-PCF can reach 10^{-1} over a long wavelength span. Besides, the UHB-PCF has many advantages because of the all-solid structure in the core surrounded by periodic arranged air holes simple periodic hexagon cladding, such as low splice loss, averting the collapse during drawing process of fiber core, preserving the Gaussian distribution characteristics of mode field and simplifying the fabrication process.

1 Geometries of the proposed UHB-PCF

The cross section of the schematic diagram of the proposed UHB-PCF is showed in Fig. 1. Air holes are arranged in the silica glass material (SiO_2) according to a hexagonal lattice structure. One elliptical hole doped with PG glass ($80PbO \cdot 20Ga_2O_3$) is used as defected core to increase the birefringence and the cladding is composed of circular air holes completely. $\eta = d_x/d_y$ is the ellipticity of the elliptical hole, which d_x and d_y are the lengths of the x and y axes of the central elliptical-hole, respectively. Λ is the center-to-center spacing between the circular air holes and D is the diameter of the circular air holes of the cladding. Taking the confinement loss and the modal distribution into account, we set up six rings of air hole in order to decrease the value of the confinement loss.

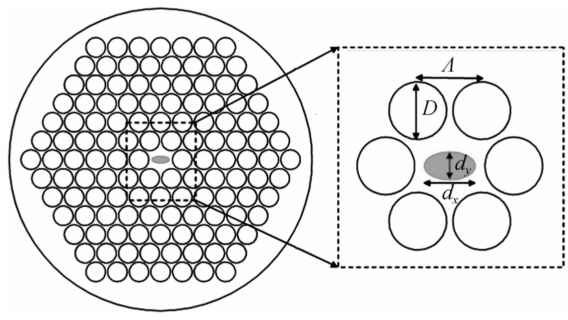

Fig. 1 Cross section and specific parameters of the proposed UHB-PCF

To make the analysis more accurately, the refractive index of the air holes is assumed to be Eq. 1 and the refractive index of the silica substrate is calculated by Sellmeier equation[18]. The refractive index of PG glass is calculated by an experienced formula[16]

$$n(\lambda) = \frac{a}{\lambda^4} + \frac{b}{\lambda^2} + c + d\lambda^2 + e\lambda^4 \tag{1}$$

where a, b, c, d and e are constant, λ is the wavelength of the light. The refractive index of PG glass is 2.18 at the wavelength of 1 550 nm.

In general, the modal birefringence is a major parameter to describe the polarization properties of birefringence fibers. We can define B as the birefringence of the proposed UHB-PCF, which can be expressed by the following formulation[10]

$$B = \frac{\lambda}{2\pi} \left| \beta_x(\lambda) - \beta_y(\lambda) \right| = \left| \mathrm{Re}(n_{\mathrm{eff}}^y) - \mathrm{Re}(n_{\mathrm{eff}}^x) \right| \tag{2}$$

where $\beta_x(\lambda)$, $\beta_y(\lambda)$ are the propagation constants and n_{eff}^x, n_{eff}^y are the effective refractive index of the x-polarized and y-polarized fundamental mode of the PCF, respectively. λ is the wavelength of the light, and $\mathrm{Re}(n_{\mathrm{eff}})$ are the real part of the effective refractive index of fundamental mode. The pace length L is determined by the phase delay of the two polarization modes which is relating to the modal birefringence according to the following formulation

$$L = 2\pi / \left| \beta_x(\lambda) - \beta_y(\lambda) \right| = \lambda / B \tag{3}$$

So, the pace length will decrease with the increase of

B. The mode area can be described as[19]

$$A_{\mathrm{eff}}=\frac{[\iint I(x,y)\,\mathrm{d}x\mathrm{d}y]^2}{\iint I^2(x,y)\,\mathrm{d}x\mathrm{d}y}$$

where $I(x, y)$ is the transverse distribution of light field.

