Highly Birefringent Photonic Crystal Fiber Based on Index-Enhanced Fiber Core

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Abstract: A highly birefringent photonic crystal fiber (PCF) was achieved by increasing the index of the fiber core region. A full-vector finite-element method and a plane-wave expansion method were employed and characteristics of this kind of PCF were fully investigated for different parameters of the high-index region such as the shape or the refractive index. Simulation results show that the birefringence of the PCF can be greatly improved under optimized parameters. And nonlinear coefficient (together with the birefringence) of the PCF can also be enhanced synchronously.

Key words: Fiber optics; Photonic crystal fiber; Birefringence

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0 Introduction

Photonic crystal fibers which are also called as microstructured fibers have attracted considerable attentions over the past few years[1-7]. Components and devices based on photonic crystal fibers (PCFs) have been widely investigated recently due to their good performances and important applications in some fields such as optical fiber communications[8], fiber sensors[9], fiber light sources[10-11], and fiber filters[12]. Comparing with the conventional fibers, many novel characteristics of PCFs have been demonstrated and studied, among which the high birefringence have been greatly improved due to the flexible design of PCFs. So far, several designs of highly birefringent PCFs have been reported[13-18]. The methods to achieve highly birefringent PCFs can be roughly classified as two categories. One is to introduce the asymmetry into the fiber core of the PCF. The typical designs are reported in Ref. [13-15], where double defect or triple defect is employed in the fiber core. The other is to introduce the asymmetry into the fiber cladding. The typical designs are reported in Ref. [16-18], where high birefringence is achieved by employing elliptical air holes in the fiber cladding. For the conventional highly birefringent fibers, high birefringence can be introduced by stresses or asymmetric fiber core which has a higher index than the fiber cladding.

In this paper, a novel method is proposed to further enhance the birefringence of the PCFs by increasing the index of fiber core (such as by doping e. g. Germanium in the PCF). As an example, the birefringence of the doped triangular PCF with double defect is studied for different parameters (different indices or area of the fiber core). Effective method to enhance the birefringence of the PCF can be found based on the analysis under the parameters.

1 Simulation and discussion

The cross section of the proposed triangular-lattice PCF is shown as Fig. 1. Circular air holes with the diameter $d=0.4\Lambda$, where $\Lambda=2.2\ \mu$m is the lattice constant (center-to-center distance between two neighboring holes) are employed in the fiber cladding of the present PCF. The fiber core of the PCF consists of two neighboring rods (namely, double defect is employed here). In the fiber core, the high-index region is shown as a circular (or ellipse in the context) with the simulation parameters $R_x = 2.25\ \mu$m and $R_y =$

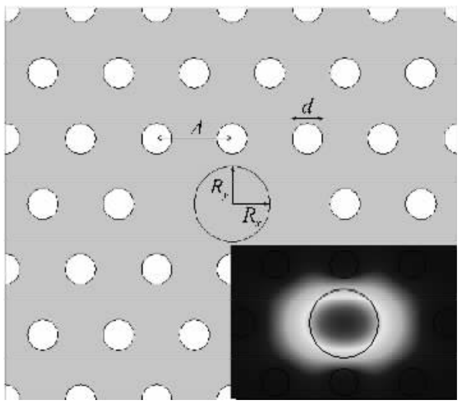

Fig. 1 Cross section of the proposed PCF. Inset shows a typical profile of the x-component of electric field of the x-polarized fundamental mode, when the normalized frequency is 0.8

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2.25 μm, inside which the refractive index is n_d = 1.46 (because of the dopant). The air refractive index and background refractive index of the present PCF is $n_a = 1$ and $n_b = 1.45$, respectively. A normalized frequency is used to describe the characteristics of the PCF, which is defined as $\nu = \Lambda/\lambda$ (where λ is the operation wavelength). A full-vector finite-element method (FEM)[19] is used to analyze the characteristics of the present PCF. Note that the calculation window (with the length 10Λ in x direction and the length $5\sqrt{3}\Lambda$ in y direction) is much larger than what is shown in Fig. 1.

The dispersion of the proposed PCF for the parameters ($d = 0.4\Lambda$, $R_x = 2.25$ μm, $R_y = 2.25$ μm and $n_d = 1.46$) is shown in Fig. 2. The solid curve and the dashed curve shows the effective index[16] of the x-polarized fundamental mode (XFM) and y-polarized fundamental mode (YFM), respectively. Birefringence which is defined as $\Delta n = n_{\text{eff}}^x - n_{\text{eff}}^y$ (where n_{eff}^x and n_{eff}^y are the effective index difference of the x-polarized fundamental mode and the y-polarized fundamental mode, respectively) can be found from the inset of Fig. 2, where the birefringence is shown for the normalized frequency from 0.8 to 0.9. In order to know the single mode operation region, a plane-wave expansion method[20] is used to obtain the effective index for the fundamental space-filling mode (FSM) of the fiber cladding of the present PCF, which is shown as the dot curves in Fig. 2. The dot dashed curve, which shows the effective index of the second-order mode (SM), crosses with curve for FSM. It is found that the single mode cutoff frequency is about 1.1. A typical profile of the x-component of electric field of the x-polarized fundamental mode is shown in the inset of Fig. 1, where the normalized frequency is 0.8. So far, it has been shown that the disperision of the doped PCF is similar with the PCF without any dopant. Then the birefringence-enhanced effect will be shown when the fiber core of the PCF is doped.

