Silica Based Birefringent Large Mode Area Fiber with a Nanostructure Core

X. Yu, P. Shum *IEEE Senior Member*, M. Yan, G. B. Ren

***Abstract*—** Nanostructure photonic crystals with two-fold symmetry are introduced into a silica-based fiber core to induce high birefringence between the two nearly-orthogonal fundamental modes. We theoretically study and provide our preliminary findings on the birefringence property of such fibers over a large wavelength range. Large mode area structure with a typical high birefringence in the order of 10^{-4} is easily realized.

***Index Terms*— Photonic crystal fiber, photonic crystal, birefringence, nanostructure, mode area**

I. INTRODUCTION

It has been a new era for fiber optics ever since the first photonic crystal fiber (PCF) was fabricated by Knight *et al.* in 1996 [1]. Such novel microstructure fiber has attracted research attention worldwide and has been intensively studied owing to its potential device applications in optical communication systems. Many transmission properties of PCFs such as the cutoff wavelength, dispersion, birefringence, nonlinearity can be tailored beyond the possibilities in conventional step index fiber. Among the study of these properties, there have been many works on the investigation of birefringent PCF, both index-guiding and bandgap guiding structures [2, 3]. Most previous studies have concentrated on PCFs with a photonic crystal (PC) cladding and a homogeneous core where birefringence up to 10^{-3} has been demonstrated. Simulation has also shown that the value can be further increased by employing elliptical air holes in the fiber cladding. Generally speaking, for PCF with microstructured cladding, the form birefringence can achieve maximum when the wavelength is close to the pitch size of the cladding. The mode area increases with the pitch size, but the birefringence decreases rapidly. Therefore, single mode operation in a large mode area (LMA) structure with a birefringence on the order of 10^{-4} cannot be easily achieved [4]. In fact, a fiber is able to guide light with a PC core as shown in our earlier work [5]. A birefringent fiber with a finite one dimension PC core has been fabricated in Ref. [6].

In this paper, we theoretically demonstrate for the first time a silica based all-solid fiber with a PC core formed by a 2D array of elliptical rods. Such periodic core can be designed to achieve LMA as well as large form birefringence. The birefringence characteristics are evaluated numerically in a systematic manner.

II. FIBER DESIGN

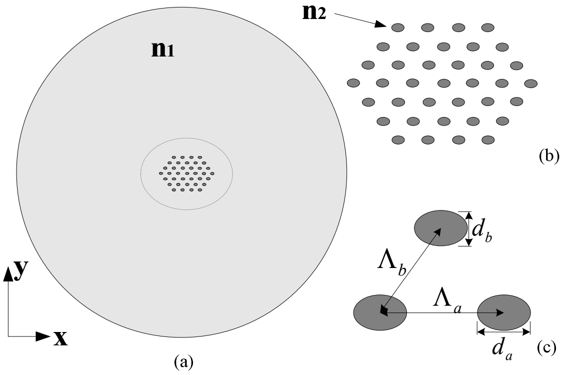

Fig. 1. Birefringent PCFs with a PC core and a homogeneous cladding. (a) Cross-section of the whole fiber structure. (b) Core structure of our PCF design: a finite 2D PC. (c) Structural parameters for our birefringent PCF.

The cross section of our proposed PCF is shown in Fig. 1(a). It is made of high index rods (n_2) immersed in low-index background material (n_1). Core region is made of a finite 2D PC. The high index rods are elliptical to allow the composite be macroscopically anisotropic. It is noticed that the cladding material is one of the element materials of the core. In general, the cladding can be a third material or a micro-/nanostructure [7]. For simplicity, homogeneous cladding is chosen for our analyses. However, such simplified approximation does not affect our argument significantly since the birefringence of the optical fibers is mainly induced by the core composite material itself. The diameter along the major and minor axes of the higher index rods in the core region are defined as d_a and d_b. The lattice period in two different directions are Λ_a and Λ_b, for a typical hexagonal/triangular array lattice, $\Lambda_a=\Lambda_b$, however, lattice deformation might happen due to the "squashing" in the fabrication, namely $\Lambda_a \neq \Lambda_b$. Our designed structure should be easily fabricated using the existing PCF fabrication technology experimentally [8].

