Effect of single point defects on the confinement losses of air-guiding photonic bandgap fibers*

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The confinement losses in air-guiding photonic bandgap fibers (PBGFs) with air hole missing are studied with the full-vector finite-element method. It is confirmed that there are two loss peaks (1.555 and 1.598 μm) if there is a hole missing in the cladding far from the core. The closer to the core the hole missing is, the larger the confinement losses are, and even no mode could propagate in the core. The main power of the fundamental mode leaks from the core to the cladding defect. The quality of PBGFs can be improved through controlling the number and position of defects.

Keywords: photonic bandgap fiber, photonic bandgap (PBG), defect mode, confinement loss

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1. Introduction

Air-guiding photonic bandgap fibers (PBGFs)[1,2] are expected to possibly have new applications for extremely low-loss propagation, high-power delivery, tunable group velocity dispersion, and so on. However, the transmission losses in air-guiding PBGFs are larger than the theoretical values.[3] The lowest loss in hollow core photonic crystal fiber (PCF) reported by BlazePhotonics Ltd. in 2004 is 1.1 dB/km at 1550 nm, which is guided by the photonic bandgap effect.[4] However, the loss of the common fiber can drop to 0.2 dB/km.

It is very important to know what causes the high transmission loss in air-guiding PBGFs and how to reduce it. At the current production level, parameter control alone is sometimes inadequate in achieving the desired geometry.[5] Many defects are introduced in the manufacturing process, especially for the point defects. Only single point defect in the PBGF has to be considered. The existence of a defect breaks the symmetry of the cross section of PBGFs. The two fundamental modes linearly polarized along two orthogonal directions would no longer degenerate.[6] In other words, the loss curves of the two polarization modes would be different.

2. The modulation mechanism

For the material with a dielectric constant of $\varepsilon_{\rm r}$, and a magnetic permeability of $\mu_{\rm r}$, Maxwell's equations can be written in the following form:

$$\nabla \times \left(\frac{1}{\varepsilon_{\rm r}} \times \boldsymbol{H}\right) = k_0^2 \mu_{\rm r} \boldsymbol{H}, \tag{1}$$

where k_0 is the wave vector, and the magnetic field $\boldsymbol{H} = H\,{\rm e}^{-{\rm j}\beta z}$. The propagation constant β is a complex number ($\beta = k_0 n_{\rm eff} - {\rm j}\alpha$, with $n_{\rm eff}$ being the effective refraction index and α the loss factor) and can be calculated by using the vector finite-element method (FEM) with a perfectly matched anisotropic layer,[7] through solving the following discrete equation:

$$\left(\frac{\beta}{k_0}\right)^2 \{H\} = \{Q\}\{H\}. \tag{2}$$

The confinement loss $L_{\rm c}$ is deduced from the value of propagation constant β as

$$L_{\rm c} = 20 Im[\beta] \lg {\rm e} \approx 8.686 Im[\beta]\ ({\rm dB/m}). \tag{3}$$

If the two fundamental modes that are linearly polarized along the horizontal (x) and vertical (y) directions do not degenerate, the mode birefringence can be calculated according to

$$B(\lambda) = |n_{\rm eff}^x - n_{\rm neff}^y|, \tag{4}$$

where λ is the wavelength. The value of $n_{\rm eff}$ is also deduced from the value of propagation constant β.

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3. Simulation results and discussion

The structure of PBGF is shown in Fig. 1. The core mode and surface mode will not intersect in the bandgap, and thus the confinement losses of the core mode will not be more affected by the surface mode (see Fig. 2). It is shown that the minimum loss value is 0.16 dB/m at about 1.55 μm. Therefore, for PBGFs with point defects, the coupling between the core mode and the cladding defect mode can be mainly considered.

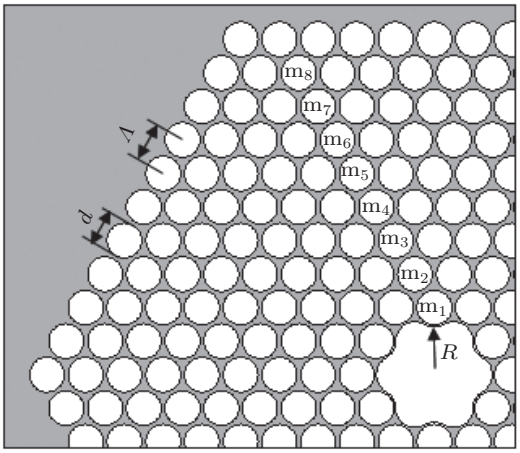


Fig. 1. Schematic of the air-guiding PBGF. The core is a seven-unit-cell air hole, the lattice constant $\Lambda = 2.325$ μm, the diameter of the circular air hole is $d = 0.9\Lambda$, the core radius $R = 1.232\Lambda$, and the background index of silica is 1.45. m_1–m_8 denote the positions of air hole at different layers.

