Single-Polarization Elliptical-Hole Lattice Core Photonic-Bandgap Fiber

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Masashi Eguchi, *Member, IEEE and Senior Member, OSA,* and Yasuhide Tsuji, *Member, IEEE and OSA*

***Abstract*— In photonic bandgap (PBG) fibers, light is confined by a photonic bandgap caused by a periodic structure of air holes in the cladding regions. The doubly degenerate fundamental mode in ideal PBG fiber structures becomes slightly nondegenerate in actually produced fibers, and this causes polarization instability and polarization mode dispersion. Here, to avoid these problems, we propose a novel absolutely single-polarization PBG fiber structure with an elliptical-hole lattice core. A PBG fiber with a single-polarization bandwidth of 420 nm is numerically demonstrated. Furthermore, based on the proposed fiber structure, we report another single-polarization PBG fiber that has two absolutely single-polarization bands being orthogonal to each other.**

***Index Terms*— Photonic bandgap fiber, honeycomb lattice, elliptical-hole lattice, absolutely single-polarization, finite-element method.**

I. INTRODUCTION

OPTICAL fibers consisting of a single material with air holes, which are referred to as photonic crystal fibers (PCFs) [1]–[3], have made remarkable advances over the past decade. PCFs were first developed by Knight et al. in 1996 [1] and fall into two categories: an index-guiding fiber, in which light is confined in the core region having a higher refractive index than the cladding region including many low-index air holes, and a photonic bandgap (PBG) fiber, in which light is trapped in the low-index core region surrounded by a two-dimensionally periodic medium by PBG confinement [4]. In PCFs, PBG fibers especially have the potential of achieving unusual properties that are quite impossible in conventional fibers and index-guiding PCFs based on total internal reflection. In standard PCFs consisting of a triangular or honeycomb arrangement of air holes [1], [5]–[10], the two orthogonally polarized fundamental modes are degenerate for their ideal structures [11], as the same in conventional circular core fibers. However, imperfections in actually produced fibers and/or random perturbations arising from practical installations cause the doubly degenerate fundamental mode to be nondegenerate and thus may lead to polarization instability due to mode coupling, polarization dependent loss, and polarization mode dispersion. These problems could be avoided by breaking the symmetry of the fiber cross sections, and various birefringent PCFs and single-polarization PCFs with asymmetric structures have been proposed. While single-polarization fibers supporting only one polarization state especially have a high resistance to external perturbations, there are not so many reports proposing single-polarization fibers. To the best of our knowledge, most of the single-polarization PCFs so far reported use effective index guidance [12]–[17], while there are only a few reports on single-polarization PBG fibers [18]–[21]. A single-polarization fiber can be generally achieved by designing a birefringent fiber so that one of two separated polarized-modes will not be guided. In index-guiding fibers this is accomplished by lowering the effective index of the fast mode to below the cladding index, whereas in PBG fibers by pushing one polarized mode out of the PBG. Compared to using index-guiding mechanism, the use of PBG guidance thus allows more flexibility in the design of single-polarization fibers. In this work, we report a novel absolutely single-polarization fiber design based only on PBG guidance and a double absolutely single-polarization band PBG fiber. A PCF with two single-polarization transmission bands has recently been reported in [20]. This PCF is a hybrid PCF

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This paper has supplementary downloadable material available at http://ieeexplore.iee.org provided by the authors. This includes four multimedia MOV format movie clips, which show light propagations along the proposed single-polarization PBG fibers.

