Design of tunable bandgap guidance in high-index filled microstructure fibers

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Tunable photonic bandgap (PBG) microstructure fibers, which were filled nematic liquid crystals (NLC), were theoretically investigated based on bandgap theory. By means of the modified plane-wave method, it is found that PBGs shift to the longer wavelength with increasing refractive index of NLC [$n_y(\theta)$] for y-polarized light. Fundamental modes are found in these PBG reigns, whose effective mode area, leakage loss and group velocity dispersion (GVD) have been calculated by using the full-vector finite-element method with anisotropic perfectly matched layers. The mode fields become larger with the increase of $n_y(\theta)$, whereas the leakage loss varies slightly. Moreover, GVD is strongly dependent on $n_y(\theta)$ and wavelength, which is much larger than the material dispersion of silica. © 2006 Optical Society of America

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1. INTRODUCTION

Microstructure fibers (MFs) belong to a class of fibers that have a periodic array of materials with varying refractive indices. Their operation usually relies on light being guided by total internal reflection (TIR) or the photonic bandgap (PBG) effect.[1] PBG MFs, in contrast to TIR MFs, have attracted significant interest over the past few years owing to their unique advantages over conventional fibers.[2–4] Later, successful fabrication of solid microstructure optical fiber[5] suggests the possibility of forming other-type microstructure fiber whose "holes" can be filled with a relatively higher or lower index material. A high interaction between light and hole material can be obtained while maintaining the microstructure of the waveguide.[6,7] Recently, novel PBG MFs obtained by filling high-index material in the holes of MFs was demonstrated. T. P. White *et al.*[8] presented their work on guidance of MFs consisting of high-refractive-index cylinders embedded in a low-index background using a full-vector multipole method. A. Fuerbach *et al.*[9] investigated femtosecond-pulse propagation in a microstructured optical fiber consisting of a silica core surrounded by air holes filled with a high-index fluid.[9] Furthermore, Bise *et al.*[10] demonstrated a tunable PBG fiber, which was obtained by filling high-index fluid in MFs, and the resulting bandgaps can spectrally shift with adjusting the temperature. Recently, a electrically tunable NLC-filled MF was demonstrated by M. W. Haakestad *et al.* and Du *et al.*[11,12] Moreover, transformation of an optical transmission mechanism was theoretically presented via comparison of the nematic-liquid-crystal (NLC)-filled MF to the nonfilled MF in an earlier paper.[13] To the best of our knowledge, however, the theoretical analysis of the characteristics of tunable PBG MFs with varying refractive indexes and filled MFs based on PBG theory has not been reported in literature.

In this work, we present the theoretical analysis of tunable PBG guidance, which can be obtained by filling high-index material, such as NLC, in the holes of normal-index guiding solid-core MF. Moreover, we present the theoretical analysis of this tunable bandgap guidance in virtue of bandgap theory. By means of the modified plane-wave method,[14] the PBG maps have been found; furthermore, the shifting of PBG has been investigated, as we vary the nematic directors of NLCs in the holes. In addition, some characteristics of fundamental modes existing in PBGs for the NLC-filled MFs, such as leakage loss, effective area, and waveguide group velocity dispersion (GVD), are investigated by changing the nematic directors of the NLC using a full-vector finite-element method (FEM) with anisotropic perfectly matched layers (PMLs).[15,16]

2. PRINCIPLE

To evaluate leakage losses and to enclose the computational domain without affecting the numerical solution, a full-vector FEM using anisotropic PMLs as absorbing boundary conditions has been introduced. From Maxwell's equations the following vectorial wave equation is derived[15]:

$$\nabla \times ([s]^{-1} \nabla \times \mathbf{E}) - k_0^2 \bar{\epsilon}[s]\mathbf{E} = 0, \tag{1}$$

where $\mathbf{E}$ is the electric field vector, k_0 is the free-space wave number, $\bar{\epsilon}$ is the dielectric tensor, $[s]$ is the PML matrix, and $[s]^{-1}$ is an inverse matrix of $[s]$. Because of the uniformity of the fiber, we can write the electric field $\boldsymbol{E}$ as

$$\mathbf{E}(x,y,z) = e(x,y)\exp(-\gamma z), \tag{2}$$

with $\gamma = \alpha + j\beta$, where γ is the complex propagation constant along the invariant z axis and α and β are the attenuation constant and phase constant, respectively. The complex propagation constant is computed by means of full-vector FEM with anisotropic PMLs.

