Twin defect modes in one-dimensional photonic crystals with a single-negative material defect


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State Key Laboratory of Optronics and Technologies, Zhongshan (Sun Yat-Sen) University, Guangzhou 510275, China

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Twin defect modes are found in one-dimensional photonic crystals stacking with single-negative-permittivity and single-negative-permeability media layers and a single-negative defect. The frequency interval of the two defect modes can be changed by varying the thickness of the defect layer or the thickness ratio of the two stacking layers. Conditions for the emergence of such twin defect modes only relate to the phase thicknesses of the defect layer and the two stacking layers. In addition, the electric fields at the frequencies of the defect modes are strongly localized at the interfaces between the defect layer and its adjacent layers. © 2006 American Institute of Physics. [DOI: 10.1063/1.2357600]

Since the initial prediction of Yablonovitch and John, photonic crystals (PCs) have attracted a great deal of interest for their unique electromagnetic properties and potential applications in optoelectronics and optical communications. One-dimensional (1D) PCs with defect layers have been used for filters that have narrow passbands. By changing the size of the defect layers, filters that have narrow passbands have been used for filters that have narrow passbands. However, in such PC structures consisting of positive-index materials with both positive permittivity and permeability, the localized modes will just move from a higher passband to a lower passband by increasing the thickness of the defect. Furthermore, the frequencies of the transmission peaks will blueshift as the incident angle increases. So the applications of the defect modes are restricted.

Recently, it was shown that a type of photonic band gap (PBG) with zero effective phase (denoted as zero-ε_eff gap) will appear in a 1D photonic crystal containing two kinds of single-negative (SNG) metamaterials. The two types of SNG materials include the mu-negative (MNG) media with negative permeability (μ) and the epsilon-negative (ENG) media with negative ε but positive μ. Such materials have attracted great interest recently. The zero-ε_eff gap comes from the interaction of evanescent waves in SNG materials, i.e., it originates from tunneling mechanism instead of Bragg scattering. The zero-ε_eff gap has many properties that are distinct from those of the Bragg gap. The properties of the defect modes inside the zero-ε_eff gap are expected to be evidently different from those inside the Bragg gap.

In this letter, a SNG defect layer is introduced into a 1D PC stacked with alternative layers of MNG and ENG materials. Twin defect modes are found in the zero-ε_eff gap of the PC. The properties of such twin defect modes will lead to potential applications.

Consider a 1D PC consisting of alternating layers of MNG material and ENG material. We use a transmission-line model to describe the isotropic single-negative materials, that is,

\[ e_1 = e_a, \quad \mu_1 = \mu_a = \frac{\omega_p^2}{\omega^2}, \quad (1) \]

in MNG materials and

\[ e_2 = e_b = \frac{\omega_p^2}{\omega^2}, \quad \mu_2 = \mu_b \quad (2) \]

in ENG materials, where \( \omega_p \) and \( \omega_m \) are, respectively, the magnetic plasma frequency and the electronic plasma frequency. These kinds of dispersion for μ and ε may be realized in special microstrips. In Eqs. (1) and (2), \( \omega \) is the angular frequency measured in gigahertz. In the following calculation, we choose \( \mu_a = e_b = 1 \), \( e_a = \mu_b = 3 \), and \( \omega_m = \omega_p = 10 \text{ GHz} \). The thicknesses of the MNG and ENG slabs are assumed to be \( d_1 \) and \( d_2 \), respectively.

Let a monochromatic plane wave, either a transverse electric (TE) or a transverse magnetic (TM) wave, be incident (along the z direction) from vacuum onto the considered structure. Suppose the plane wave in the \( nth \) layer has a wave vector \( k_0 = k_{zz} + k_{xz} \), whose magnitude is \( \omega_m / c \) (where \( c \) is the speed of light in vacuum). The amplitudes of the forward and the backward wave of the electric component can be related via a transfer matrix

\[ M_i = \begin{pmatrix} \cos klz & i & \sin klz \end{pmatrix} \begin{pmatrix} \sin klz & \eta_i & \cos klz \end{pmatrix}, \quad (3) \]

where \( \eta_i = \eta = \cos klz / \omega \mu_i \) for TE wave and \( \eta_i = \eta_T = \omega e_i / ck_{zz} \) for TM wave. For a perfect 1D PC, the periodic structure can be regarded as a superlattice, and the dispersion relation of the PC can be obtained by using the Bloch-Floquet theorem

\[ \cos(KB \Lambda) = \frac{1}{2} \mathrm{Tr}(M_1 M_2) = \xi_1^{12} - \eta_1^{12} \xi_1^{12}, \quad (4) \]

