Coupling of two defect modes in photonic crystal fibers

Yuntuan Fang (方云团)[1] **and Tinggen Shen (沈廷根)**[2]

[1]*Department of Physics, Zhenjiang Watercraft College, Zhenjiang 212003*

[2]*Department of Physics, Jiangsu University, Zhenjiang 212003*

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The coupling characteristics of two defect modes in photonic crystal fibers are investigated theoretically by the finite-difference time-domain (FDTD) method. The transmission spectrum and eigenmodes of optical wave are found to be very sensitive to the geometrical and physical parameters of the structure, as well as to the relative position of the two defects.

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Photonic crystals, also known as photonic microstructures or photonic band gap structures, have matured from an intellectual curiosity concerning electromagnetic waves to a field with real applications in both the microwave and optical regimes. If we consider the propagation of an electromagnetic wave in the structure, under certain circumstances a "photonic band gap" (PBG) can be opened up[1−6], providing a promising way to greatly improve the performance of optical devices. When a defect or a cavity is introduced in the otherwise perfect crystal, one can obtain localized modes associated with the defect in the band gap of the photonic crystal. Recently, the realization of a dual-core square-lattice photonic crystal fiber (PCF) presenting acoustic defect modes was reported[7]. The results show a coupling between the two acoustic defect modes and provide a basis for developing acousto-optical devices based on PCFs.

The object of this letter is to theoretically study the coupling properties of photonic defect modes in PCFs with two defects. We present a comprehensive analysis of the different localized photon modes that can occur in such a PCF and discuss the sensitivity of the results with respect to the geometrical and physical parameters of the system. This is achieved by using the finite-difference time-domain (FDTD) method. The FDTD method solves the electromagnetic wave equation by discretizing time and space and replacing derivatives by finite differences. The details on FDTD method can refer to the following Refs. [8—10]. We firstly consider the PCFs which have triangular geometry (with lattice constant of a) composed of periodically arranging air holes (with diameter of $0.36a$) all oriented in the z direction in a background material with dielectric constant ε=10.5. A defect is introduced by missing out the center air hole. We select a calculating region in which the air holes are placed 12 layers along the x axis and 13 layers along the y axis (Fig. 1(a)). The absorbing boundary condition used is perfectly matched layers (PMLs) which surround all boundaries by 12 layers of FDTD cells. An incident probe optical wave with TE (H_z, E_x, and E_y) polarization propagates through the PCFs along y axis. The transmission spectrum (Fig. 1(b)) displays two eigenfrequencies of the defect modes corresponding to the peaks at $a/\lambda = 0.282$ and $a/\lambda = 0.345$ within the band gaps, i.e., the basic mode and high order mode localized in fiber core, respectively. Then we study the transmission spectrum of the PCFs with two adjacent defects along the y direction, i.e., the direction of propagation (Fig. 2(a)). Obviously, from the transmission spectrum (Fig. 2(b)), the coupling between the cavities results in the splitting of each of the defect modes associated with a single defect, but with the distance of two coupled defects increasing, the splitting of each of the modes vanishes eventually. Hence, we think that when two defects are separated large, the coupling between them is weak, i.e., the overlap of the new electromagnetic wave function of defect modes can be ignored, which results in localized state of degeneracy; but when the two defects close, the new electromagnetic wave function of defect modes happen to overlap and results in strong coupling, which can take out the degeneracy and induce the splitting of the defect modes.

We still consider the coupling of two defect modes from different structure parameters. Firstly we introduce defects by changing the diameter of air hole as $0.55a$. The lattice constant and other diameter of air holes do not change. The system configurations and relevant transmission spectra are shown in Figs. 3—5. The maps of field distributions (H_z) corresponding to a defect mode are also presented in these figures. These maps are

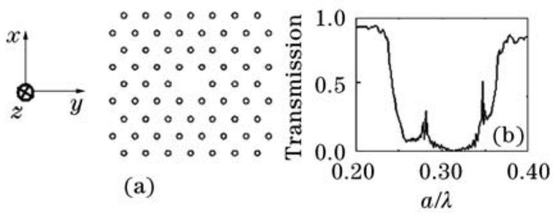

Fig. 1. (a) Two-dimensional (2D) cross section of the PCFs with a center defect and (b) its transmission spectrum.