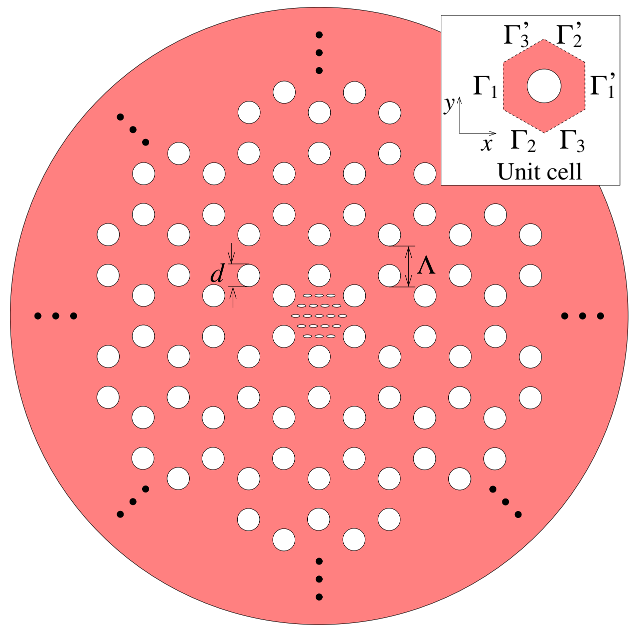


Fig. 1. Honeycomb lattice PBG fiber with an elliptical-hole lattice core (absolutely single-polarization elliptical-hole lattice core PBG fiber). The inset shows the unit cell structure, which was used in calculating the PBG of honeycomb lattices.

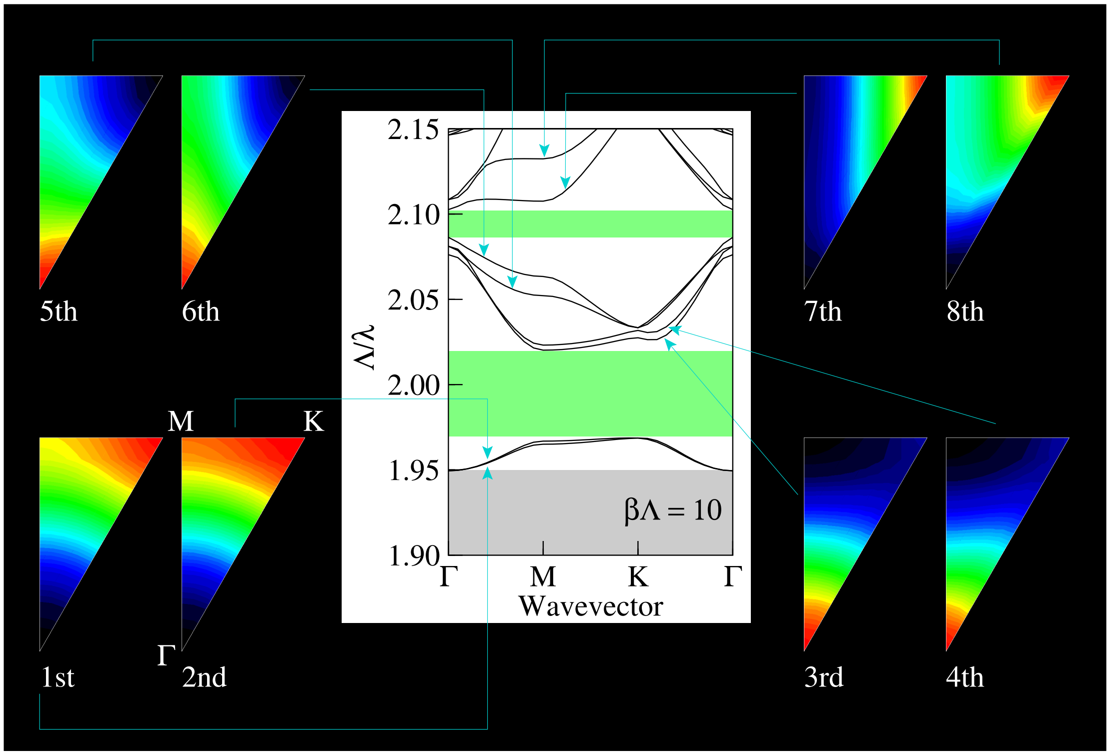


Fig. 2. Band structure of a honeycomb air-hole lattice at a fixed $\beta\Lambda$ value of 10. The contour maps illustrate the normalized-frequency distributions inside the Brillouin zone for the lowest eight propagation modes (red, high frequencies; black, low frequencies) .