III. THEORETICAL ANALYSIS

The preliminary reason for index-guiding PCF attracting research attention is that the fundamental space filling mode index of the cladding lattice is a strong function of wavelength. Here in our fiber design, the fiber core instead of cladding is formed by a periodic structure, which indicates the core index

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to be a function on wavelength. As the PC in such fiber has only C_2 symmetry, the two fundamental modes will not degenerate with each other. If we treat the PC core as an array of waveguides (attributed to individual high-index rods), such break in degeneracy is caused by the asymmetry in individual waveguides. Or, if we make a homogenization of the composite core material, the break in degeneracy is caused simply by the anisotropy of the homogenized core material. The latter interpretation is especially valid if the wavelength is much larger than the PC feature size. Upon achieving the effective indices of HE_{11}^x and HE_{11}^y modes, we can calculate the birefringence for a range of wavelength by:

$$B(\lambda) = n_{eff}^x - n_{eff}^y$$

where n_{eff}^x and n_{eff}^y are the effective indices of HE_{11}^x and HE_{11}^y modes respectively.

The structural parameters of the 2D PC are shown in Fig. 1(c). Unlike a conventional triangular PC with circular units and identical lattice size (which has only Λ and d two parameters), the PC core with elliptical rods is characterized by four variables: Λ_a, Λ_b, d_a and d_b. This increases the degree of freedom for achieving high birefringence, large mode area and low loss properties. The background index n_1 is assumed to be 1.45 (fused silica), and the high index rods are assumed to be 2.5% GeO_2 doped (n_2) for composing the core PC. Material dispersion is ignored in this paper because birefringence is a relative value between the two non-degenerated modes.

Our analysis is divided into two steps. Firstly, we use the plane wave method (PWM) [9] to study the birefringence between the first two space-filling modes of the core PC, which is assumed in an infinite bulk. Optimized fiber parameters for achieving high birefringence are hence derived. The results are compared with a full-vector finite difference method (FDM) to verify the accuracy. After that, a semi-vector beam propagation method (SVBPM) as shown in Reference [3] is used to calculate explicitly the modes propagating in an actual fiber, which confirms the high birefringence in such fibers. The parameters used in the SVBPM are as follows: the domain size is 4μm×4μm, the numbers of grid points along two transverse directions are 400 and 400, and the propagation step size in longitudinal direction is 0.5μm. Transparent boundary condition is used to enable leaky mode analysis.

In Fig. 2 we plotted the longitudinal E-field of two space-filling modes of the PC with d_a/Λ_a=0.9, d_b/d_a=0.5. Similar to a fiber with a homogeneous core, the two fundamental modes in our fiber still have nearly-orthogonal polarization states, i.e. one polarized in x-direction and the other in y-direction. The numerical result also shows the transverse field component is much larger than the longitudinal field component in amplitude which is the major component of our concern. As the wavelength is roughly four times the period Λ_a, fields propagating in such a composite are not heavily modulated by the material inhomogeneity, and they appear rather like plane waves. However, the waves with two orthogonal polarizations macroscopically experience two different material dielectric constants, which induce the high birefringence. It is noticed that when the wavelength is much less than Λ_a, the PC behaves more like an array of individual waveguides, and in turn a PC-core fiber is likely to be multimode due to the mode folding effect.

