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Properties of defect modes in one-dimensional symmetric defective photonic crystals

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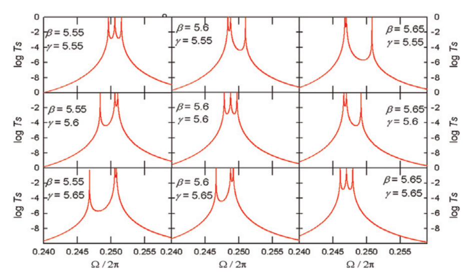
HIGHLIGHTS

- Defect modes in three model structures of defective photonic crystals are analyzed.
- The positions and number of defect modes are strongly dependent on thickness of defect layer.
- With the multiple defect modes, the structures can be used as multi-channel filters.

GRAPHICAL ABSTRACT



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ABSTRACT

We theoretically investigate the properties of defect modes in one-dimensional symmetric defective photonic crystals. We consider three defective photonic crystal structures, air/$[(AB)^{Ns}A^{\alpha}(BA)^{Ns}]^{Np}$/air, air/$[(AB)^{Ns}AB^{\beta}A(BA)^{Ns}]^{Np}$/air, and air/$\{[(AB)^{Ns}AB^{\beta}A(BA)^{Ns}]B^{\gamma}\}^{Np-1}[(AB)^{Ns}AB^{\beta}A(BA)^{Ns}]$/air, where A and B are respectively taken to be the high- and low-index dielectric materials. The first has a defect layer of A^{α}, the second has a composite defect, $AB^{\beta}A$, and the third has a interleaving defect B^{γ}. The effect of thickness on the defect mode is studied by varying the parameters α, β, and γ, respectively, for the above model structures. It is found that the positions and the number of defect modes can be significantly changed due to the change in the defect thickness. In addition, by increasing the repeated number N_p, we can have multiple defect modes, leading to a possible design of tunable multichannel filter.

1. Introduction

Photonic crystals (PCs), artificially periodic multilayer structures, are known to possess photonic band gaps (PBGs) within which the propagation of an electromagnetic wave is forbidden [1–3]. PBGs, which arise from the structurally periodic property, are analogous to the electronic band gaps (EBGs) in solids because the potential energy seen by electrons is also periodic in space. Research topics on PCs, including fundamental issues and novel systems for photonic applications, have been of much interest to the communities of optics, photonics, material science, and condensed matter physics. In addition to the periodic structures, PBGs can also be found in quasiperiodic structures. For example, non-periodic multilayers such as one-dimensional (1D) triadic Cantor sets (TCSs) can also possess PBGs [4–9].

Another fundamental issue related to the PBG is the existence of defect modes within the PBG. The defect modes are generally to be generated when the translational symmetry in a PC is broken. This can be done by inserting a defect layer into the PC or removing a single layer from the structure [10–14]. The defect layer, in principle, acts as a cavity such that the resonant tunneling mode can exist in the PBG. The tunneling mode is best understood by the

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presence of sharp peak in the transmission spectrum. Similarly, defect modes may also be generated for an aperiodic TCS containing a defect layer [15,16]. Moreover, recently, it is shown that there also exist defect modes within the PBG in a cascading system with a building block of TCS [17].

The presence of defect modes within the PBG is strongly dependent on the considered PC structure, including the material as well as the thickness of defect layer. Thus, to explore the relationship between the defect modes and the PC structure is an important and fundamental issue. Furthermore, the knowledge of properties of defect modes will be informative to the design of a PC-based transmission narrowband filter.

The purpose of this paper is to give a numerical study on the properties of defect modes in 1D symmetric defective dielectric PCs. We shall consider three defective PCs which are mirror-symmetric with respect to the defect. The first structure containing a single defect layer is air/$[(AB)^{Ns}A^{\alpha}(BA)^{Ns}]^{Np}$/air, where the defect layer is A^{α}. The second with a composite defect is denoted as air/$[(AB)^{Ns}AB^{\beta}A(BA)^{Ns}]^{Np}$/air, where the composite defect is $AB^{\beta}A$ and the third is a modified structure of the second with an interleaving layer B^{γ}, i.e., the structure is air/$\{[(AB)^{Ns}AB^{\beta}A(BA)^{Ns}]B^{\gamma}\}^{Np-1}[(AB)^{Ns}AB^{\beta}A(BA)^{Ns}]$/air. Here, layers A, B are assumed to be nonmagnetic dielectric media and their refractive indices and thicknesses are denoted by n_a, n_b, and L_a, L_b, respectively. α, β, and γ are three controlling parameters used to modify the thicknesses of defects in the above three model structures, respectively. For example, $\alpha=1/3$ means that the thickness of A^{α} is $L_a/3$ where L_a is the thickness of layer A. $N_s=0$, 1, 2, …, is the stack number of the mirrors AB and BA, and $N_p=1$, 2, …, is the repeated number of PC structure. In the analysis that follows we shall employ the transmittance spectra to investigate the properties of defect modes for the above three structures. The transmittance spectra will be calculated by the transfer matrix method (TMM) [18].

