Transformation of a transmission mechanism by filling the holes of normal silica-guiding microstructure fibers with nematic liquid crystal

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Transformation of an optical transmission mechanism was achieved when the holes of normal silica-guiding microstructure fiber (MF) were filled with nematic liquid crystal (NLC). Moreover, two photonic bandgaps (PBGs) were obtained by using a plane-wave method to create the pattern. The wavelength dependence of the effective mode area, leakage loss, and group velocity dispersion (GVD) has been theoretically investigated by using a full-vector finite-element method with anisotropic perfectly matched layers. The results reveal that the characteristics of the NLC-filled PBG-MFs are particularly wavelength dependent. This research gives a physical insight into the propagation mechanism in MFs and is crucial for future transmission applications. © 2005 Optical Society of America

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Photonic bandgap microstructure fibers (PBG-MFs) have attracted significant interest in the past few years: their propagation loss is exceedingly low,[1,2] nonlinear effects are very small,[3] and the air core can be filled with liquids or gases.[4,5] In PBG-MFs, light is confined in the low-index core by the bandgap effects of the cladding. It is important to know the leakage loss and dispersion properties of PBG-MFs for practical applications. While recent successful fabrication of solid holey fiber suggests the possibility of forming other types of MF, whose "holes" can be filled with a relatively higher- or lower-index material,[6–8] it is difficult to find a suitable material. There have been some reports in the literature of experimental PBG fibers obtained by filling the holes in the fiber with high-index material.[5] To the best of our knowledge, however, theoretical analysis of the structural dependence of transmission characteristics in MFs whose holes were filled with high-index material based on the bandgap theory has not been reported in the literature.

In this Letter, we report that we have achieved transformation in an optical transmission mechanism by filling the holes of silica-guiding solid-core MFs with nematic liquid crystal (NLC). That is, the fiber can conduct light through the PBG effect and does so by means of total internal reflection (TIR) before it is filled with NLC. A theoretical analysis of the characteristics of PBG-MFs based on the bandgap theory is presented. By means of the plane-wave method,[9] a PBG map of NLC-filled MFs is obtained. The wavelength dependence of confinement losses, the effective area, and the group velocity dispersion (GVD) of our PBG-MFs are investigated by use of a full-vector finite-element method (FEM) with anisotropic perfectly matched layers (PMLs).[10] Moreover, a comparison between the dispersion and the loss properties of the MF before and after filling is developed.

To enclose the computational domain without affecting the numerical solution and to evaluate leakage losses, anisotropic PMLs are placed before the cladding's outer boundary. Because of the uniformity of the fiber, we can write electric field E as $\mathbf{E}(x,y,z) = e(x,y)\exp(-\gamma z)$ with $\gamma=\alpha+j\beta$, where γ is the complex propagation constant along the z axis and α and β are the attenuation and the phase constant, respectively. γ is computed by means of a full-vector FEM with anisotropic PMLs. The leakage loss L_c, which is an important parameter of MFs with a finite number of airholes, is deduced from the value of α as $L_c = 8.686\alpha$ in decibels per meter.

Figure 1 shows the structure of the MF, which has a silica core surrounded by 6 periods of airholes arranged in a triangular lattice. The hole diameter d and pitch length Λ are 1.8 and 3.38 μm, respectively, and the fiber can guide light by the principle of modified TIR; moreover, the refractive index of silica is assumed to be 1.444 in the model. However, when we fill the holes with NLC, the infiltration section cannot be guided by TIR but can support a number of guided wavelength bands due to Bragg reflections in the transverse direction, since the fiber now has a low-index core surrounded by high-index rods. Note that NLC is anisotropic. For our model, however, the refractive index tensor will remain constant if there are

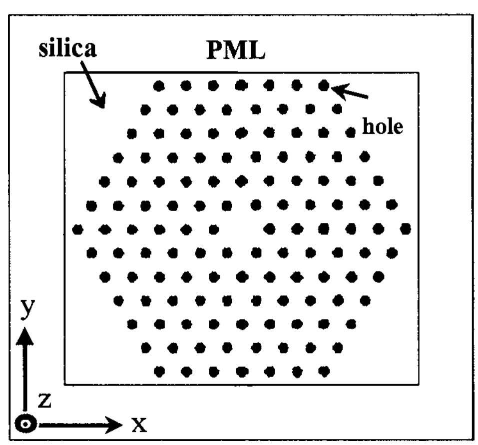

Fig. 1. Cross section of the microstructure fiber.