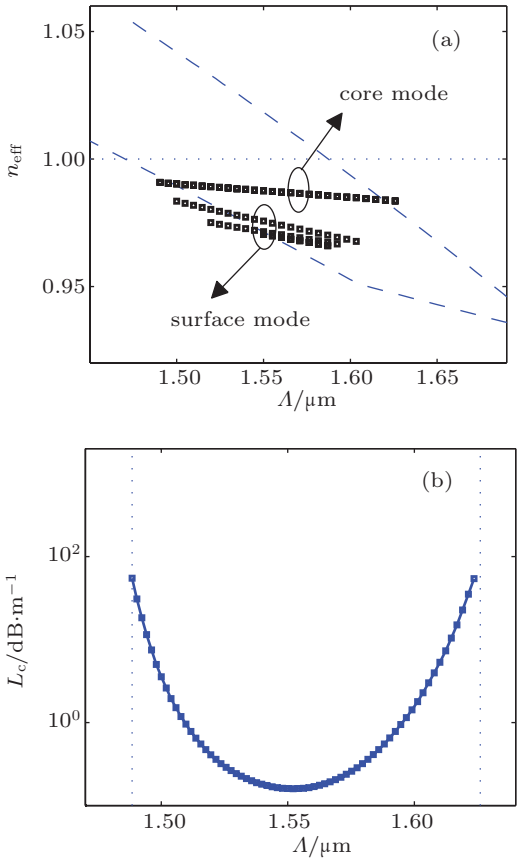


Fig. 2. (colour online) (a) Defect modes in the bandgap of PBGFs. (b) Confinement loss curve.

3.1. Defect modes

A point defect in the PBGF can introduce some of the defect modes which exist in the band gap, some even have an intersection point with the core mode. If so, there will be an "avoided-crossing" phenomenon at every intersection points. The core mode dispersion curve will be cut in these areas. Three defect modes are imported by one air hole missing defect (see Fig. 3).

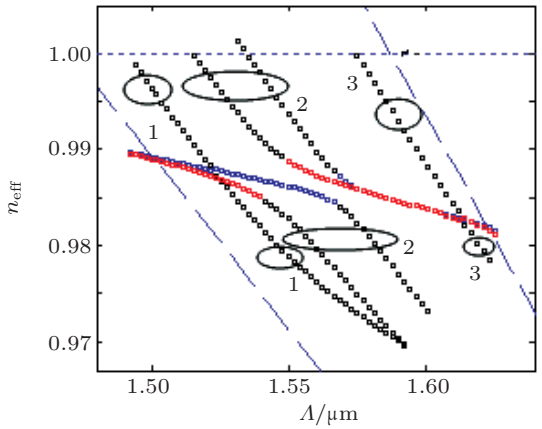


Fig. 3. (colour online) "Avoided-crossing" phenomenon when there is an air hole missing at m_1.

Among three modes, two (1 and 3) are single-polarization modes, one (2) is a degenerate mode which splits into two single-polarization modes due to the coupling with core mode. The "avoided-crossing" phenomenon only occurs between a defect mode and a core mode with the same polarization, and their mode fields must be very close. The farther from the core the point defect is, the weaker this phenomenon is (see Fig. 4).

3.2. Confinement losses

A strong "avoided-crossing" phenomenon can induce a strong coupling between defect modes and the core. For the core mode at the wavelength near "avoided-crossing" points, the main power does not exist in the core (see Fig. 5). The calculated core mode confinement loss does not make sense. In this paper the confinement losses are calculated for the PBGFs, which each have a point defect at the positions from m_4 to m_8.

