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Highly Birefringent Index-Guiding Photonic Crystal Fibers

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***Abstract*—Photonic crystal fibers (PCFs) offer new possibilities of realizing highly birefringent fibers due to a higher intrinsic index contrast compared to conventional fibers. In this letter, we analyze theoretically the levels of birefringence that can be expected using relatively simple PCF designs. While extremely high degrees of birefringence may be obtained for the fibers, we demonstrate that careful design with respect to multimode behavior must be performed. We further discuss the cutoff properties of birefringent PCFs and present experimental results in agreement with theoretical predictions on both single- and multimode behavior and on levels of birefringence.**

***Index Terms*—Birefringence, optical fiber polarization, optical fibers, photonic crystal fiber.**

I. Introduction

IN RECENT years, there has been a significant interest in photonic crystal fibers (PCFs) [1]–[4]. Generally, two different kinds of PCFs exist, classified by their light-guiding mechanism. The first experimentally realized-type guides by a *modified* form of total internal reflection (M-TIR) and fibers of this type are also known as index-guiding PCFs [3]. The second type of fiber provides guidance by the photonic bandgap (PBG) effect, allowing for novel features such as light confinement to a low-index core [2]–[4]. The polarization properties of these fibers, known as PBG PCFs, have been investigated in [5]. In this letter, we will focus on index-guiding PCFs, as these fibers are presently most common and have less stringent requirements on structural uniformity, and as the spectral behavior of the polarization properties have yet to be covered in literature.

PCFs are commonly characterized by a series of holes that run throughout the length of the fiber arranged in a microscale structure around the core. Prior to drawing, the structure is created by stacking a number of silica tubes, whereby a preform is created that may be drawn into fiber using conventional drawing techniques [1]. The stacking procedure allows fabrication of close-packed, air-hole cladding structures, and the fiber core may readily be realized by replacing a number of tubes by solid rods of silica. This way of making fiber preforms allows for a large tailorability of the core geometry, where the core may be made almost circularly symmetric or highly asymmetric by replacing one or more tubes. The replacement of silica tubes with solid rods results in fibers having a high-index core region—allowing for light confinement through M-TIR. One possible use of asymmetric core fibers is as PMFs. In standard fiber transmission systems, imperfections in the core-cladding interface introduce random birefringence that leads to light being randomly polarized. These problems with random birefringence are in PMFs overcome by deliberately introducing a larger uniform birefringence throughout the fiber. Current PMFs, such as PANDA or Bow-tie fibers [6], achieve this goal by applying stress to the core region of a standard fiber, thereby creating a modal birefringence up to $\Delta n \sim 5 \cdot 10^{-4}$ [7], [8]. In this letter, we demonstrate that by utilizing the intrinsically large index contrast in PCFs in combination with asymmetric core designs, it becomes feasible to create modal birefringence of at least one order of magnitude larger than for conventional PMFs. While previous experimental results for polarization maintaining PCFs have yielded a birefringence as high as $\Delta n = 3.7 \cdot 10^{-3}$ [9], our results provide important insight into realization of single-mode PCFs with even higher birefringence.

II. Design and Cutoff Properties

In one of the simplest design cases of an asymmetric core PCF, the core consists of two neighboring rods. This design is different from the PCF design studied in [9] and is shown in Fig. 1. The purpose of creating highly birefringent fiber is to reduce the coupling between the orthogonal states of the fundamental mode. This is mostly relevant, if no higher order modes are supported. Triangular-lattice PCFs with a symmetric core consisting of one rod are endlessly single mode for normalized hole sizes up to a value as large as $d/\Lambda = 0.4$ (where d is the hole diameter and Λ is the hole spacing) [1]. This is not expected to be the case for the present fiber, due to the different (larger area) core design. Using a full-vectorial method [10], we have accurately simulated the guided modes as a function of propagation constant for fibers according to the above-presented design; see Fig. 2. For a hole size of $d/\Lambda = 0.40$, the design is indeed found to support a second-order mode with a cutoff for a normalized frequency of $\Lambda/\lambda = 1.67$. Further investigation shows that fibers with a hole size as small as $d/\Lambda = 0.35$ support a second-order mode.