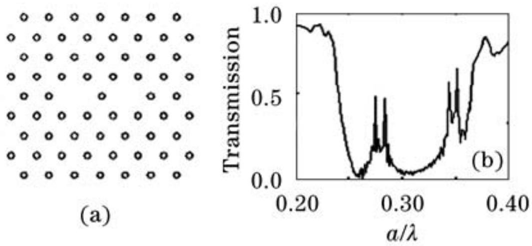

Fig. 2. (a) 2D cross section of the PCFs with two adjacent defects along the y direction and (b) its transmission spectrum.

obtained by considering an incident harmonic probe signal at the frequency of the peak in the transmission spectrum. Figure 3(a) shows a structure of single center defect. A peak at $a/\lambda = 0.267$ comes out on the bottom of band gap in Fig. 3(b) and corresponding field distribution is given in Fig. 3(c). From Fig. 3(c), we find that the field is strongly localized around the center defect and has a hexagonal symmetry agreeing with the structure symmetry. Another small peak also comes out at about $a/\lambda = 0.24$, but because it is close to the pass band, we do not find obviously localized state. Figure 4(a) presents two adjacent defects around the center point and along the y axis. The coupling between two defects results in a coupling mode near $a/\lambda = 0.24$ and intensifies the peak of the basic mode at $a/\lambda = 0.268$ on the bottom of band gap (Fig. 4(b)). Because the defect form is different from Fig. 2, we do not observe the splitting for the peak at $a/\lambda = 0.268$ in this system. The map of eigenvector (Fig. 4(b)) corresponding to frequency $a/\lambda = 0.268$ appears like the result of Fig. 3, which can attribute to the strong coupling of the two defect modes. Compared with Fig. 4(a), Fig. 5(a) just enlarges the distance of two defects along the y axis. From Fig. 5(b), the eigenfrequency of basic defect mode is found at $a/\lambda = 0.265$ which is slightly smaller than that of Fig. 4(b), and the coupling mode at $a/\lambda = 0.24$ is split a little. The corresponding map of field distribution is depicted in Fig. 5(c). Obviously, the field is localized at two separate region which are symmetrical with respect to x axis and each localized region has a hexagonal symmetry. Furthermore, we find that the field intensity of each localized region is contrary to that of Fig. 4(c), for example, the field intensity at the center of the defect in Fig. 4(c) is the biggest in the whole region, whereas at the centers of the separate localized region in Fig. 5(c) is the smallest.

In order to observe the relation of the coupling of two defect modes and the configuration and structure parameters, we set up two adjacent defects oriented perpendicular to the incident signal, i.e., along the x axis. In this model, the diameters of the two air holes forming the defects are set to $0.6a$ and those of the other air holes are set to $0.3a$ (Fig. 6(a)). Three peaks come out in transmission spectrum (Fig. 6(b)) with the basic mode at $a/\lambda = 0.26$ and two coupling modes at $a/\lambda = 0.22$ and $a/\lambda = 0.233$, respectively. Compared with Figs. 4 and 5, the width of band gap becomes smaller. Only two defect modes with eigenfrequency at $a/\lambda = 0.233$

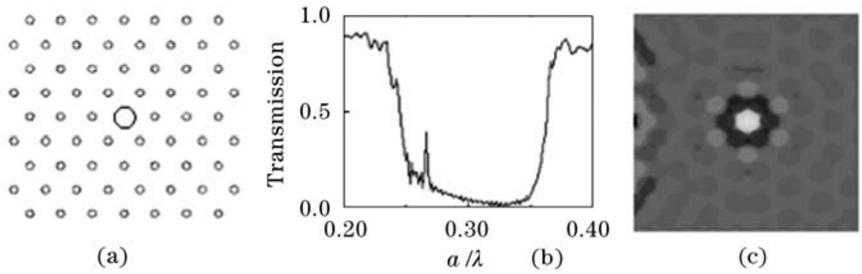

Fig. 3. (a) The center air hole with diameter of $0.55a$ form a defect; (b) transmission spectrum; (c) the field distribution for the eigenfrequency of the defect mode at $a/\lambda = 0.267$.