[22], in which two polarized fundamental modes are guided by different guiding mechanisms: the index-guiding and PBG effects. In this PCF, the PBG mechanism was used to increase its modal birefringence and leak either polarization mode going outside the PBG in the direction of the PBG structure formed by high-index rods so that single-polarization guidance can be realized in the PCF. Therefore, while double single-polarization guidance is certainly shown in [20], this PCF is not a pure single-polarization PBG fiber.

II. Band Structure of Honeycomb Air-Hole Lattice

Our absolutely single-polarization PBG fibers are based on a honeycomb photonic crystal lattice of air holes. Conventional honeycomb PBG fibers have a low-index core region with an extra central air hole and a cladding region consisting of a honeycomb lattice of air holes [4]–[6]. The two orthogonally polarized fundamental modes of these PBG fibers with sixfold rotational symmetry are degenerate [11]. We must break this mode degeneracy in some way to obtain single-polarization guidance in them. We here achieve that through a large anisotropy caused by an elliptical-hole lattice, as shown in Fig. 1. The elliptical-hole PCFs with an elliptical-hole lattice cladding reported in [23], [24] are typical birefringent index-guiding PCFs using such an anisotropy. We first calculate the band structure of a honeycomb lattice cladding. Since for out-of-plane propagation, the guided waves in a honeycomb lattice cannot be decomposed into independent TE and TM modes, we should solve the vector wave equation,

$$\nabla \times (p \nabla \times \boldsymbol{\Phi}) - k_0^2 q \boldsymbol{\Phi} = 0, \quad (1)$$

$$p = 1, \quad q = n^2 \quad \text{for} \quad \boldsymbol{\Phi} = \boldsymbol{E}, \quad (2)$$

$$p = 1/n^2, \quad q = 1 \quad \text{for} \quad \boldsymbol{\Phi} = \boldsymbol{H}, \quad (3)$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ represent the electric- and magnetic-field vectors, respectively, k_0 is the free-space wavenumber, and n is the refractive index. A finite-element formulation based on Eq. (1) is referred to as the vector finite-element method (FEM). For wave propagations in periodic structures, the following periodic boundary conditions based on Bloch-Floquet theorem are applied on the interface between the periodic unit cells.

$$\boldsymbol{n}_i \times \boldsymbol{\Phi}|_{\Gamma_i'} = \boldsymbol{n}_i \times \boldsymbol{\Phi}|_{\Gamma_i} \exp\{-j(\boldsymbol{k} \cdot \boldsymbol{n}_i) a_i\}, \quad i = 1, 2, 3, \quad (4)$$

$$\boldsymbol{n}_i \times (p \nabla \times \boldsymbol{\Phi})|_{\Gamma_i'} = \boldsymbol{n}_i \times (p \nabla \times \boldsymbol{\Phi})|_{\Gamma_i} \exp\{-j(\boldsymbol{k} \cdot \boldsymbol{n}_i) a_i\}, \quad (5)$$

where $\boldsymbol{\Phi}$ represents $\boldsymbol{E}$ or $\boldsymbol{H}$, $\boldsymbol{k}$ is the wave vector in the xy plane, Γ_i and Γ_i' are a pair of periodic boundaries in a unit cell as shown in the inset of Fig. 1, $\boldsymbol{n}_i$ is a unit normal vector from Γ_i to Γ_i', a_i is the distance between each pair of periodic boundaries, and the unit cell, which was used in calculating the PBG of honeycomb lattices, is shown in the inset of Fig. 1. By applying a Galerkin procedure to Eq. (1) and then using the periodic boundary conditions Eqs. (4) and (5), we obtain the eigenvalue problem,

$$([K(\beta)] - k_0^2 [M(\beta)])\{\phi\} = \{0\}, \quad (6)$$

where β is the propagation constant along the fiber axis, $[K]$ and $[M]$ are the finite-element matrices for internal edges/nodes, and $\{\phi\}$ is the edge/nodal electric- or magnetic-field vector. The band structure of a honeycomb lattice with a material refractive index of $n = 1.45$ and hole diameter of $d = 0.55\Lambda$ at a fixed $\beta\Lambda$ value of 10, with Λ being the lattice pitch, is illustrated in Fig. 2. Each curve in this figure represents the propagation mode in the honeycomb lattice. As seen from this figure, there are forbidden frequency bands for all directions, which correspond to the light green-colored areas. In addition, the normalized-frequency contour distributions inside the Brillouin zone for the lowest eight lattice modes are also shown in this figure (red, high frequencies; black, low frequencies). These contour distributions show that the highest and lowest values of the frequency of each lattice mode in the honeycomb lattice are located on the edge of the Brillouin zone. The PBG diagram can thus be obtained based on the band structures along the edge of the irreducible Brillouin zone obtained varying the value of $\beta\Lambda$.