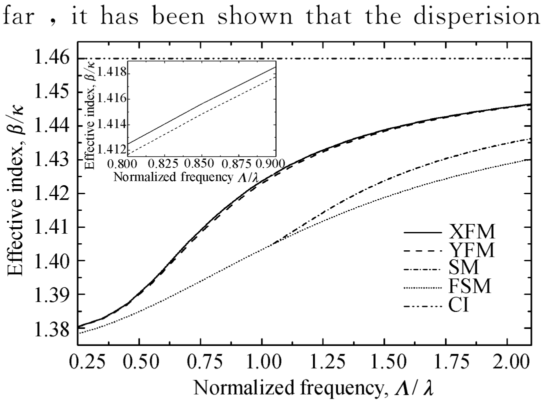

Fig. 2 Effective indices of different modes. Inset shows the details of the birefringence

Fig. 3 shows the birefringence of the PCFs when the parameters are (a) $d = 0.4\Lambda$ or (b) $d = 0.5\Lambda$. The detailed parameters of the PCFs are $n_d = 1.45$ for dotted curve (non-doped PCF), ($n_d = 1.46$, $R_x = 2.25$ μm, $R_y = 2.25$ μm) for short dotted curve and ($n_d = 1.46$, $R_x = 4.5$ μm, $R_y = 2.25$ μm) for solid curve, respectively. Some conclusions are drawn from Fig. 3. Firstly, the birefringence can be greatly enhanced by doping in the fiber core. Secondly, the birefringence also depends on shape of the doped region. In Fig. 3 it is known that the doped region with the parameters $R_x = 4.5$ μm, $R_y = 2.25$ μm (an elliptical doped region with the ellipticity of 2) can introduce higher birefringence than that with the parameters $R_x = 2.25$ μm, $R_y = 2.25$ μm (a circular doped region). Thirdly, for different diameters of the circular air holes in the fiber cladding there is a little difference for the effects of the doped method. The doped PCF with the parameter of $d = 0.4\Lambda$ has a peak birefringence of 0.009 which is as 1.5 times as the one of non-doped PCF in Fig. 3 (a). However, the peak birefringence of the doped PCF with the parameter of $d = 0.5\Lambda$ is 0.002 35 which is only about as 1.3

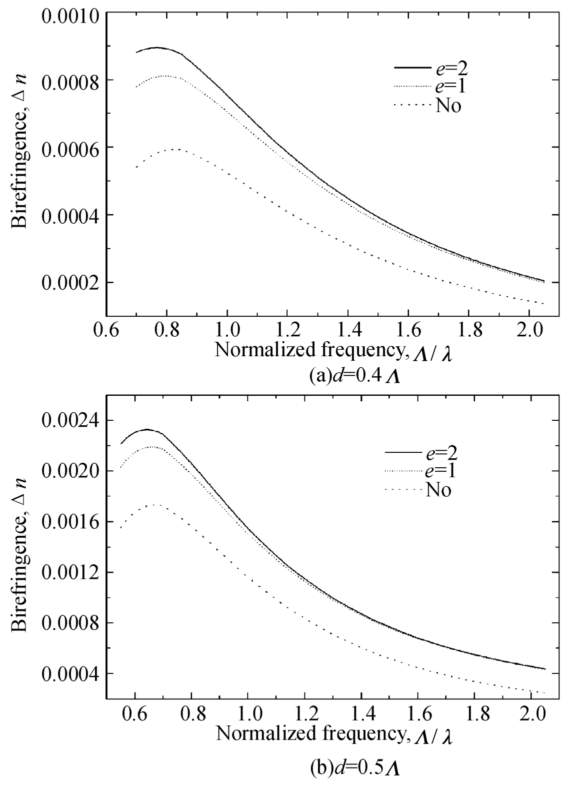

Fig. 3 Birefringence of the PCF

times as the one of non-doped PCF.

The area of the doped region will be an important parameter which can influence the birefringence of the PCF. We define a parameter of the normalized area $A' = A/\Lambda^2$ where A is the area of doped region. The birefringence of the doped PCF as a function of the normalized area is shown in Fig. 4 (a) (for the parameters $d = 0.4\Lambda$, $\nu = 0.8$, and $R_x = R_y$) and in Fig. 4 (b) (for the parameters $d = 0.4\Lambda$, $\nu = 0.8$ and $R_x = 2R_y$) with the refractive index of the doped region of $n_d = 1.46$ (for the curve connected by triangles), $n_d = 1.47$ (for the curve connected by circulars) and $n_d = 1.48$ (for the curve connected by squares). From Fig. 4, one can see that there is an optimum normalized area for the given doped PCF with a certain refractive index of the doped region. For example, highest birefringence can be found for the normalized area of about 1.5 in Fig. 4(a). And, the larger doping concentration the higher birefringence can be achieved.