To indicate the effect of the PBG in the NLC-filled MF on the effective mode area, the effective mode area A_{eff} is introduced in this working, which is a quantity of great importance in fiber optics. It can be calculated with the following equation:

$$A_{\mathrm{eff}} = \frac{\left(\int\int |\mathbf{E}|^2 \mathrm{d}x\mathrm{d}y\right)^2}{\cdot\int\int |\mathbf{E}|^4 \mathrm{d}x\mathrm{d}y}. \quad (3)$$

The leakage loss is another important parameter in the design of MFs with a finite number of air holes. In this paper, the number of filled-NLC holes in the cladding is finite, and so the modes of such fibers are inherently leaky. The leakage loss L_c is deduced from the value of α as

$$L_c = 8.686\alpha. \quad (4)$$

Once the propagation constant is obtained, the waveguide GVD, D_w, is easily calculated from the computed propagation constant as

$$D_w = -\frac{2\pi c}{\lambda^2}\frac{\mathrm{d}^2\beta}{\mathrm{d}\omega^2}, \quad (5)$$

where λ is the operating wavelength, c is the velocity of light in vacuum, and ω is the frequency. The wavelength dependence on the index of silica and NLC is neglected. Of course, the material dispersion should be taken into account to evaluate total wavelength dispersion of MFs.

3. MODELING AND ANALYZING

We have filled NLC in the holes of triangular structured TIR MF, shown in Fig. 1, with a silica core surrounded by six periods of air holes. The holes', diameter (d) and the pitch length (Λ) are 1.8 and 3.38 μm, respectively. The NLC is a uniaxial birefringent medium with an ordinary and extraordinary refractive index $n_o = 1.65$ and $n_{\mathrm{e}} = 1.83$, respectively. We assumed that the silica refractive index was 1.444 and the refractive index of the NLC was independent of wavelength. Because the initial alignment of directors depends on the capillary interface interaction of the NLC, the holes of the MF make the nematic directors of the NLC align along the z axis of the fiber when NLC is filled in the MF.[17] Moreover, the infiltration changes the

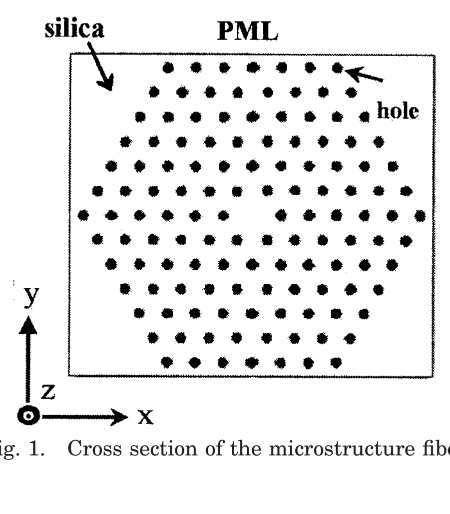

Fig. 1. Cross section of the microstructure fiber.

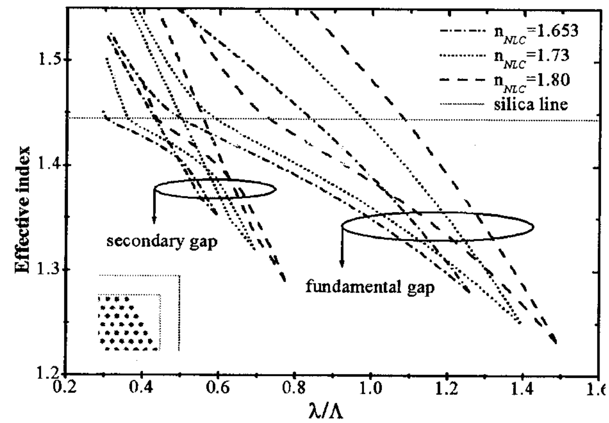

Fig. 2. Bandgap map of the NLC-filled MF versus normalized wavelength when the refractive index of the NLC for y-polarized light is 1.635, 1.73, and 1.80.