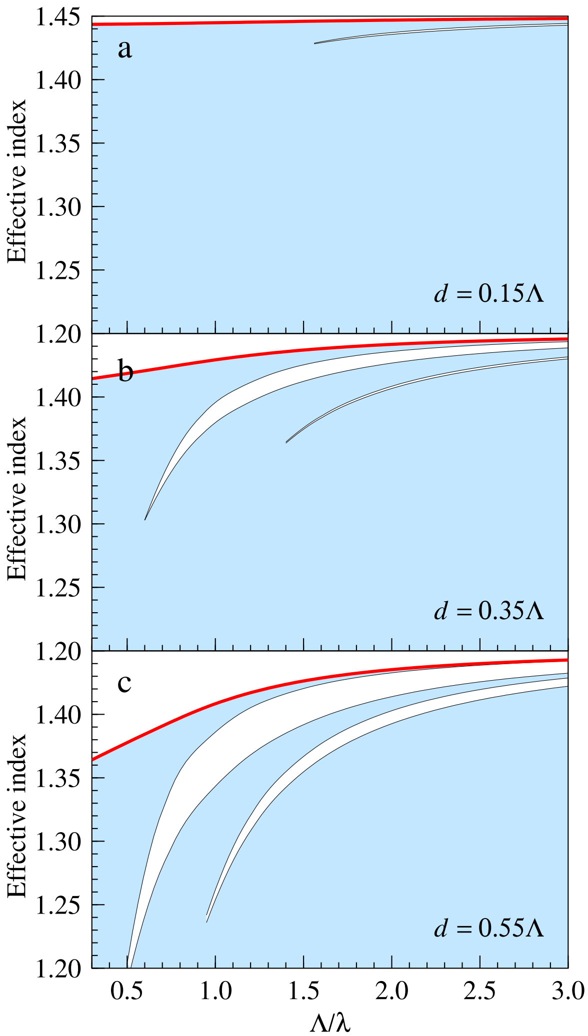


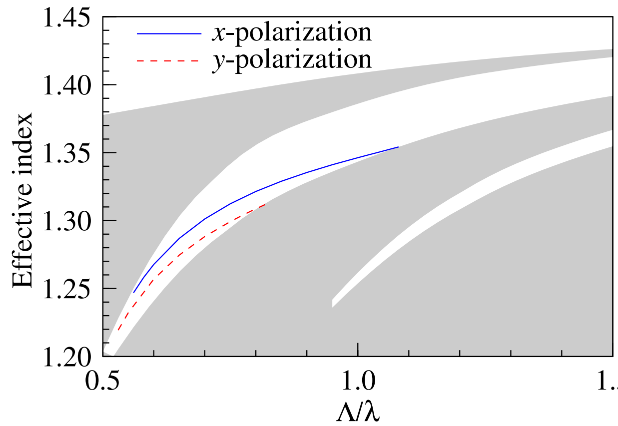
Fig. 3. PBG property of honeycomb air-hole lattices. The white-colored areas represent PBG and the thick red-colored curves show the fundamental space-filling mode of air-hole lattices. (a) PBG diagram for a hole diameter of $d = 0.15\Lambda$. (b) $d = 0.35\Lambda$. (c) $d = 0.55\Lambda$.