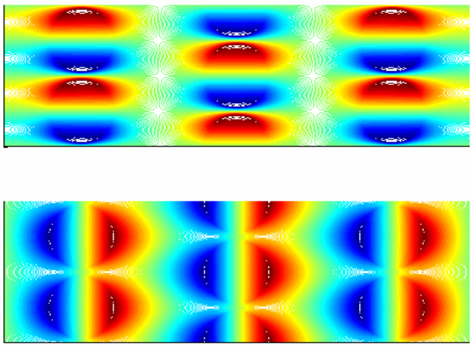


Fig. 2. The E fields of the first two modes (upper: x-polarized; bottom: y-polarized) in a bulk PC. The structural parameters are d_a/Λ_a=0.9, d_b/d_a=0.5, Λ_a=Λ_b (roughly at λ=1.55μm). The longitudinal field is in color-shaded contour plot.

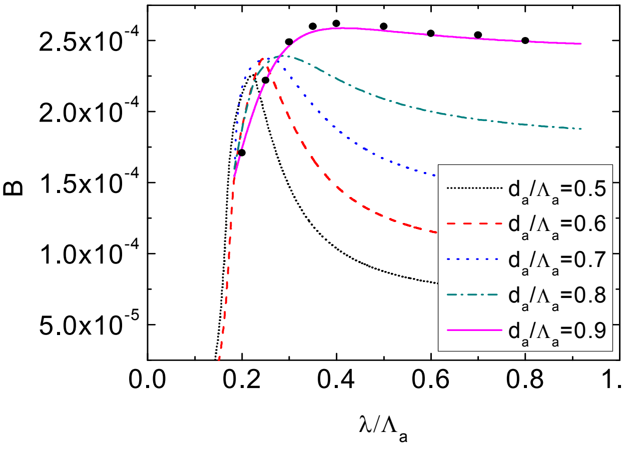


Fig. 3. Calculated birefringence versus normalized wavelength for different rod size with fixed d_b/d_a=0.5. The black dots are calculated results from FDM for d_a/Λ_a=0.9.

The modal birefringence can be calculated for a range of wavelength. The numerical calculations in this paper have shown that the birefringence in the proposed fiber can easily achieve to the order of 10^{-4}. The evolution of B value is shown in Fig. 3 for fibers with different rod size. The x-axis is the normalized wavelength, and the y-axis is the birefringence value. As rod size increases (while the ellipticity of the rods is fixed), the birefringence increases in general (Fig. 3). For d_a/Λ_a<0.9, the birefringence first increases with wavelength, and reaches a maximum value at a wavelength shorter than Λ_a. After that it gradually decreases to an almost constant value. When the rod size is larger, e.g. d_a/Λ_a>0.9, the birefringence value appears to increase monotonically with wavelength. It should be mentioned that, when d_a gets even bigger, the rods are closer to each other along the x-direction, and the PC appears more like a 1D PC. As long as the long wavelength limit is concerned, numerical results suggest that the optimized relative rod width (d_a/Λ_a) should be kept as close to one as possible for achieving high birefringence. At the long wavelength side, the core can be treated as a homogeneous birefringent material. When λ/Λ_a reduces, especially when λ is comparable to the rod size, most light intensity will be confined in the rods. Hence the local ellipticity induces the maximized birefringence. When λ further reduces, the fast-decreasing birefringence is caused by the smaller effective index difference in the x- and y- directions as most light is confined in the center of the high index rods. The results from FDM are shown in Fig. 3 by the black dots, which agree well with the PWM calculation. In Fig. 4 we show the birefringence evolution calculated for a bulk PC with a constant width d_a (d_a/Λ_a=0.9). In the long wavelength region, $\lambda/\Lambda_a>1$, the birefringence value first increase with respect to the rod height d_b and then starts to decrease when d_b/d_a exceeds 0.45. Fig. 4 shows that there is an optimized rod ellipticity for achieving the maximized birefringence.

