Effect of multi-point defects on the bandgap and defect mode of two-dimensional photonic crystal

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Bandgap and defect mode are important properties of two-dimensional (2D) photonic crystal, which determine the application of photonic crystal. At present, researchers have done a large amount of studying on point defect and line defect photonic crystal. In this paper, we introduce multi-point defects into 2D photonic crystal by removing medium rods (InGaAsP), and then simulate their bandgap and mode field using plane wave method (PWM). The simulation results are useful to design the multi-wavelength photonic crystal laser.

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Photonic crystal is a kind of material with unique periodic structure, and this structure can form photonic bandgap that will prohibit the transmition of electromagnetic wave. This means that the electromagnetic wave in certain frequency range can not spread in this kind of photonic crystal[1−3]. But, if the periodicity is destroyed at some places, namely introducing defects into the periodic structure, defect modes with certain frequency will appear in the bandgap, and these defect modes can be well confined in or near the defects. This kind of characteristics of photonic crystal, such as photonic cavity and photonic waveguide is widely used[4−6].

At present, researchers have done a large amount of research to point defect and line defect photonic crystal[7−9]. In this paper, we introduce multi-point defects into two-dimensional (2D) photonic crystal by removing medium rods (InGaAsP). Figure 1(a) is the central defect structure, Fig. 1(b) is the central defect combined with four symmetrical defects structure. In this paper, we have introduced the concept of supercell into the plane wave method (PWM). We analyze the influence of multi-point defects on transerse magnetic (TM) wave's bandgap and defect mode, and then carry out the numerical simulation. The result indicates, the more the defects introduced, the wider the width of bandgap, and the boundary frequency of bandgap will move to high frequency.

While calculating the bandgap of photonic crystal, we deal with the TM and transverse electric (TE) waves respectively; which propagate in photonic crystal and follow

$$\nabla \times \frac{1}{\varepsilon(\vec{r})} \nabla \times \vec{H}(\vec{r}) = \left(\frac{\omega}{c}\right)^2 \vec{H}(\vec{r}), \tag{1}$$

$$\frac{1}{\varepsilon(\vec{r})} \times \nabla \times \nabla \times \vec{E}(\vec{r}) = \left(\frac{\omega}{c}\right)^2 \vec{E}(\vec{r}), \tag{2}$$

where $\varepsilon(\vec{r})$ represents periodic dielectric constant. Equation (1) describes the propagation equation of magnetic field, in other words, it is for the TE wave. Equation (2) describes the electric field, and it is for the TM wave. Because $\varepsilon(\vec{r})$ is periodic function for ordinate $\vec{r}$, $E(\vec{r})$, and $H(\vec{r})$ are the periodic function for ordinate $\vec{r}$, too. They can be expanded in Fourier series according to Bloch's theorem. This Fourier expansion leads to the following eigenfunctions[11],

$$\sum_{G'} K(\vec{G}-\vec{G}')(\vec{k}+\vec{G})(\vec{k}+\vec{G}')H_{z,kn}(\vec{G}') = (\frac{\omega_{kn}}{c})^2 H_{z,kn}(\vec{G}), \tag{3}$$

$$\sum_{G'} K|\vec{G}-\vec{G}'|^2 E_{z,kn}(\vec{G}') = (\frac{\omega_{kn}}{c})^2 E_{z,kn}(\vec{G}), \tag{4}$$

where $K(\vec{G})$ is the expansion coefficient of $1/\varepsilon(\vec{r})$ in reciprocal lattice space, and $\vec{G}$ donates the reciprocal lattice vector. $\vec{k}$ is the wave vector in the first Brillouin zone. When we solve this two eigenfunctions using (PWM), first giving a wave vector $\vec{k}$, then choosing the reciprocal lattice vector $\{\vec{G}\}$, thus we can obtain a series eigenvalues for a given $\vec{k}$. If calculating a series of $\vec{k}$,

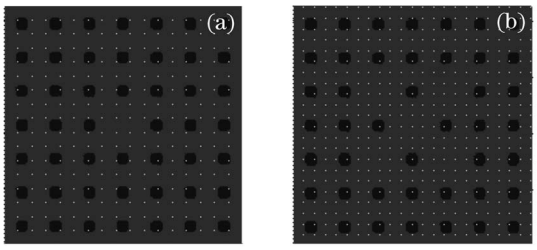

Fig. 1. 2D photonic crystal structure with central defect (a); and five defects (b).

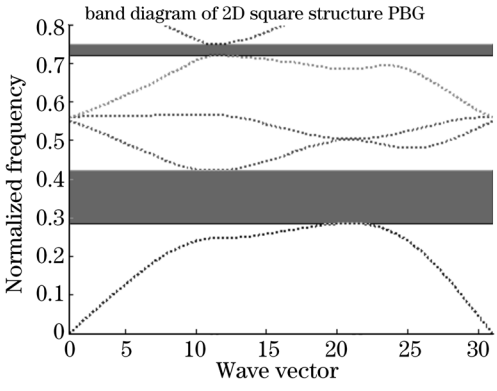

Fig. 2. The bandgap structure of TM wave without defect.

we can obtain the eigenvalues for every $\vec{k}$, and then get the bandgap structure. In this paper, the calculated zone is 7×7 cells, and the number of plane wave is 1089.