III. Photonic Bandgap Diagram of Honeycomb Air-Hole Lattice

The PBG diagram of honeycomb lattices with a material refractive index of $n = 1.45$ for three diameters of the air hole is shown in Fig. 3, where the white-colored areas represent PBG while in the light blue-colored areas lattice modes exist. Figures 3(a)-3(c) correspond to honeycomb lattices with hole diameters of $d = 0.15\Lambda$, 0.35Λ, and 0.55Λ, respectively. In Fig. 3, the region above the thick red-colored curve in each multi-part figure corresponds to the higher effective-index region than that of the fundamental space-filling mode [25] of the air-hole lattice and modes lying within this region are guided by index-guiding mechanism. One can see in Fig. 3 that, with increasing hole diameter, the PBG shifts to lower frequencies and gets broader, and, in addition, the second bandgap appears for $d = 0.35\Lambda$ and 0.55Λ. Since guided modes need to lie within the PBG, it is very desirable that the air holes should be designed as large as possible for more flexible design. However, since higher-order PBGs caused by increasing the hole diameter may allow higher-order modes to propagate, it is more desirable that the higher-order PBGs should be suppressed for single-mode guiding. Based on these considerations, we devise here an absolutely single-polarization PBG fiber structure based on a honeycomb lattice with a hole diameter of $d = 0.55\Lambda$ shown in Fig. 3(c).

IV. Absolutely Single-Polarization Elliptical-Hole Lattice Core PBG Fiber

The elliptical-hole lattice core PBG fiber with a honeycomb-structured cladding (Fig. 1) proposed here supports two separated orthogonally polarized fundamental modes. In the cross-sectional structure shown in Fig. 1, the slow and fast modes correspond to the x-polarized (HE$_{11}^{x}$) and y-polarized (HE$_{11}^{y}$) modes, respectively. When the elliptical-hole size and the lattice pitch in the core region are designed so that the fast mode is pushed out of the PBG, the PBG fiber can be constructed to operate in a single-polarization state. Figure 4(a) shows the dispersion property of an elliptical-hole lattice core honeycomb PBG fiber consisting of 19 elliptical holes with a major-axis length of 0.21Λ and minor-axis length of 0.07Λ, which are arranged in a triangular lattice with a lattice pitch of $\Lambda/(2\sqrt{3})$, and has been obtained using the vector FEM with an improved virtual-boundary condition [26]. Here, the blue-colored solid and red-colored dashed curves correspond to HE$_{11}^{x}$ and HE$_{11}^{y}$ modes, respectively. From this figure, we can confirm that there are no guided modes in the second bandgap and, therefore, this PBG fiber is an absolutely single-polarization single-mode fiber guiding only one polarized mode component of the fundamental mode. At frequencies above approximately $\Lambda/\lambda = 0.81$, the HE$_{11}^{y}$ mode is pushed out of the PBG and the single-polarization guidance is achieved in the frequency range from approximately $\Lambda/\lambda = 0.81$ to 1.08. Figure 4(b) shows the mode field distribution of the HE$_{11}^{x}$ mode at $\Lambda/\lambda = 0.95$. The mode field is seen to have a similar distribution to that of the fundamental mode of conventional optical fibers. Because the elliptical holes in the core region of this fiber are relatively small and, thus,



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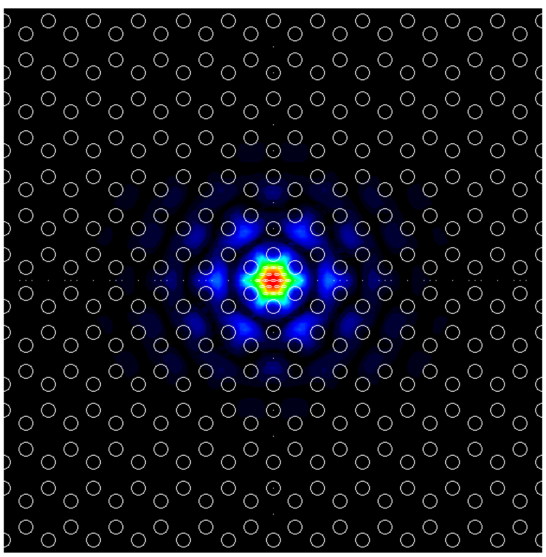
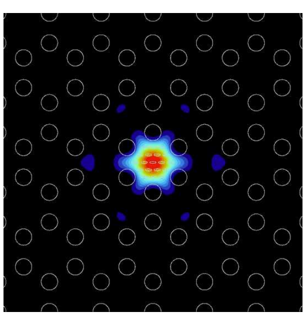


(b)

Fig. 4. Guided modes of a single-polarization elliptical-hole lattice core PBG fiber shown in Fig. 1. (a) Effective index as function of normalized frequency for the x-polarized (HE_{11}^{x}) and y-polarized (HE_{11}^{y}) fundamental modes, which correspond to the blue-colored solid and red-colored dashed curves, respectively. (b) Mode field distribution for the HE_{11}^{x} mode at $\Lambda/\lambda = 0.95$.