2 Numerical results and discussion

The numerical results are reported for an optimized structure with the parameters of $\Lambda=1\ \mu\mathrm{m}$, $d_x=0.8\ \mu\mathrm{m}$, $\eta=d_x/d_y=2.5$, and $D/\Lambda=0.9$. Fig. 2 indicates the effective index of the x-polarized and y-polarized fundamental modes as a function of a wavelength range from 900 nm to 1 950 nm for the proposed UHB-PCF. According to Fig. 2, we can know that the effective index of the x-polarized is larger than the y-polarized and the modal birefringence keeps a magnitude of 10^{-1} in a range of wavelength from 910 nm to 1 931 nm, which reveals an excellent property of high birefringence at a broad range of wavelength for the proposed UHB-PCF. Besides, the modal birefringence increases firstly and then gradually decreases with increase of wavelength. It is because that the refractive index curves present slight inward attenuation curves and the refractive index of y-polarized mode is more sensitive to wavelength than x-polarized since the mode field of y-polarized fundamental spreads easier outside the elliptical core than x-polarized. An extraordinarily modal birefringence of the proposed UHB-PCF, 1.256×10^{-1}, is obtained at the wavelength of 1 550 nm, which is obviously higher than the reported HB-PCFs[9-14].

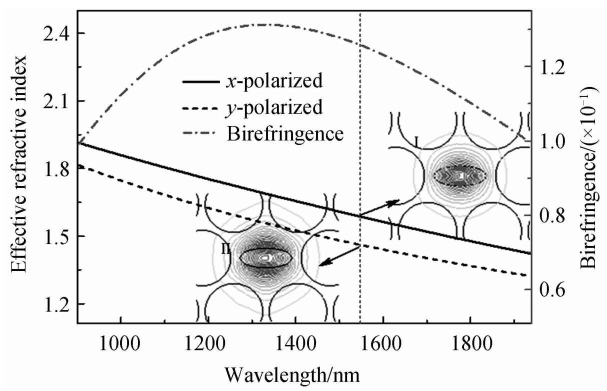

Fig. 2 The effective refractive index, the modal birefringence and intensity contour maps of the proposed UHB-PCF

The distribution of mode field is an effect of ultra-high birefringence which mainly depends on the refractive index anisotropy. Insets I and II in Fig. 2 present intensity contour maps of the fundamental x-polarized and y-polarized modes at 1 550 nm. It is obviously observed that the x-polarized mode is confined in the elliptical core region better than y-polarized mode, and x-polarized mode preserves the Gaussian distribution characteristics of mode field better than y-polarized mode, which may be used as a single polarization device.

Fig. 3 shows the effective mode area for the x-polarized fundamental mode and y-polarized fundamental of the proposed UHB-PCF. The proposed UHB-PCF can achieve small mode area of $0.43\ \mu\mathrm{m}^2$ for x-polarized at the wavelength of 1550 nm. The effective mode area of y-polarized is $0.68\ \mu\mathrm{m}^2$, with more than half of x-polarized. The difference between the values of mode area for x- and y-polarized increases with wavelength increasing. It is known that those phenomenon result from the high relative refractive index difference and small cross-section of fiber core.

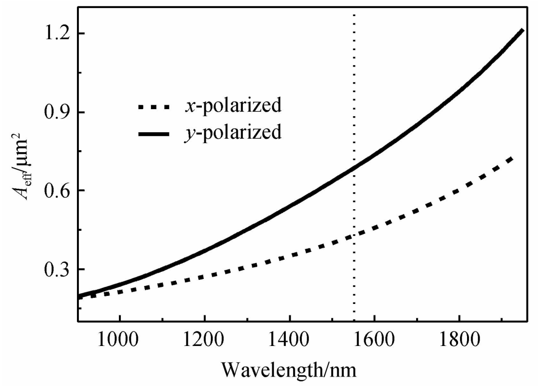

Fig. 3 The effective mode area of the proposed UHB-PCF

For the purpose of further researching on the impact of the design parameters for modal birefringence, we analyzed the relationship between that properties with the parameters of η, d_x and Λ. Fig. 4 (a) shows the modal birefringence varying with d_x, where $D/\Lambda=0.9$, $\Lambda=1\ \mu\mathrm{m}$ and $\eta=2$. The value of modal birefringence decreases with d_x increasing at the short wavelengths and the modal birefringence peak shifts toward red as the d_x increases. It is easy to understand by noting that the increase of d_x promotes the mode field of y-polarized confined in elliptical core, leading to the decrease of refractive index difference between x-polarized and y-polarized mode. The peak shifts toward red because that the refractive index curves of both x-polarized and y-polarized fundamental modes shifted upward with d_x increasing.