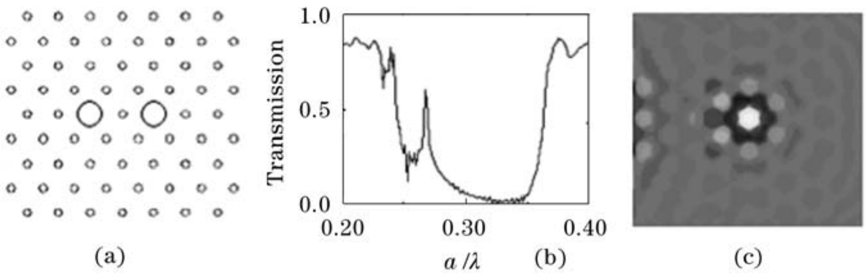

Fig. 4. (a) Two adjacent air holes with diameter of $0.55a$ along the y axis form two defects; (b) transmission spectrum; (c) the field distribution for the eigenfrequency of the defect mode at $a/\lambda = 0.268$.

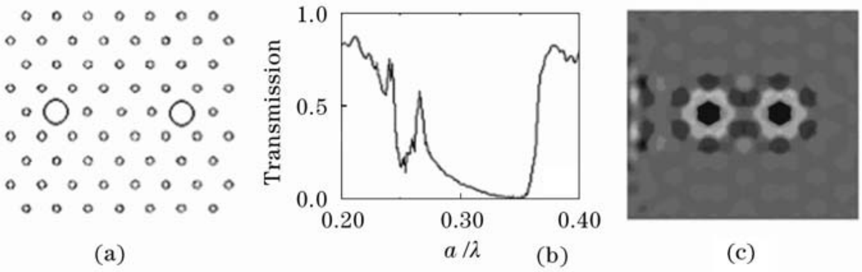

Fig. 5. (a) Two adjacent air holes with diameter of $0.55a$ along the y axis form two defects; (b) transmission spectrum; (c) the field distribution for the eigenfrequency of the defect mode at $a/\lambda = 0.265$.

and $a/\lambda = 0.26$ result in obviously localization. For the eigenfrequency at $a/\lambda = 0.233$, the field distribution is symmetrical with respect to y axis and around the center of the two defects, moreover, the symmetrical parts with respect to y axis alternate with the time increasing (Fig. 6(c)). On the other hand, For the eigenfrequency at $a/\lambda = 0.26$, the field distribution is symmetrical with respect to both x axis and y axis and around the center of the two defects, and keeps constant up to enough time (Fig. 6(d)).

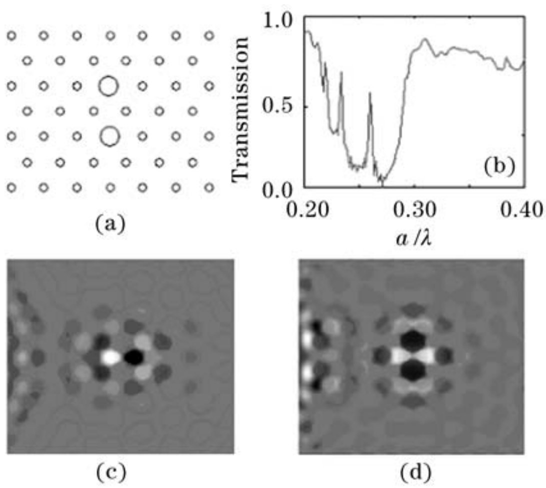

Fig. 6. (a) Two adjacent air holes with diameter of $0.6a$ along the x axis form two defects and the other air holes with diameter of $0.3a$; (b) transmission spectrum; (c), (d) the field distributions for the eigenfrequency of the defect modes at $a/\lambda = 0.233$ (c) and $a/\lambda = 0.26$ (d), respectively.