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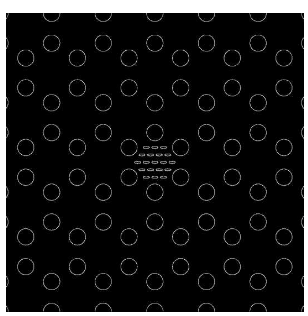


(b)

Fig. 5. Field distribution at $\Lambda/\lambda = 0.91$ in a single-polarization elliptical-hole lattice core PBG fiber after 150 μm of propagation and the light propagation along the fiber of length 150 μm (Supplemental video data: S1.mov and S2.mov). (a) x-polarized beam (S1.mov). (b) y-polarized beam (S2.mov).

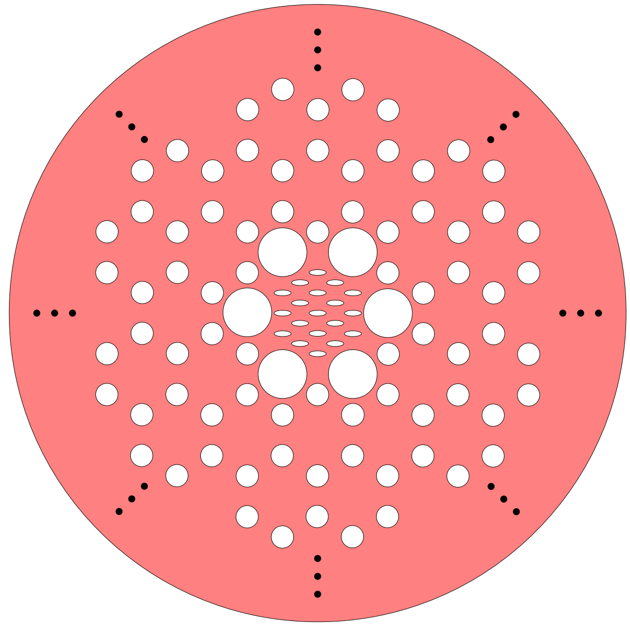
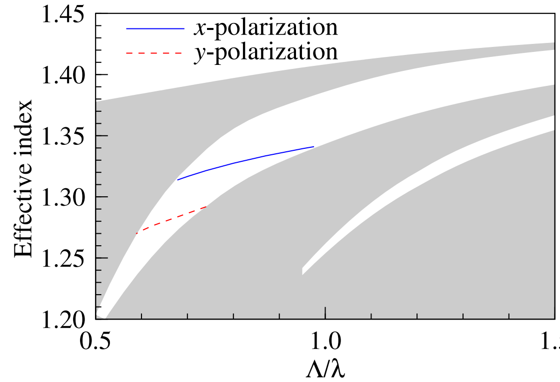


Fig. 6. Double single-polarization band PBG fiber.

the mode field is not influenced strongly by the air holes. To verify whether this PBG fiber really operates in a single-polarization state, we also simulated the light propagations at $\Lambda/\lambda = 0.91$ over a length of 150 μm of the x-polarized and y-polarized Gaussian beams, using a vector finite-element beam propagation method (FE-BPM) [27]. Figures 5(a) and 5(b) show the field distributions in the fiber after 150 μm of propagation for the x-polarized and y-polarized beams, respectively, and Supplemental video data, S1.mov and S2.mov, correspond to their light propagations over a length of 150 μm. This PBG fiber supports only the x-polarized fundamental mode. Thus, while the x-polarized beam proves to be guided as the fundamental mode, the y-polarized beam is not guided over a length of 150μm. For a lattice pitch of 1.35 μm, the single-polarization bandwidth ($0.81 \leq \Lambda/\lambda \leq 1.08$) is equal to 0.42 μm.