where \( K_B \) is the Bloch wave vector, \( \Lambda = d_1 + d_2 \), \( \xi_1^{12} = \cos k_{zz} d_1 \cos k_{zz} d_2 + \sin k_{zz} d_1 \sin k_{zz} d_2 \), and \( \eta_1^{12} = (\eta_1/\eta_2 + \eta_2/\eta_1)/2 \) (\( \alpha, \beta = 1, 2 \), where 1 and 2 denote MNG and ENG layers, respectively). Solutions of the infinite system can be propagating or evanescent, corresponding to real or imaginary Bloch wave numbers, respectively.
A structural defect is sandwiched within two symmetric semi-infinite superlattices to compose systems with the form of $N_{\mu}N_{\nu}N_{\mu}N_{\nu}, \ldots, N_{N}N_{\nu}N_{\mu}N_{\nu}$ and $N_{N_{\mu}}N_{\nu}N_{\mu}N_{\nu}, \ldots, N_{N}N_{\mu}N_{\nu}N_{\mu}$, where $N_{\mu}(N_{\nu})$ represents a layer of MNG (ENG) material and $D$ represents a defect layer with a geometrical thickness of $d_D$. Equation (4) is still effective, and the Bloch wave number of the defect states should take a complex value in the form as $K_{B}=N\pi/\Lambda + iq$ (where $q>0$, $N$ is an integer).

After some algebra calculation, we obtain the equations for determining the structural defect states as

$$(-1)^N\cosh(q\Lambda) = \xi^{12} - \eta_{12}^{12}\xi^{12}$$  \hspace{1cm} (5)

$$\sinh(q\Lambda) = \frac{(\eta_{12}^{12}\psi_1^2)(\eta_{12}^{12}\psi_2^2+\eta_{12}^{12}\psi_2^2)-\eta_{12}^{12}\eta_{12}^{12}\xi^{12}}{(-1)^N(\xi^{12} - \eta_{12}^{12}\xi^{12})}.\hspace{1cm} (6)$$

By using Eqs. (5) and (6), the properties of the defect modes inside the zero-$\varphi_{\text{eff}}$ gap are investigated. We now consider an infinite PC structure of $(N_{\mu}N_{\nu})^2D_{\mu}(N_{\mu}N_{\nu})^2$ (system A), where $D_{\mu}$ represents a defect layer of MNG material, $s \to \infty$. We choose the parameters $\varepsilon_{\mu} = \varepsilon_1$, $\mu_{\mu} = \mu_1$. Firstly, we fix the thicknesses of the MNG layer ($d_1$) and the defect layer ($d_D$) and study the dependence of the zero-$\varphi_{\text{eff}}$ gap and the defect modes on the ratio of the thicknesses of the two periodic stacking layers ($d_D/d_1$) at normal incidence. In Fig. 1, we select $d_1 = 6\text{ mm}$ and $d_D = 24\text{ mm}$. The gray areas represent the regions of propagating states, whereas the white areas represent regions containing evanescent states. The circles represent the defect modes. It can be seen from Fig. 1 that as $d_D/d_1$ varies, the width of the forbidden gap varies. The zero-$\varphi_{\text{eff}}$ gap will be closed when $d_D/d_1 = 1$. This phenomenon can be understood from a phase-match condition of the MNG-ENG multilayered periodic structures. Moreover, as shown in Fig. 1, twin defect modes exist at situations when $d_D/d_1 > 1$. The two defect modes appear near the mid-frequency of the PBG when $d_D/d_1$ is larger than 1, and they deviate from each other as $d_D/d_1$ increases. However, when $d_D/d_1 < 1$, there is no defect mode exists at all as $d_D/d_1$ varies. The emergence of such phenomenon can be understood as follows. For situations when $d_D/d_1 > 1$, the difference between the effective phase thicknesses of the two periodic layers is $\Delta \varphi = \varphi_{N_{\mu}} - \varphi_{N_{\nu}} = |n_1|d_1 - |n_2|d_2 > 0$. When a MNG defect ($n_D = n_1$) with a thickness $d_D > d_1$ is introduced, the difference between the effective phase thicknesses of the defect layer and the MNG layer is $\Delta \varphi' = \varphi_{D_{\mu}} - \varphi_{N_{\mu}} = |n_{D_{\mu}}|d_{D_{\mu}} - |n_1|d_1 > 0$, which tends to diminish $|\Delta \varphi|$, and then, the twin defect modes appear. However, for situations when $d_D/d_1 < 1$, it can be obtained that $|\Delta \varphi| > 0$ and $|\Delta \varphi'| > 0$, so $\Delta \varphi'$ tends to enlarge $\Delta \varphi$, and there is no propagation mode exists.

Next, we study the dependence of the defect modes inside the zero-$\varphi_{\text{eff}}$ gap on $d_D$ when $d_1$ and $d_2$ are fixed. In Fig. 2, we select $d_1 = 6\text{ mm}$ and $d_2 = 12\text{ mm}$. As shown in Fig. 2, the phenomenon of the twin defect modes also exists. When $d_D$ exceeds 6 mm, the two defect modes are pulled out from the upper and lower passbands, respectively. Then the defect modes shift to the middle of the band gap, gradually, as $d_D$ increases. The frequency interval between the two defect modes becomes very small when $d_D$ is greater than 90 mm. However, instead of merging into the other, the two defect modes are located in different regions that are higher and lower than the central frequency of the band gap, respectively. In addition, when $d_D$ is less than $d_1$, the effective phase thickness difference between the defect layer and the MNG layer is $\Delta \varphi' = \varphi_{D_{\mu}} - \varphi_{N_{\mu}} = |n_{D_{\mu}}|d_{D_{\mu}} - |n_1|d_1 < 0$. As $\Delta \varphi = \varphi_{N_{\mu}} - \varphi_{N_{\nu}} < 0$, so $\Delta \varphi'$ tends to enlarge $|\Delta \varphi|$ and no defect mode appears.