waveguide properties of the infiltrated section, since the fiber now has a low-index core surrounded by high-index anisotropic rods. The infiltration section cannot guide by TIR but can support a number of guided-wavelength bands owing to Bragg reflections in the transverse direction. That is to say, the PBG MFs can be achieved when high-index material is filled in the air holes.[18] The results suggest that increased fiber functionality can be obtained in high-index inclusion MFs. When a tunable electric field is applied in the direction of the y axis, the nematic directors deviate from the z axis, making an angle θ. Thus the y-polarized light is expected to be polarization dependent whose refractive index is given by $1/n_y^2(\theta) = \sin^2\theta/n_e^2 + \cos^2\theta/n_o^2$, while the x-polarized light is the ordinary wave whose refractive index is $\mathrm{n_o}$.[11,17] In the model, the effect of E_z on the transmission characteristices was not considered, because the effecting of E_z is limited compared with E_y.[6] Figure 2 shows the PBG edges and variation of these PBGs for the NLC-filled MF when the refractive index of NLC $[n_y(\theta)]$ for y-polarized light is 1.635, 1.73, and 1.80, which are obtained by the modified plane-wave method described.[14] The modified method is a fully vectorial, three-dimensional algorithm to compute the definite-frequency eigenstates of Maxwell's equations in arbitrary periodic dielectric structures, including systems with anisotropy materials, using preconditioned block-iterative eigensolvers on a plane-wave basis. The band diagram reveals the existence of two PBGs (fundamental and secondary gap) for a fixed refractive index of a NLC. We note that the silica line (gray solid curve) crosses fundamental and secondary gap regions. For the specific propagation constant value, no fundamental modes are allowed to propagate in the NLC-filled MFs if their frequencies do not fall within one of the two PBGs and below the silica line, according to PBG theory. The PBGs transfer with the variety of the nematic directors of NLC, as the positions of bandgaps are dominated by the contrast of refractive index of silica and $n_y(\theta)$. According to Fig. 2, we can find that PBGs shift toward the longer wavelength, and the width of PBGs is larger with an increase of $n_y(\theta)$. From the results the tunable NLC-filled PBG MFs can be obtained; moreover, the transmission properties of the fibers can be easily tuned by varying the nematic directors of NLC.

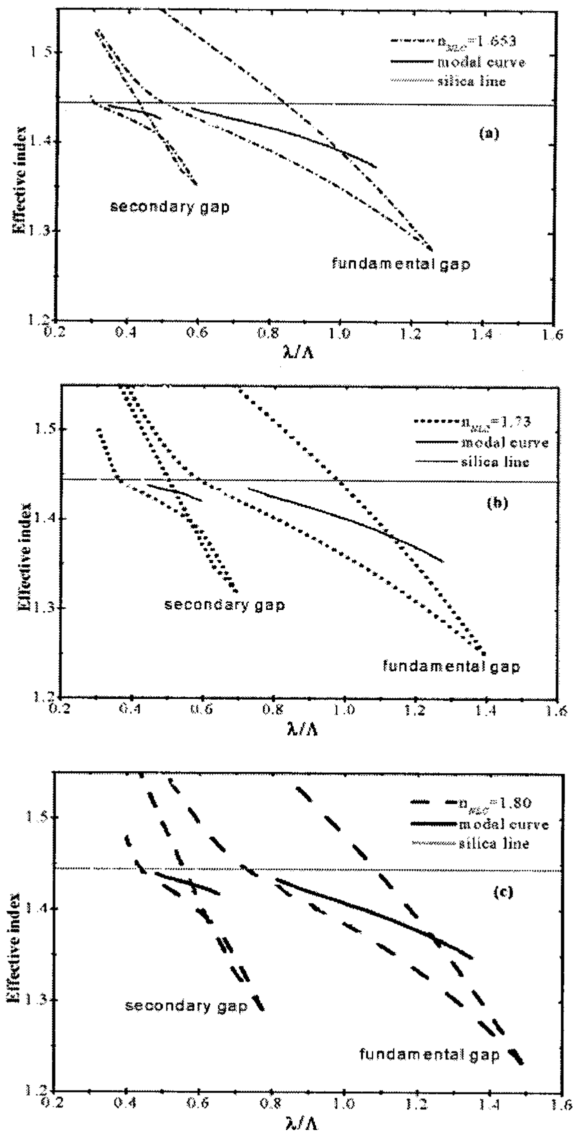

Fig. 3. Modal dispersion curve versus normalized wavelength when the refractive index of the NLC for y-polarized light is (a) 1.635 (b), 1.73, and (c) 1.80.