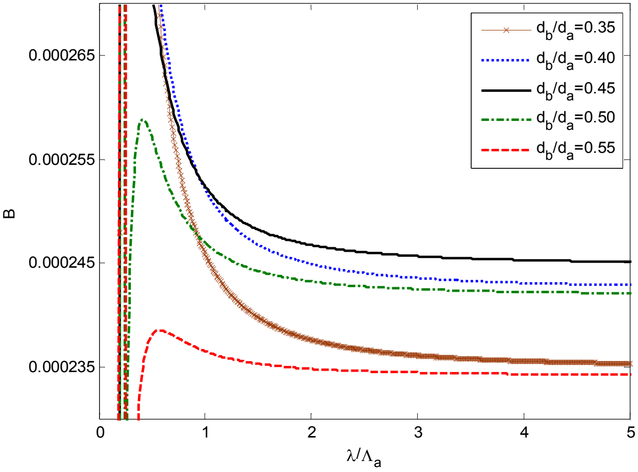
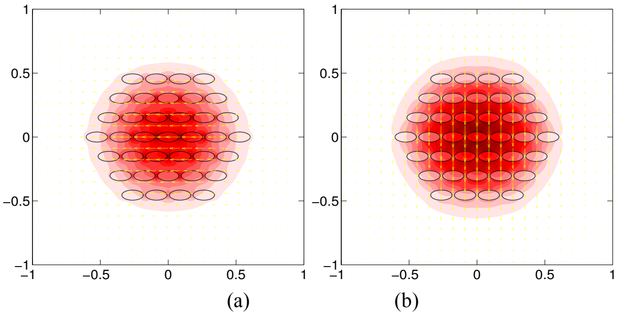


Fig. 4. Calculated birefringence versus normalized wavelength for different rod ellipticity when d_a/Λ_a=0.9.

In the rest of the section, we will study in particular a bulk PC with d_a/Λ_a=0.9 and d_b/d_a=0.45. The birefringence value of a complete fiber with such a PC core will also be examined. The complete fiber under study has 37 elliptical rods arranged in 4 ring layers. The core PC is the same as what we have examined in Fig. 2. When the pitch Λ_a is chosen at 500nm, we can facilitate operation at 1550nm wavelength which can fulfill the long wavelength assumption $\lambda/\Lambda_a>3$. Such a small dimension should be realizable in practice from a multiple-stage stretching and drawing. The doped glass rods will be stacked and fused together followed by a drawing process. The all-solid perform will be inserted to a hollow jacket tube and drawn into a fiber in the last stage. It should be mentioned that the macroscopic Maxwell equation does not fail at such a small feature size. In fact, for the Bragg fiber reported in [10], though its cladding layer widths are in tens of nanometers, the bandgaps derived from the macroscopic Maxwell equation are in excellent agreement with the experimental results. Figure 5 shows the two fundamental modes with nearly-orthogonal polarizations and Gaussian field profile. Effective mode index for the mode in Fig. 5(a) is 1.449517, and that for the mode in Fig. 5(b) is 1.449253. Birefringence is therefore 2.64×10^{-4}. The value is quite close to the predicted 2.46×10^{-4} derived from the PWM result. The two modes are analogous to the HE_{11}^x and HE_{11}^y modes in a conventional step index fiber. This fiber is found to be single mode at 1550nm. If we increase the number of layers N of high index rods in the core region, i.e, N=10, the mode field diameter will be about 10μm, while the high birefringence is still maintained. Another group of modes is observed in the fiber when the mode area further increases, which is analogous to the TE_{01}, HE_{21} and TM_{01} modes in a step index fiber.



(a) (b)

Fig. 5. The first two modes in a nanostructured core for fiber with four layers of solid rods. The PC's parameters are: d_a/Λ_a=0.9, $\Lambda_a=\Lambda_b$ (roughly at λ=1.55μm). (a) HE_{11}^x-like mode; (b) HE_{11}^y-like mode. The transverse field is in quiver plot, and the longitudinal component of Poynting vector is in grey color-shaded contour plot.

IV. CONCLUSION

In conclusion, we have proposed a silica-based fiber with 2D PC core whose individual unit is a nanostructure with reduced symmetry. The all-solid silica structure makes the fiber ready for fabrication from the existing technology. Birefringence in the order of 10^{-4} is easily achievable with a large mode field diameter up to 10μm, which will be useful for fiber lasers and gyroscopes applications.

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