In order to obtain a better visualization of the birefringence that occurs in the fibers, we introduce an effective normalized propagation constant B_{eff}, based on standard fiber techniques [8]. B_{eff} is defined by replacing the constant cladding index of a standard fiber with the highly frequency-dependent effective cladding index, $n_{\text{cl,eff}}$, of a PCF. B_{eff} is given as (n_{eff} −

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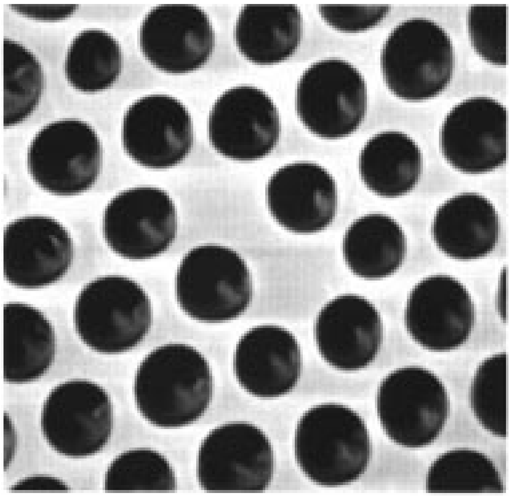

Fig. 1. Scanning electron micrograph of inner part of an asymmetric core PCF. The cladding of the fiber consists of a highly regular triangular lattice of air holes with a pitch, Λ, of 4.5 μm. The core is formed by the omission of two adjacent air holes.

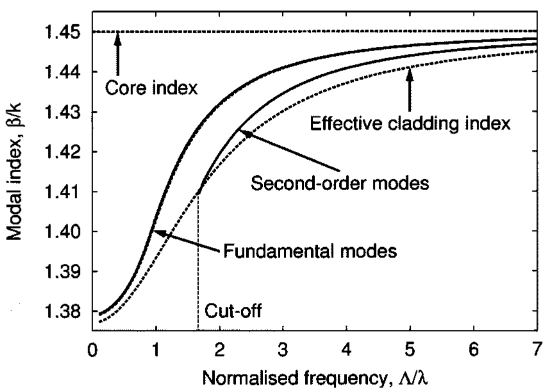

Fig. 2. Modal index illustration of the operation of asymmetric core PCF. The fiber has air holes of diameter 0.4Λ and is seen to become multimode at normalized frequencies, Λ/λ, larger than 1.67. Ideal, nonsymmetric core PCF, as studied in [1], are found to be endlessly single mode for an air hole diameter of 0.4Λ.

$n_{\mathrm{cl,eff}})/(n_{co} - n_{\mathrm{cl,eff}})$, where n_{co}, the refractive index of the core, is a constant equal to the index of fused silica, and $n_{\mathrm{cl,eff}}$ is equal to the index of the fundamental space-filling mode of the cladding. Finally, n_{eff} denotes the effective index of a guided mode. Fig. 3 shows the B_{eff}-parameter as a function of the normalized frequency for the same fiber as in Fig. 2. Here, the lifted degeneracy of the two polarization states is apparent. In the low-frequency limit, the normalized propagation constant tends to zero causing the field to extend far beyond the core region. In this limit, the asymmetric core shape has a vanishing influence on the polarization splitting and the birefringence becomes negligible. It should, however, be noticed that in the case of noncircularly shaped cladding holes, which is not studied here, it does become possible to achieve significant polarization effects due to also a splitting of the degeneracy of the fundamental cladding mode [11]. As for the low-frequency limit, we find that the birefringence becomes vanishing in the high-frequency limit, providing an optimum frequency window for the design of high-birefringent fibers. The fiber in Fig. 3 was found to exhibit a highest birefringence of $6.9 \cdot 10^{-4}$ at a normalized

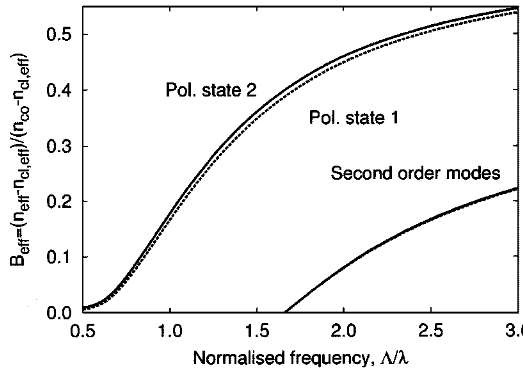

Fig. 3. Effective normalized propagation constant B_{eff} for a fiber with hole size d/Λ = 0.40. The nondegeneracy of polarization state 1 and 2 of the fundamental mode is evident. Second-order cutoff is seen to occur at the same frequency as in Fig. 2.