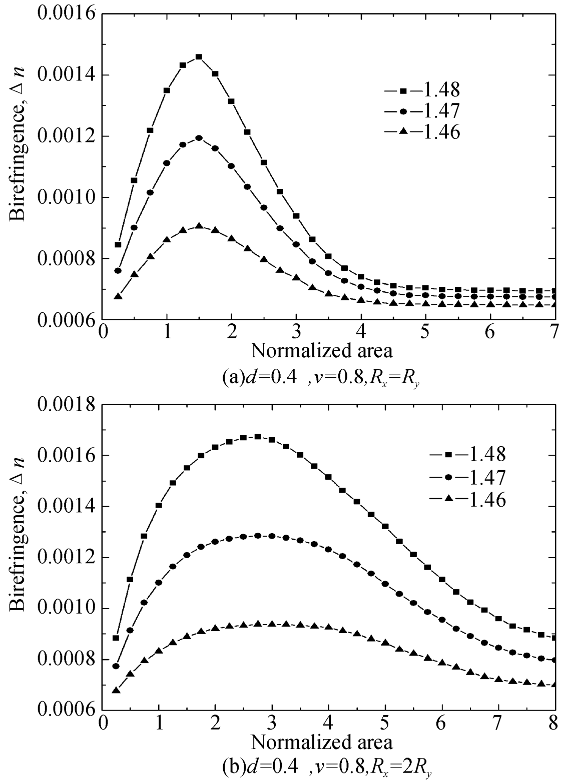

Fig. 4 Birefringence of the doped PCF as a function of the normalized area for the parameters

Another advangtage accompanying the proposed method is that by employing the doped region in fiber core the nonlinear coefficient of the PCF can also enhanced, since the confinement of the light become stronger when the refractive index of the doped region is higher than the background refractive index, which results into the less effective mode area (larger nonlinear coefficient). Fig. 5 shows the normalized power distribution along x-direction (cross the center of the PCF) (a) and y-direction (cross the center of the PCF) (b) with the solid curve (PX1 or PY1) for the non-doped PCF and the short dotted curve (PX2 or PY2) for the doped PCF ($n_d = 1.46$). The correspongding parameters are $d = 0.4\Lambda$, $\nu = 0.8$ and $R_x = R_y = 2.25$ μm. What's more, if the doped chemical is Germanium, the doped chemical itself has higher nonlinearity than Silica [21].

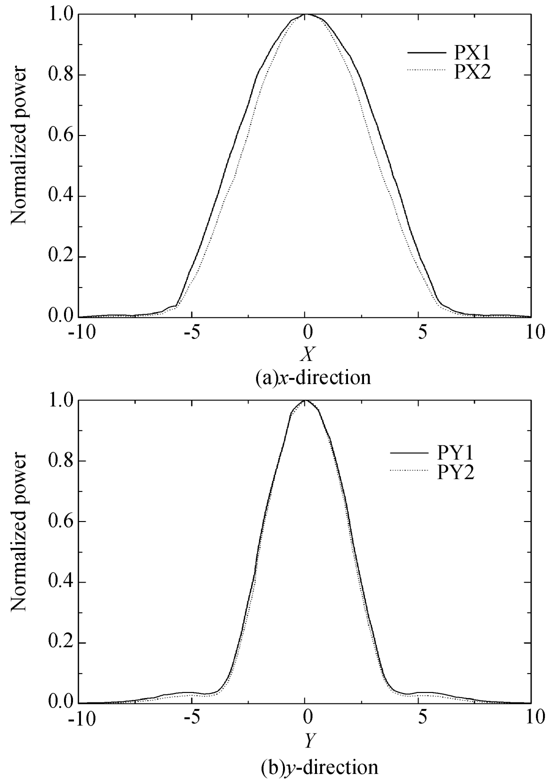

Fig. 5 Normalized power distribution

2 Conclusion

A novel method is proposed to enhance the birefringence of the PCF. That is to increase the index of the fiber core (by employing dopant such as Germanium in fiber core) in a symmetric region, which will lead to high birefringence of the PCF. A full-vector finite-element method and a plane-wave expansion method have been employed to investigate the PCF with double defect, where the index of the fiber core has been enhanced. The birefringence of the proposed PCF has been studied for different parameters, such as the shape or the refractive index of the doped region. Simulation results show the birefringence of the PCF can be greatly enhanced by doping in the fiber core under optimized parameters. An accompanying advantage of larger nonlinear coefficient of the doped PCF has also been shown in this paper.

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基于纤芯折射率增强的高双折射光子晶体光纤

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摘　要:通过增加光纤纤芯区域折射率实现了一种高双折射光子晶体光纤.采用全矢量有限元和平面波展开方法,系统地研究了这种高双折射光子晶体光纤在不同的高折射率区域参数(比如区域形状、折射率)情况下的光纤特性.模拟结果表明,光子晶体光纤的双折射可以在优化的参数条件下获得很大提高,光子晶体光纤的非线性系数(连同双折射)也可以同时得到提高.

关键词:光纤光学;光子晶体光纤;双折射

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