2. Theoretical method

According to the TMM, the transmission coefficient for a multilayer system is determined by the total transfer matrix and is expressed as [18].

$$t = \frac{1}{m_{11}}, \tag{1}$$

where m_{11} is one of the elements of the total transfer matrix **M** given by

$$\mathbf{M} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \mathbf{D}_0^{-1}\left(\prod_{j=1}^{N}\mathbf{D}_j\mathbf{P}_j\mathbf{D}_j^{-1}\right)\mathbf{D}_S. \tag{2}$$

Eq. (2) is expressed for an N-layer system with a starting (input) medium 0 and a substrate (output) of medium S. In layer j with a thickness of L_j, there is a translational matrix, namely

$$\mathbf{P}_j = \begin{pmatrix} e^{ik_{jx}L_j} & 0 \\ 0 & e^{-ik_{jx}L_j} \end{pmatrix}, \tag{3}$$

where the wave propagation is taken to be along $+x$ direction and the corresponding wavenumber is

$$k_{jx} = \frac{\omega}{c} n_j \cos\theta_j, \tag{4}$$

where n_j and θ_j are respectively the refractive index and the ray angle of layer j, c is the speed of light in vacuum, and ω is the wave frequency. In addition, in Eq. (2) there is a dynamical matrix for every single medium in the system, i.e.,

$$\mathbf{D}_j = \begin{pmatrix} 1 & 1 \\ n_j\cos\theta_j & -n_j\cos\theta_j \end{pmatrix}, \tag{5}$$

for the TE wave, and

$$\mathbf{D}_j = \begin{pmatrix} \cos\theta_j & \cos\theta_j \\ n_j & -n_j \end{pmatrix}, \tag{6}$$

for the TM wave, respectively. The transmittance is thus given by

$$T = \frac{n_s\cos\theta_s}{n_0\cos\theta_0} t^* t. \tag{7}$$

For normal incidence, the ray angle in every single medium is set to be zero.

3. Numerical results and discussion

In the following calculations, we shall set $n_a=3.6$, $n_b=1.5$, $L_a=0.29\Lambda$, $L_b=0.71\Lambda$, respectively, where $\Lambda=L_a+L_b$ [17]. In addition, we use the dimensionless frequency $\Omega=\omega\Lambda/c$ in the frequency domain for our numerical results.

3.1. Effects of α and β at $N_p=1$

In the beginning, we would like to investigate how the defect mode can be influenced by the thickness of the defect layer. For the structure with a single defect layer, air/$[(AB)^{Ns}A^{\alpha}(BA)^{Ns}]^{Np}$/air, the defect layer is a high-index medium. In Fig. 1(a), we plot the transmittance spectra at $N_p=1$ and $N_s=3$ for different values in $\alpha=0$, 1/3, 2/3, 1, 4/3, 5/3, and 2, respectively. It can be seen from the figures that the transmittance spectra are changed at a different value of α, i.e., different thickness of the central defect layer. At $\alpha=0$, we see that there is a defect mode which locates near the center of the PBG. The presence of a single defect mode is because that structure, in this case, is $(AB)^{Ns}(BA)^{Ns}$, which is equal to a PC containing a defect layer, i.e., $(AB)^{Ns}/B/(AB)^{Ns-1}A$. At $\alpha=1/3$ and 2/3, the defect mode is then red-shifted. At $\alpha=1$, the defect mode disappears and a clear PBG is obtained. This result is clear because the structure at $\alpha=1$ is equivalent to $(AB)^{Ns-1}A$ which is effectively a pure PC. At $\alpha=4/3$ and 5/3, the defect mode at $\alpha=0$ is then blue-shifted. In addition, the defect modes at $\alpha=1/3$ and 4/3 are symmetric about the center of PBG. Similar behavior is seen for $\alpha=2/3$ and 5/3. At $\alpha=2$, the defect mode reappears and the same as that at $\alpha=0$. Conclusively, to have a defect mode, the value of α must be taken to be an even number in addition to zero. If α is an odd number, we will have no defects inside the PBG. Finally, if α is a fractional number, the defect mode will be red-shifted or blue-shifted, depending on the value of α.

To further investigate how the incident angle affects the defect position, we have taken $\alpha=0$ for purpose of illustration and the results are shown in Fig. 1(b), in which the results of TM and TE waves are plotted in blue and red, respectively. It can be seen from the figure that the defect mode in TM-wave is blue-shifted as the angle of incidence increases. As for the TE wave, the defect mode is also blue-shifted as a function of the angle of incidence. However, it will be red-shifted at a large angle, as can be seen at 60° and 75°.

Next, we consider the structure with a composite defect, air/$(AB)^3AB^{\beta}A(BA)^3$/air which has a variable thickness in the low-index medium of B. Fig. 2(a) shows the transmittance spectra at different values of β. At $\beta=0$, the structure reduces to that in Fig. 1 with $\alpha=2$ and there is a defect mode. When β increases to 1/3 and 2/3, the defect mode is red-shifted. The defect mode then disappears at $\beta=1$. The defect mode reappears at $\beta=2$. Importantly, the overall behaviors in Fig. 2 are similar to those in Fig. 1, meaning that the role played by A in single defect structure is the