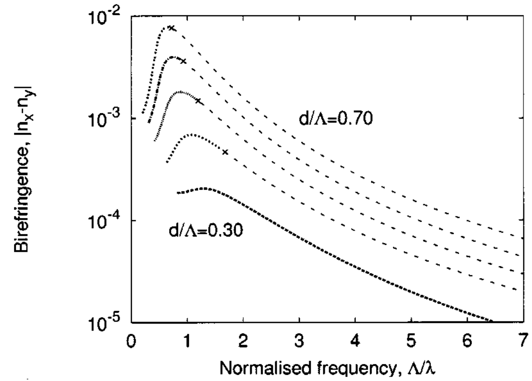

Fig. 4. Dependence of modal birefringence on hole size. The hole sizes shown are ranging from d/Λ = 0.30 to 0.70 in steps of 0.10. In each case the second-order cutoff is shown, except for a hole size of 0.30, as this fiber is endlessly single mode (dashed curves indicate multimode operation).

frequency of 1.05. The knowledge of an optimum normalized frequency is, naturally, important from a design point of view, as it provides information on the exact fiber dimensions of optimized high-birefringent fibers. If the fiber in Fig. 3, for example, were to be designed to provide highest birefringence at a wavelength of 1.55 μm, the optimum normalized frequency dictates a pitch of 1.7 μm. Furthermore, it is important to notice that the optimum normalized frequency for the fiber in Fig. 3 is found under single-mode operation. As shall be demonstrated, this is a valuable property valid for all studied fibers with a design as in Fig. 1.

III. Birefringence Results—Theory and Experiments

The theoretically predicted birefringence for a series of fibers with different hole sizes is illustrated in Fig. 4. As expected, the birefringence is seen to strongly increase with increasing hole size. Also marked on the figure is the second-order cutoff of the fibers. It is important to notice that only fibers with a hole size of $d/\Lambda = 0.30$ or smaller may be classified as endlessly single mode, making cutoff analysis of high-birefringence fibers vital. For all studied hole sizes, however, the birefringence is seen to reach its maximum value while the fiber is single mode. For a fiber with air holes of size $d/\Lambda = 0.70$, a maximum value of $\Delta n = 7.7 \cdot 10^{-3}$ is reached at a normalized frequency of

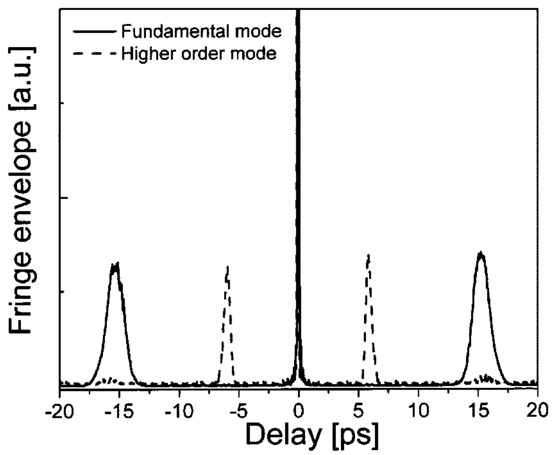

Fig. 5. Group delay between different polarization states of fundamental and higher order mode for the fiber in Fig. 1. The corresponding birefringence is $9.3 \cdot 10^{-4}$ and $3.6 \cdot 10^{-4}$ for the fundamental and higher order mode, respectively. The central peak is due to autocorrelation.