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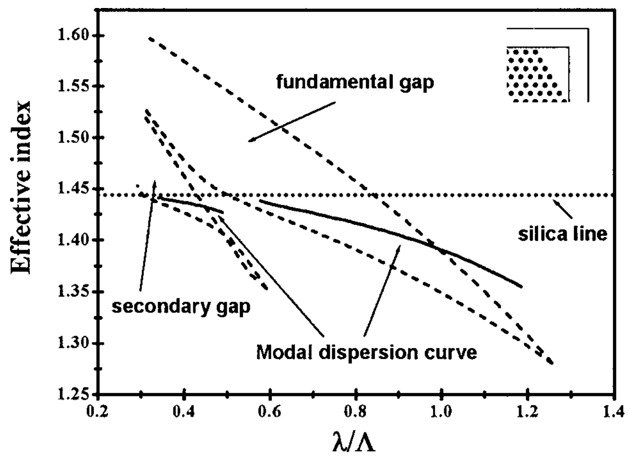

Fig. 2. Modal dispersion curve for the fundamental mode of NLC-filled MFs as a function of normalized wavelength.

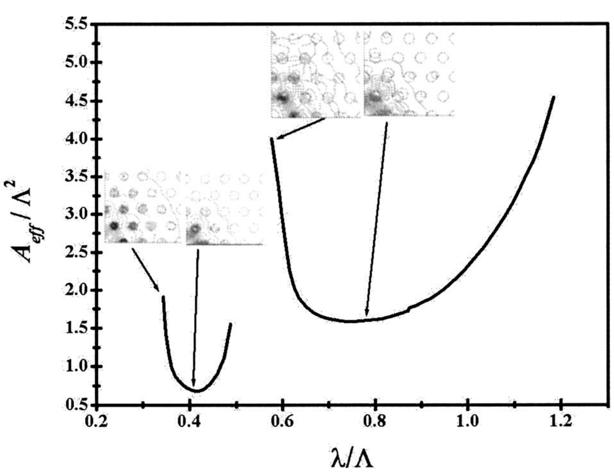

Fig. 3. Normalized effective mode area for the fundamental mode of NLC-filled MFs as a function of normalized wavelength.

no environmental perturbations. Therefore we assume the refractive index to be 1.653. In Fig. 2, we depict the bandgaps of the pattern by using the plane-wave method. The diagram reveals the existence of two PBGs and a silica line crossing the 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 are not located in the PBGs and below the silica line.

The FEM can arbitrarily select the order and the number of elements, depending on the required computational accuracy. One-quarter of the NLC-filled MF (inset of Fig. 2) was used to investigate the symmetrical structure of the MFs to reduce the time of calculation. Using a full-vector FEM with anisotropic PMLs, the dispersion curves have been computed. Figure 2 shows the modal dispersion curve (solid curve) of the fundamental mode as a function of normalized wavelength, λ/Λ. The fundamental mode exists in both PBG regions and the lower and higher cutoff wavelengths in these regions are $\lambda/\Lambda \cong 0.34-0.49$ and $\lambda/\Lambda \cong 0.57-1.18$, respectively. Figure 2 also shows that the curves are always below the silicon line. The nonnormalized transmission that is characteristic of NLC-filled fiber shows that light is guided over only discrete frequency bands by the PBG effect.

Figure 3 shows the effective mode area of the NLC-filled PBG-MF. The inset of Fig. 3 illustrates the intensity profile of the fundamental modes in bandgaps, and the normalized wavelengths are 0.346, 0.406, 0.577, and 0.785. According to Fig. 3, the mode fields are well confined to the silicon-core region when the modes are located around the center of the PBG, but they rapidly enlarge when the mode frequencies are close to the edges of the PBG.

Assuming PBG-MFs with an infinite number of air holes, the light would be confined to the core region by a fully two-dimensional PBG and leakage losses would not occur. However, the number of airholes in the cladding is finite in practice, and so the mode is leaky. Figure 4 shows the wavelength dependence of the normalized leakage loss of the MF before and after it is filled with NLC. The results reveal that the leakage loss unfortunately became much larger when the holes were filled with NLC. As expected, the leakage loss becomes minimum around the center of the PBG and increases as it approaches the band edges after filling. This effect indicates that the mode fields are confined to the core of the fiber when the modes appear around the center of the PBG, but they enlarge to the size of the cladding rapidly when the modes are close to the edges of the PBG. Moreover, the leakage loss in the fundamental gap is larger than that in the secondary gap. However, the leakage