In Fig. 4 (b), we can see the modal birefringence is sensitive to the ellipticity of the elliptical doped hole and increases with η increasing, where $D/\Lambda=0.9$, $\Lambda=1\ \mu\mathrm{m}$ and $d_x/\Lambda=0.8$. The larger the η is, the more asymmetric will be generated in the fundamental mode field, which can enhance the value of modal birefringence. However, the mode field will spread cross the elliptical core when the η is too large, which leads to the destruction of the Gaussian distribution of fundamental mode. According to the results, we can posit the beneficial effect on modal birefringence from the elliptical defected core. The proposed UHB-PCF produces asymmetry structure in the core region and leads to different effect on the two polarized modes because of the existence of the elliptical all-solid hole doped with PG glass.

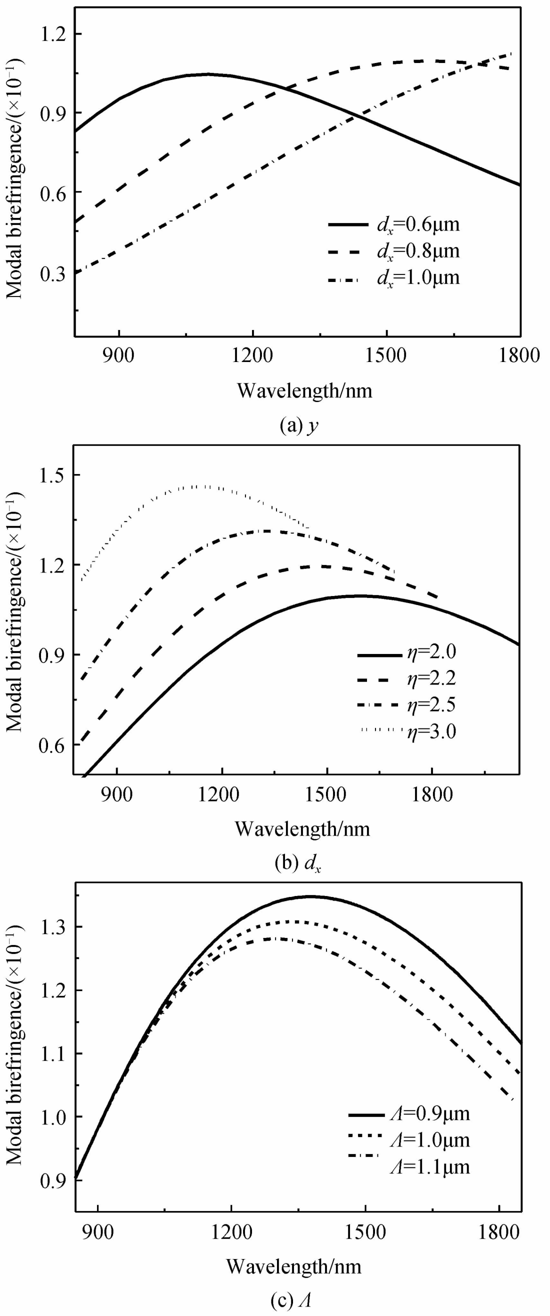

Fig. 4 Influences of structure parameters for the proposed UHB-PCF on the birefringence

Fig. 4 (c) displays the modal birefringence varying with Λ, where $D/\Lambda=0.9$, $d_x=0.8$ μm and $\eta=2.5$. As Λ increases, the modal birefringence peak shifts toward the blue and decreases in the modal birefringence is observed. Different from other elements, the modal birefringence changes are weakly affected in the short wavelength. It is because the mode field is well confined in the elliptical doped core at short wavelengths. At the medium long wavelength, the mode field gradually spreads outside the elliptical core that leads to the refractive index sensitive to Λ. the smaller Λ is, the easier the mode field spreads. According to the Eq. (3) and the Fig. 4, the pace length L increases with wavelength and Λ increasing, which can be explained by the same reason.

3 Conclusions

In this paper, we proposed an ultra-high birefringence photonic crystal fiber which is composed of an elliptical defected core doped with PG glass. The simulation results demonstrate that the elliptical defected core doped with PG glass can greatly improve the modal birefringence in a broad range of wavelengths. An ultra- high modal birefringence in the whole wavelength range from 910 to 1 931 nm, a magnitude of order of 10^{-1}, is obtained. At the wavelength of 1 550 nm, we acquired an extremely high birefringence of 1.256×10^{-1} and the small effective area of both polarized modes. The UHB-PCF, whose all-solid structure of core and traditional cladding can reduce splice loss and simplify the fabrication process, may be highly meaningful for the field of polarization-maintaining devices and coherent communication system.

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