V. DOUBLE ABSOLUTELY SINGLE-POLARIZATION BAND PBG FIBER

The high birefringence of an elliptical-hole lattice allows the design of single-polarization fibers with unusual properties that have never been achieved before. Here, we devise another novel absolutely single-polarization PBG fiber that has two single-polarization bands supporting only the x-polarized mode and only the y-polarized mode. The PBG fiber structure is shown in Fig. 6 and has a large hole ring around the core formed by an elliptical-hole lattice. This structure has relatively large background material regions around the elliptical-hole lattice and this easily generates the first-higher order mode. Therefore, the large holes were placed to suppress the first-higher order mode. In addition, these large holes cause strong confinement of the fundamental mode around its long-wavelength side cutoff and suppress the influence of the cladding lattice on it, and have resulted in opening up the single-polarization band of the fast mode largely. Figure 7(a) shows the dispersion property of a double single-polarization band PBG fiber consisting of 19 elliptical holes with a major-axis length of 0.42Λ, minor-axis length of 0.14Λ, and lattice pitch of $\Lambda/2$, and 6 large circular air holes with a diameter of 1.2Λ. The center-to-center distance between a large hole and a cladding hole adjacent to the large hole is Λ. In this fiber structure, the slow and fast modes correspond to the x-polarized (HE_{11}^{x}) and y-polarized (HE_{11}^{y}) fundamental modes, respectively, which correspond to the blue-colored solid and red-colored dashed curves in Fig. 7(a). There are only two orthogonally polarized fundamental modes in the primary PBG and, moreover, the second PBG hardly opens up in the transmission bands of the fundamental modes. This PBG fiber proves to have two orthogonally polarized absolutely single-polarization bands of $0.59 \leq \Lambda/\lambda \leq 0.68$ and $0.74 \leq \Lambda/\lambda \leq 0.97$, which guide only the y-polarized mode and only the x-polarized mode, respectively. This indicates that a single-polarization PBG fiber whose polarization direction can be switched depending on the wavelength of light is achievable in the fiber structure shown in Fig. 6. To our knowledge, such a single-polarization fiber based only on PBG guidance has never been reported before and is applicable for simultaneous transmission of two absolutely single-polarization bands (e.g., 1.3μm and 1.5μm) being orthogonal to each other. Figures 7(b) and 7(c) show the mode field distributions of the HE_{11}^{y} mode at $\Lambda/\lambda = 0.65$ and the HE_{11}^{x} mode at $\Lambda/\lambda = 0.85$, respectively. One can see in these figures that the distributions around the core center are a little different from that of a conventional fiber, whereas light is well confined within the core region by means of the large air holes located around the elliptical-hole lattice. Therefore, these fluctuations in the mode fields due to the elliptical holes in the core region will cause few problems in practical use. We demonstrate the wave propagations at $\Lambda/\lambda = 0.83$ over a length of 2 mm of the x-polarized and y-polarized Gaussian beams by the vector FE-BPM in Figs. 8(a) (Supplemental video data: S3.mov) and 8(b) (Supplemental video data: S4.mov), respectively. The wavelength of $\Lambda/\lambda = 0.83$ is within the x-polarization band, as shown in Fig. 7(a), and, thus, only the x-polarized beam is seen to propagate in the fiber. Supplemental video data (S4.mov) confirm that, although there are large holes around the elliptical-hole lattice core, the y-polarized beam is almost completely radiated away from the core in a propagation distance of only 2 mm. For a lattice pitch of 1 μm, the bandwidths of the two single-polarization bands are equal to 0.22μm for the HE_{11}^{y} mode and 0.32 μm for the HE_{11}^{x} mode, and their center wavelengths are 1.58 μm and 1.19 μm, respectively.