To reduce the load of calculation, a quarter (inset of Fig. 2) is used to investigate according to the symmetrical structure of MF. The FEM can arbitrarily select the order and the number of elements, which depends on the required computational accuracy. In our model, the light is assumed to be y polarized. When we tune the nematic directors of NLC, the fundamental modes curve shifts with the shift of PBGs. By using a full-vector FEM with anisotropic PMLs, the dispersion curves of NLC-filled MFs have been computed when $n_y(\theta)$ is 1.635, 1.73, and 1.80. Fig. 3 shows the modal dispersion curve (black solid curve) of the fundamental modes for the three values of $n_y(\theta)$ together with the PBG edges as a function of normalized wavelength, λ/Λ. The fundamental modes exist in the fundamental and secondary gap regions, and the modal dispersion curves shift to the longer wavelength with an increase of $n_y(\theta)$, but they are always located in respective PBG regions. The unnormalized transmission characteristic of the NLC-filled MF shows that light is guided over only discrete frequency bands by the bandgap effect.[8] Moreover, according to Fig. 3, the modal dispersion curves are always below the silicon line, which can be well explained by PBG theory. However, fundamental modal dispersion curves extend to the outside of the upper bandgap edges; the phenomenon can be illuminated by antiresonance waveguide.

To show the effect of PBG on the effective mode area in the NLC-filled MF, the effective mode area is discussed. Fig. 4 shows the variation in the normalized effective mode area for different values for $n_y(\theta)$. For a given $n_y(\theta)$ the mode fields are well confined to the silicon-core region when the modes are located around the center of PBGs, but they rapidly enlarge when the mode frequencies are close to the edges of PBG. Moreover, the mode fields around the center of the PBGs enlarge with an increase of $n_y(\theta)$; the reason is that the mode fields extend to the cladding when the wavelengths become longer. The number of air holes in the cladding is finite in practice, and so the mode is leaky based on bandgap theory. Figure 5 shows the leakage loss as a function of normalized wavelength for the silicon-core PBG-MF with six periods of NLC filled holes, where $n_y(\theta)$ is taken as a parameter. According to Fig. 5, the loss spectrum of the mode is quite complicated, consisting of multiple lower-loss regions separated by PBG edges for one given $n_y(\theta)$. This behavior is fundamentally different from that displayed by index-guiding MF structures, for which the loss increases monotonically with wavelength.[19] The leakage loss is slightly variable with increasing $n_y(\theta)$, which indicates that the nematic directors of NLC weakly affect the leakage loss, though a variety of $n_y(\theta)$ brings a shifting of PBG. Leakage losses arise fluctuating near the lower band edge; the reason is the modes are closing to the silica line when the modes are close to the lower band edge. These results suggest the possibility of tunable optical filter or switches that can be designed with NLC-filled MFs.

For PBG MFs that are resonant structures, propagation of light should be strongly wavelength dependent. Their waveguide dispersion and dispersion slope is expected to be very different from that of TIR-guiding fibers, which are the important characteristics in MFs designed for limiting the useful spectral bandwidth. We present the analytical results of GVD across the two bandgaps of the NLC-filled MF with increasing $n_y(\theta)$. Figure 6 shows the normalized GVD of the NLC-filled MF for the fundamen-

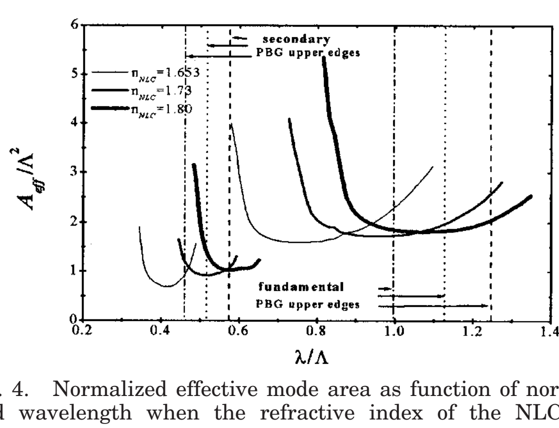

Fig. 4. Normalized effective mode area as function of normalized wavelength when the refractive index of the NLC for y-polarized light is 1.635, 1.73, 1.80.

tal mode, where $n_y(\theta)$ is taken as a parameter. According to Fig. 6 the modal GVD exhibits the same qualitative behavior: (a) the GVD is strongly wavelength dependent, (b) it goes from negative values at shorter wavelengths to positive values at longer wavelengths, (c) it increases rapidly near the upper band edge and decreases rapidly near the lower band edge, and (d) it crosses the zero point within the low-loss window, and the dispersion slope around the center of fundamental gap is smaller than that of the secondary gap. The numerical results are in good agreement with the experimental results in Ref. 7. However, there are still some differences when $n_y(\theta)$ is at different values. The dispersion slope around the center of PBG with a larger value of $n_y(\theta)$ is smaller than that of PBG with a smaller value of $n_y(\theta)$. Figure 6 also shows the material dispersion of silica (the gray curve) given by a Sellmeier formula. The waveguide GVD is larger than the material dispersion of silica, especially when the mode is located in the secondary gap region. Comparing the material dispersion of silica with the GVD of NLC-filled MFs, the former affects the total wavelength dispersion of MFs only limitedly.