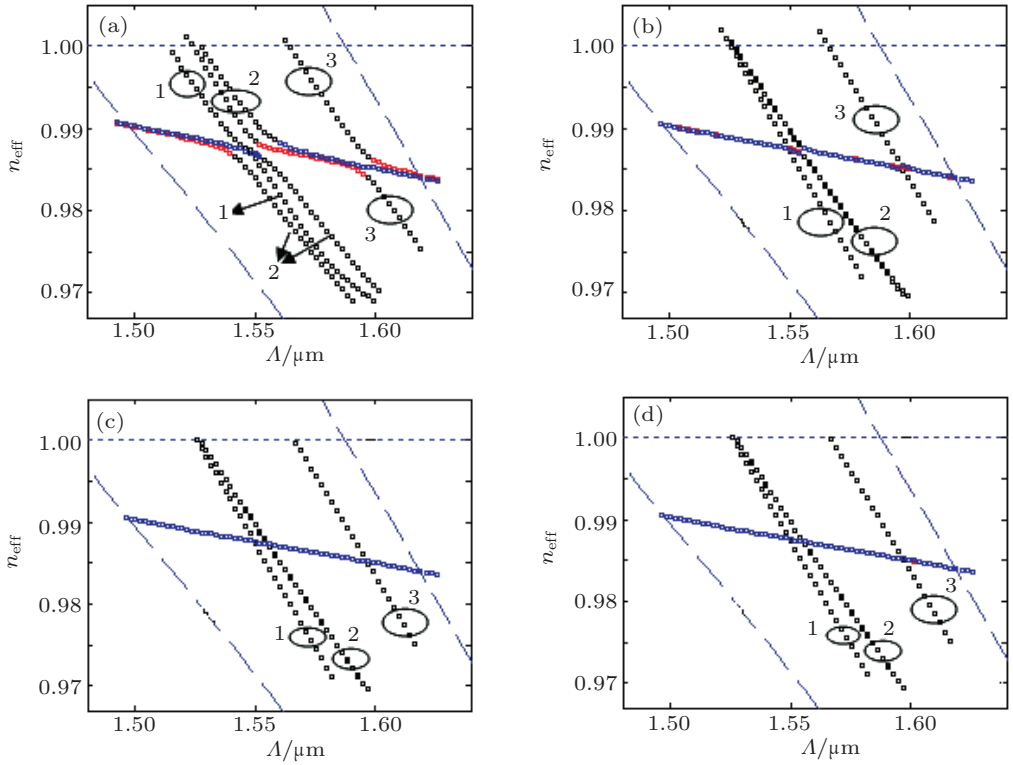


Fig. 4. (colour online) Core modes (red and blue) and defect modes (black) in the bandgap, when the point defect is at (a) m_2, (b) m_3, (c) m_4, and (d) m_5.

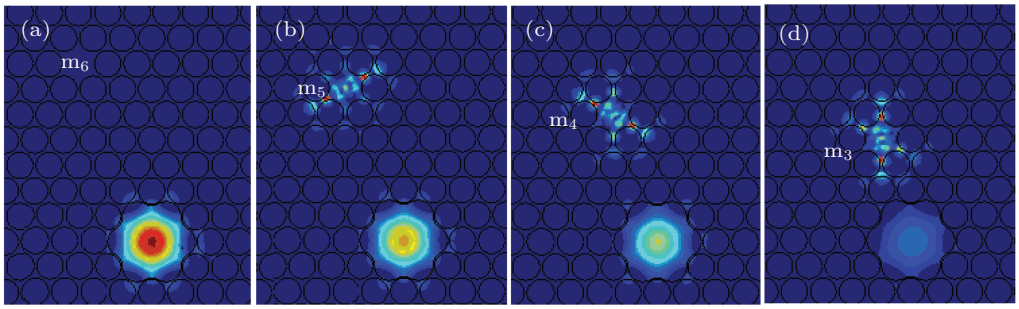


Fig. 5. (colour online) Mode fields of the core mode at wavelength near "avoided-crossing" point at (a) m_6, (b) m_5, (c) m_4, and (d) m_3.

From m_4 to m_8, the "avoided-crossing" phenomenon is weak. The core mode dispersion curve can be considered continuous, and thus the loss curve should be continuous. However, at the intersection point for core and cladding defect modes, there will be a peak on the loss curve (see Fig. 6).

It is shown in Fig. 6 that the confinement loss curves in the two polarization directions are non-overlapping, because of the impact of cladding defect modes. Cladding modes 2 and 3 have a greater impact on the core modes than mode 1. There are two peaks in the curve, which are just the intersections of the core mode with cladding modes 2 and 3 (1.555 and 1.598 μm). Because the polarization direction of mode 3 is the same as the core mode with the polarization direction (P_2), only the core mode with the polarization direction (P_2) has a loss peak at 1.598 μm. P_1 and P_2 are two orthonormal polarization directions of the core mode.