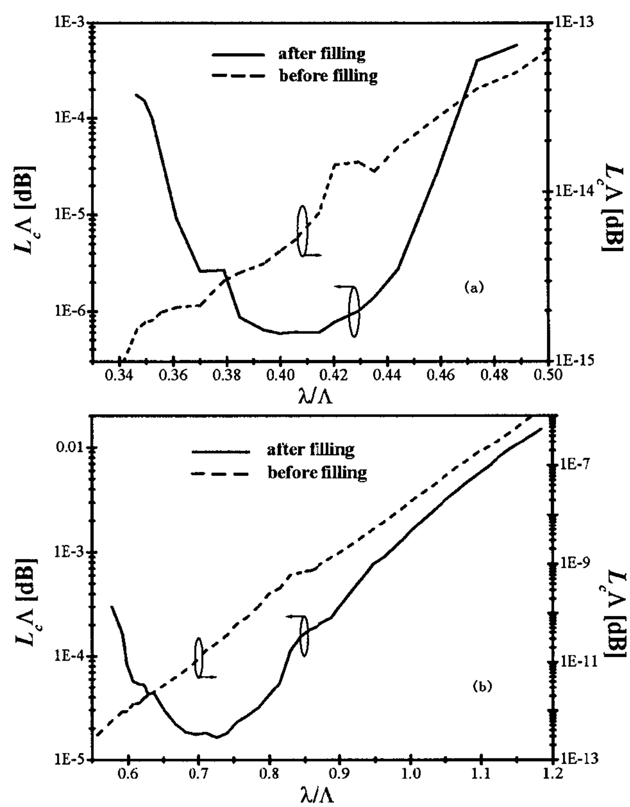

Fig. 4. Normalized leakage losses of the fundamental mode as a function of normalized wavelength in the (a) secondary and (b) fundamental gap regions of the MFs before and after filling them with NLC.

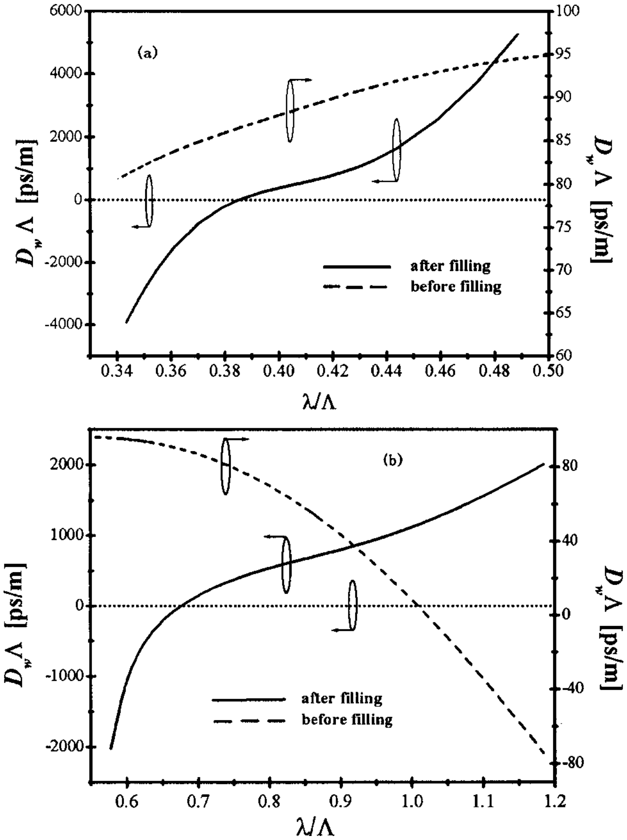

Fig. 5. Normalized GVD of the fundamental mode as a function of normalized wavelength in the (a) secondary and (b) fundamental gap regions of the MFs before and after filling them with NLC.

loss does not increase rapidly when the modes are close to the lower band edges of the fundamental and the secondary gaps. The reason for this is that the modal dispersion curves would cross the silica line, where the fundamental mode would not be guided by the PGB, when the modes are close to the lower band edge. According to Figs. 2–4, the effective mode area and leakage loss increase rapidly, although the modal dispersion curve extends outside the upper bandgap edges.

For PBG-MFs that are resonant structures, propagation of light should be strongly wavelength dependent. The wavelength dependence of the index of silica and NLC is neglected in our research. Of course, the material dispersion should be taken into account to evaluate the total wavelength dispersion of MFs. The dispersion and the dispersion slope, which are the important characteristics of MFs, limit the useful spectral bandwidth of the fibers. In Fig. 5 we present the numerical results of GVD of the fundamental mode in the two bandgap regions of the MFs before and after filling them with NLC. The GVDs in either bandgap exhibit 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, (d) it crosses the zero point within the low-loss window, and (e) the dispersion slope around the center of the fundamental gap is larger than that of the secondary gap. Contrasting the GVD before and after filling, we find that a different and larger waveguide GVD is achieved in the NLC-filled MF. The numerical results for the NLC-filled MF are in good agreement with the experimental results presented in Ref. 4.

In conclusion, a novel PBG-MF has been obtained by filling the holes of a normal index-guiding solid-core MF with NLC and has been investigated theoretically. By means of a plane-wave method, a PBG map of the pattern has been obtained. The wavelength dependence of the effective mode area, the leakage loss, and the GVD have been numerically investigated by use of a full-vector FEM with anisotropic PMLs. The mode field is well confined to the silicon-core region, and the leakage loss becomes minimum when the modes are located around the center of the PBG, but both rapidly increase when the modes are close to the edges. Moreover, the leakage loss of NLC-filled MFs is much larger than that of MFs before they are filled with NLC. Furthermore, the waveguide GVD is strongly wavelength dependent and is different from that of the MFs before filling. This research gives physical insight into the propagation mechanism of MFs and is crucial for future transmission applications.

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