4. CONCLUSION

A tunable PBG MF was theoretically investigated based on bandgap theory. By means of the modified plane-wave method, we have found the PBGs of a NLC-filled MF shift toward the longer wavelength with an increase of $n_y(\theta)$. By applying a full-vector FEM with anisotropic PMLs to the tunable PBG MFs, it has been found that the effective mode area becomes larger with increasing $n_y(\theta)$, whereas the leakage loss varies slightly. Moreover, the results also show that the waveguide GVD is strongly dependent on the refractive index of NLC and mode wavelength and is much larger than the material dispersion of silica. The research gives a physical insight into the tuning mechanism in MFs and is crucial for any future applications.

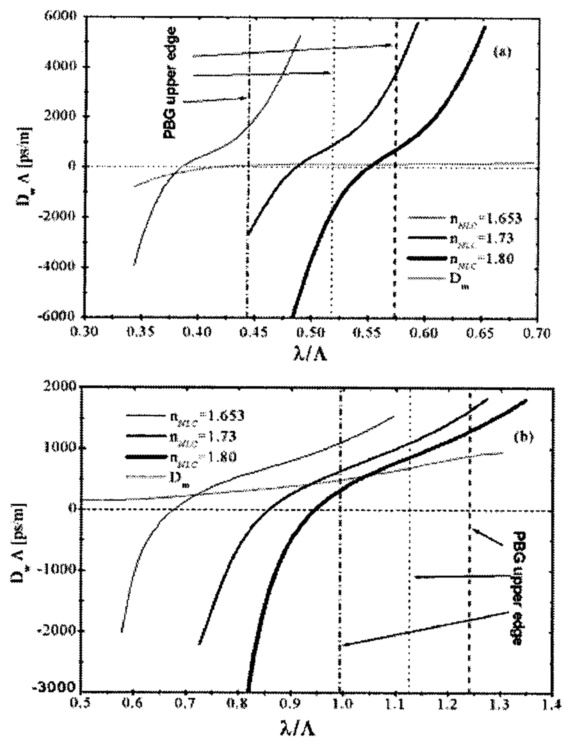

Fig. 6. Normalized GVD versus normalized wavelength with different refractive index of NLC when the refractive index of NLC for y-polarized light is 1.635, 1.73, and 1.80; (a) secondary gap region, (b) fundamental gap region.

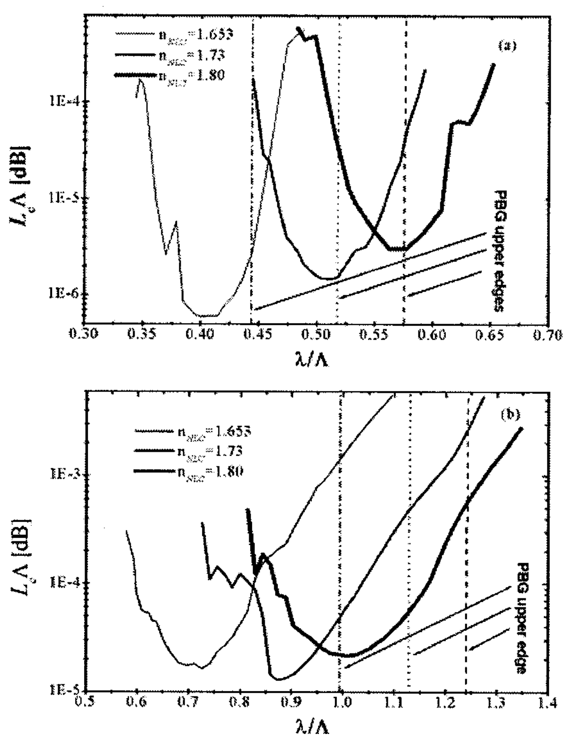

Fig. 5. Normalized leakage loss versus normalized wavelength with a different refractive index of the NLC when the refractive index of the NLC for y-polarized light is 1.635, 1.73, and 1.80; (a) secondary gap region, (b) fundamental gap region.

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