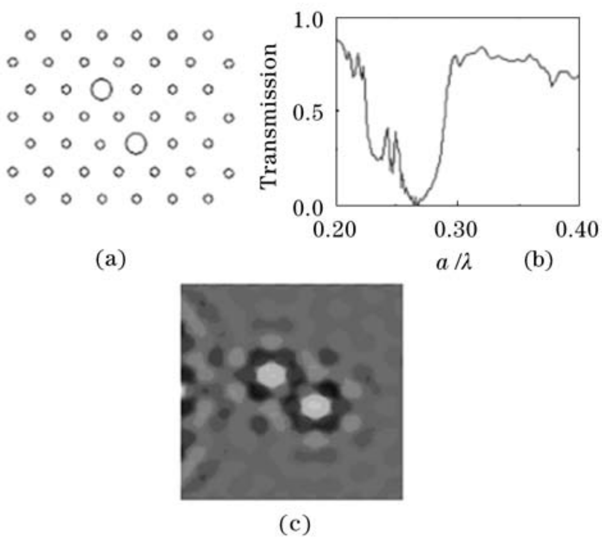

Fig. 7. (a) Two adjacent defects at 45° from the x and y axes; (b) transmission spectrum; (c) the field distribution for the eigenfrequency of the defect mode at $a/\lambda = 0.243$.

Figure 7 is associated with two adjacent defects that are at 45° from the x and y axes and the other structure parameters is the same as Fig. 6. Two adjacent peaks come out in the transmission spectrum with the basic mode at $a/\lambda = 0.255$ and a coupling mode at $a/\lambda = 0.243$, respectively (Fig. 7(b)). In this case, the frequency of the basic mode becomes a little smaller than the former. The localized field distribution for eigenfrequency at $a/\lambda = 0.243$ is also found to have two separate regions which have the same symmetry as the position of the two defects, i.e., 45° off the x and y axes (Fig. 7(c)). For the basic mode, we do not find the field localization. From above results, we find that only the coupling modes are easily influenced by the configuration of defects.

In summary, the FDTD calculation of the transmission spectrum and localized field distribution of optical waves through a PCF containing one or two coupled defects emphasizes the sensitivity to the geometrical and physical parameters of the structure, as well as to the relative position of the two defects. The understanding of the behavior of these localized modes is important to perform and interpret optical experiments in PCF structures.

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References

1. Y. T. Fang, T. G. Shen, and X. L. Tan, Acta Opt. Sin. (in Chinese) **24,** 1557 (2004).
2. B. Qin, C. J. Jin, and R. H. Qin, Acta Opt. Sin. (in Chinese) **19,** 239 (1999).
3. Y. Fang, T. Shen, and X. Tan, Phys. Stat. Sol. B **241,** 818 (2004).
4. Y. Chen, Superlattices and Microstructures **22,** 115 (1997).
5. T. F. Krauss and R. M. De La Rue, Progress in Quantum Electronics **23,** 51 (1999).
6. H. Wang and Y. P. Li, Acta Phys. Sin. (in Chinese) **50,** 2172 (2001).
7. A. Khelif, B. Djafari-Rouhani, V. Laude, and M. Solal, J. Appl. Phys. **94,** 7944 (2003).
8. M. Qiu and S. He, Phys. Rev. B **61,** 12871 (2000).
9. H.-Y. Ryu, M. Notomi, and Y.-H. Lee, Phys. Rev. B **68,** 045209 (2003).
10. J.-L. Vay, Journal of Computational Physics **167,** 72 (2001).