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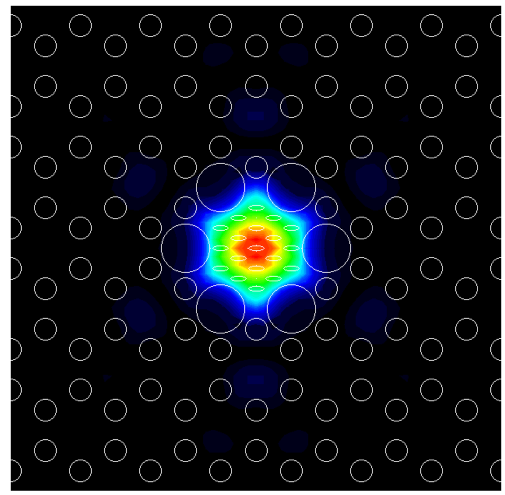

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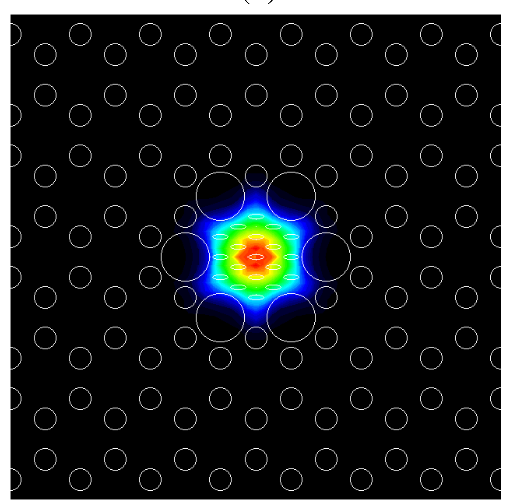
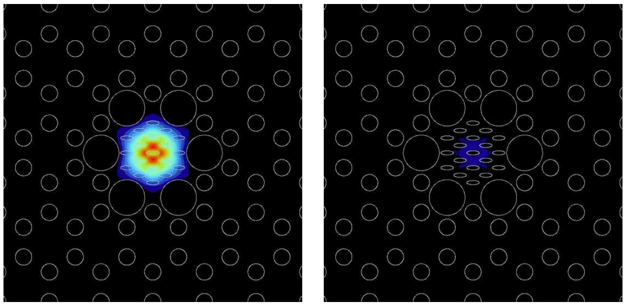


(c)

Fig. 7. Guided modes of a double single-polarization band PBG fiber shown in Fig. 6. (a) Effective index as function of normalized frequency for the x-polarized (HE_{11}^{x}) and y-polarized (HE_{11}^{y}) fundamental modes, which correspond to the blue-colored solid and red-colored dashed curves, respectively. (b) Mode field distribution for the HE_{11}^{y} mode at $\Lambda/\lambda = 0.65$. (c) Mode field distribution for the HE_{11}^{x} mode at $\Lambda/\lambda = 0.85$.

VI. CONCLUSION

Summarizing, we have proposed a novel honeycomb PBG fiber structure with an elliptical-hole lattice core and demonstrated an absolutely single-polarization elliptical-hole lattice core PBG fiber numerically. In addition, a new single-polarization PBG fiber that has two absolutely single-polarization bands being orthogonal to each other has been devised. Such a double absolutely single-polarization band fiber has been quite impossible by using index-guiding mechanism. In wavelength division multiplexing transmission using this double single-polarization band fiber, wavelength demultiplexing of two wavelength bands can easily be achieved using only



(a) (b)

Fig. 8. Field distribution at $\Lambda/\lambda = 0.83$ in a double single-polarization band PBG fiber after 2 mm of propagation and the light propagation along the fiber of length 2 mm (Supplemental video data: S3.mov and S4.mov). (a) x-polarized beam (S3.mov). (b) y-polarized beam (S4.mov).

a polarizer. Introducing an elliptical-hole lattice to the core region of a PBG fiber will open up new possibilities in the field of fiber optics.

The elliptical-hole lattice core PBG fibers proposed here may be fabricated by applying a manufacturing technique [28] that was used to fabricate a PCF having a tiny elliptical hole in its solid core region. Finally, although we have concentrated here on designing the single-polarization PBG fibers with elliptical holes having the orientation shown in Figs. 1 and 6, these PBG fibers can be designed similarly also for elliptical holes placed perpendicular to those.

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