While calculating are as follow, the dielectric constant of the rod is 11.56, and the radius of rod is $r = 0.2a$, a is the lattice constant. The bandgap structure of TM wave before introducing the defect is shown as Fig. 2. We can see that there is a wide bandgap in the normalized frequency 0.2856–0.4207, and the unit of the normalized frequency is $\omega a/2\pi c$. In this bandgap, the light can not spread in the photonic crystal.

Now we introduce point defect into the deal structure by removing a central rod. The structure is shown as Fig. 1(a). Through the calculation, we can get that the boundary of bandgap is 0.2857–0.4289. Comparing with the deal bandgap, the boundary frequency has moved to high frequency and the width of bandgap has become wider to some extent. The more important is that a defect mode whose normalized frequency is 0.3793 has appeared, and the field of this frequency can be well confined in the central defect, as shown in Fig. 3.

Then we introduce a central defect and four symmetrical defects (see Fig. 1(b)). We can see from the calculation that the bandgap is 0.2839–0.4311whose width is wider than the above, and five defect modes have appeared whose normalized frequencies are 0.3611, 0.3795, 0.3802(1), 0.3802(2), 0.3964 respectively, among them, the modes 0.3802(1) and 0.3802(2) have different mode symmetry, and they can be confined in or near the defects too. The bandgap and field distribution is shown as Fig. 4.

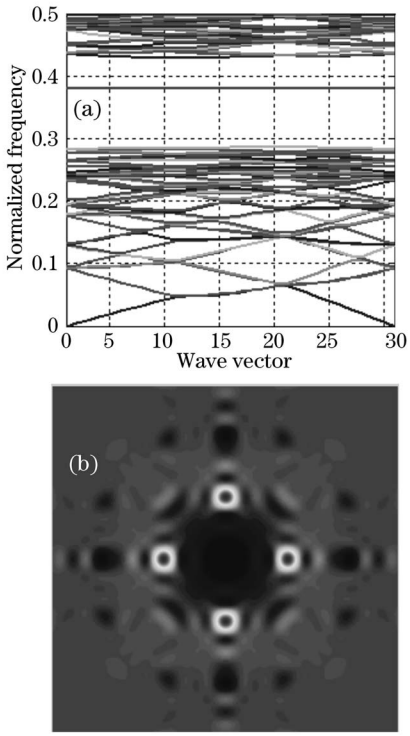

Fig. 3. (a) Bandgap of central defect structure; (b) the field of the central defect mode.

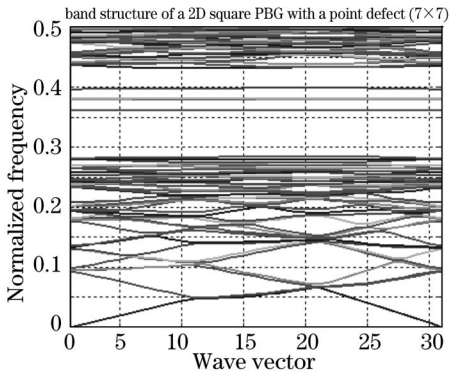

Fig. 4. Bandgaps of five defect structures.

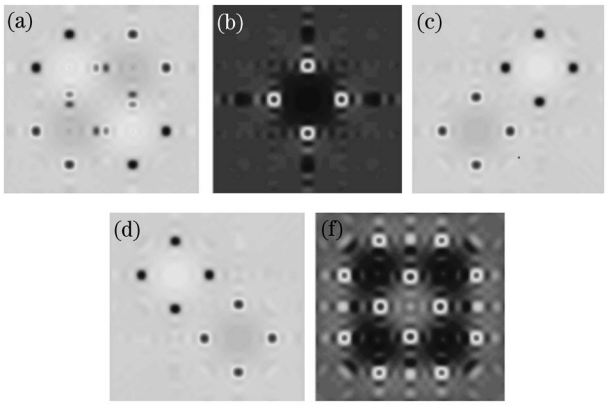

Fig. 5. The fileds of five defect modes with the frequencies of 0.3611 (a), 0.3795 (b), 0.3802(1) (c), 0.3802(2) (d), and 0.3904 (e).

Comparing the two kinds of different defect structures, we conclude that the defect frequency that exist in the central defect still exists in the bandgap of five defects structure, just the frequencies of defect modes have increased, and this is the result of the interaction between the center defect and four symmetrical defects. Because the 2D photonic crystal with central defect can be used for making cavity, but through introducing four symmetrical defects around the central defect, and some new defect frequencies have appeared near the central frequency. The interval of defect frequencies are very small, which are 0.0184, 0.007, 0.0162, respectively. These data are good reference to the mode stability of photonic crystal cavity.

In this paper, we introduce multi-point defects into 2D photonic crystal, and then simulate their bandgap and defect mode field using PWM. The result indicates, the more the defects introduced , the wider the width of bandgap, and the boundary frequency of bandgap will move to high frequency. When four symmetrical defects are introduced around the central defect structure, some new defect frequencies with very small interval have appeared near the central frequency. The fields of this defect modes can be well confined in the defects. The simulation results are useful to design the multi-wavelength photonic crystal laser.

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