$\Lambda/\lambda = 0.66$. As this fiber reaches cutoff at a normalized frequency of $\Lambda/\lambda = 0.72$, strict requirements on fabrication are imposed when the fibers are to be operated at a desired wavelength (e.g., an operation around 1.55 μm results in a Λ-tolerance of less than 100 nm). We have fabricated a number of asymmetric core PCFs, and Fig. 5 shows the measured fringe envelope as a function of delay for the interference between the two polarization states of the fundamental mode and a higher order mode of a fiber with $d/\Lambda = 3.38\ \mu\text{m}/4.50\ \mu\text{m} = 0.75$. The measurement was performed over 5 m of the fiber, using an incoherent light source centered at 1.55 μm, yielding a birefringence of $9.3 \cdot 10^{-4}$ and $3.6 \cdot 10^{-4}$ for the fundamental and higher order mode, respectively. In order to compare the experimental result to theory, we first determine the normalized frequency to be $\Lambda/\lambda = 2.9$. In agreement with Fig. 4, we find that the fiber is multimode and that the measured birefringence of $9.3 \cdot 10^{-4}$ is in good agreement with the predicted value of approximately $1.0 \cdot 10^{-3}$. In general agreement with Fig. 3, we find the birefringence for the higher order mode to be lower than that for the fundamental mode. Further, it is worth noticing that no interference between polarization states in different modes is observed experimentally. This observation may be understood from the significantly larger splitting between polarization states of different modes compared to intramode splitting (see Fig. 3). The interference between polarization states in the fundamental and the higher order mode in Fig. 3 would result in a delay of more than 200 ps, significantly beyond the measured range in our experiments.

IV. Conclusion

By utilizing the intrinsically large index contrast in PCFs in combination with asymmetric core designs, we have found that it is possible to create modal birefringence of at least one order of magnitude larger than for conventional high birefringent fibers. We have further addressed the important design consideration that must be performed with respect to cutoff properties. Our results provide valuable insight into realization of single-mode PCFs with even higher birefringence than previously demonstrated in literature.

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References

[1] T. A. Birks, J. C. Knight, and P. St. J. Russell, "Endlessly single-mode photonic crystal fiber," *Opt. Lett.*, vol. 22, pp. 961–963, July 1997.

[2] J. C. Knight, J. Broeng, T. A. Birks, and P. St. J. Russell, "Photonic band gap guidance in optical fibers," *Science*, vol. 282, pp. 1476–1478, Oct. 1998.

[3] J. Broeng, D. Mogilevtsev, S. E. Barkou, and A. Bjarklev, "Photonic crystal fibers: A new class of optical waveguides," *Opt. Fiber Technol.*, vol. 5, pp. 305–330, July 1999.

[4] J. Broeng, S. E. Barkou, and A. Bjarklev, "Analysis of air-guiding photonic bandgap fibers," *Opt. Lett.*, vol. 25, Jan. 2000.

[5] ——, "Polarization properties of photonic bandgap guiding fibers," in *Optical Fiber Communication Conf.*, vol. 4, Mar. 2000, pp. 101–103.

[6] K.-H. Tsai, K.-S. Kim, and T. F. Morse, "General solution for stress-induced polarization in optical fibers," *J. Lightwave Technol.*, vol. 9, pp. 7–17, Jan. 1991.

[7] K. Tajima and Y. Sasaki, "Transmission loss of a 125 μm diameter PANDA fiber with circular stress-applying parts," *J. Lightwave Technol.*, vol. 7, pp. 674–679, Apr. 1989.

[8] G. P. Agrawal, *Fiber-Optic Communications Systems*. New York: Wiley, 1997.

[9] A. Ortigosa-Blanch, J. C. Knight, W. Wadsworth, J. Arriaga, B. J. Mangan, T. A. Birks, and P. St. J. Russell, "Highly birefringent photonic crystal fibers," *Opt. Lett.*, vol. 25, pp. 1325–1327, Sept. 2000.

[10] S. G. Johnson and J. D. Joannopoulos, "Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis," *Opt. Express*, vol. 8, no. 3, pp. 173–190, Jan. 2001.

[11] M. J. Steel and R. M. Osgood, Jr., "Elliptical-hole photonic crystal fibers," *Opt. Lett.*, vol. 26, no. 4, 2001.