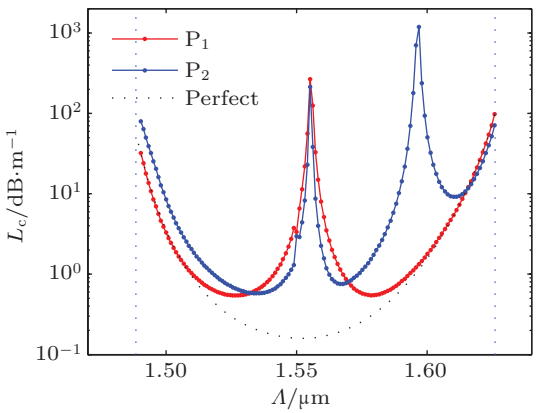


Fig. 6. (colour online) Confinement loss of PBGFs with an air hole missing at m_4.

The loss peaks are due to the coupling between core modes and cladding modes. When the point defect is farther away from the core, the coupling will be weaker and the loss peaks will be smaller, as indicated in Fig. 7. It is shown that the core mode is still affected by the cladding defect mode, even though the point defect is far from the core. This effect becomes very weak in Fig. 7.

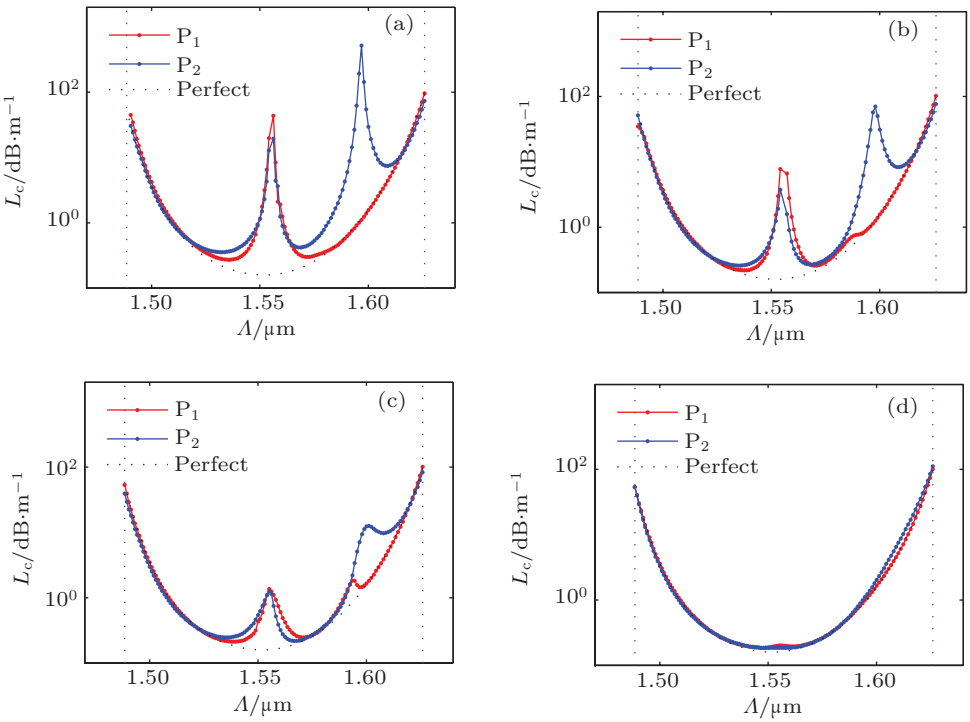


Fig. 7. (colour online) Confinement loss of PBGFs with an air hole missing at (a) m_5, (b) m_6, (c) m_7, and (d) m_8.

4. Conclusions

The air hole missing introduces three main defect modes which overlap the core defect mode in the bandgap. There is an "avoided-crossing" phenomenon at each intersection point. The core mode dispersion curve is cut in these areas.

The point defect is farther from the core and the phenomenon is weaker. Starting from the fourth level, the loss curve can be considered as continuous. However, there are still two peaks at the wavelengths of 1.555 and 1.598 μm, which are the intersection points between cladding modes and core modes.

In all, only one pattern of defect (one air hole missing) is discussed in this paper. Further conclusions can be obtained from the viewpoint of the coupling between the defect modes.

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