Then, we investigate the dependence of the defect mode on the incident angle. The dispersion relation of the PBGs and the defect modes is shown in Fig. 3, in which, we select $d_1 = 6\text{ mm}$, $d_2 = 12\text{ mm}$, and $d_D = 24\text{ mm}$. It can be seen from Fig. 3 that two defect modes appear in the zero-$\varphi_{\text{eff}}$ gap at frequencies about 0.690 and 0.917 GHz, respectively. As shown in Fig. 3, the two defect modes inside the zero-$\varphi_{\text{eff}}$ gap are almost independent of the incident angles and polarizations, in contrast with a defect mode inside the Bragg gap at frequency about 6.5 GHz. The weak incident angle dependence of the defect mode pair inside the zero-$\varphi_{\text{eff}}$ gap may be useful in applications, such as omnidirectional filters with dual transmission channels, whose frequency interval can be varied conveniently by adjusting the structure parameters of the PC.

In order to show how these twin defect modes generate in the zero-$\varphi_{\text{eff}}$ gap, the electric fields in a finite 1D PC structure $(N_{\mu}N_{\nu})^{2}D_{\mu}(N_{\mu}N_{\nu})^{2}$ are also calculated at frequencies of the two defect modes, as shown in Fig. 4. The parameters of the structure are chosen to be the same as those in Fig. 3. One can discover that the fields are strongly localized at the interfaces between the defect layer and its adjacent layers.
layers, and the fields reach minima at the middle of the defect layer. The characteristics of the field distributions lead to the unique behaviors of the defect modes in the zero-\(\varphi_{\text{eff}}\) gap.

Moreover, we have also studied the properties of the defect modes in structure of \((N_p N_{\mu})^3 D_s(N_{\mu} N_p)^3\) (system B). In our calculation, it is found that when \(d(l)^4 = d(l)^8\) is satisfied in the \(l\)th layer of the two systems (A and B), and the frequency dependence for the SNG materials remain invariant, both the band structures and the defect modes of system A will be the same as those of system B at normal incidence; whereas at oblique incidence, the dispersion relations for both the zero-\(\varphi_{\text{eff}}\) gap and the defect modes of system A in TE polarization are identical with those in system B in TM polarization, and the dispersion relations of system A in TM polarization are the same as those of system B in TE polarization. According to such dispersion relation invariability, the properties of the defect modes of system B can be easily obtained from those of system A. The conditions for the emergence of the twin defect modes in system A or B are shown in Table I.

In conclusion, we showed that twin defect modes exist in the zero-\(\varphi_{\text{eff}}\) gap of the 1D PC stacking of two kinds of SNG materials when a SNG defect layer is introduced. The frequency interval of the two defect modes can be changed by merely adjusting one of the structure parameters, including the thicknesses of the defect layer and the two SNG periodic stacking layers. Conditions for the emergence of such twin defect modes are given by the analysis of the effective phase thickness of the defect layer and the stacking layers. Then, the twin defect modes inside the zero-\(\varphi_{\text{eff}}\) gap are shown to be insensitive to incident angle. Furthermore, we found that the electric fields are strongly localized at the interfaces between the defect layer and its adjacent layers. Such twin defect modes could lead to further applications of the PCs.

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<th>Structures of the PCs</th>
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<th>(\varphi_{\text{Na}} &lt; \varphi_{\text{Ne}})</th>
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<td>(\varphi_{\text{Da}} &gt; \varphi_{\text{Na}})</td>
<td>none exists</td>
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<tr>
<td>((N_p N_{\mu})^3 D_s(N_{\mu} N_p)^3)</td>
<td>(\varphi_{\text{Da}} &lt; \varphi_{\text{Na}})</td>
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<td>(\varphi_{\text{Da}} &gt; \varphi_{\text{Ne}})</td>
<td>exists none</td>
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<tr>
<td>((N_p N_{\mu})^3 D_s(N_{\mu} N_p)^3)</td>
<td>(\varphi_{\text{Da}} &lt; \varphi_{\text{Ne}})</td>
<td>none exists</td>
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FIG. 3. Dependence of the photonic band gaps and the defect modes on the incident angle in infinite structure \((N_p N_{\mu})^3 D_s(N_{\mu} N_p)^3\), with \(d_1=6\) mm, \(d_2=12\) mm, and \(d_0=24\) mm.

FIG. 4. Electric field distributions inside the finite 1D PC of \((N_p N_{\mu})^3 D_s(N_{\mu} N_p)^3\) at resonant frequencies of the two defect modes (a) \(\omega=0.690\) GHz and (b) \(\omega=0.917\) GHz at normal incidence. The parameters are the same as those in Fig. 3. The light gray and white areas correspond to the layers of MNG and ENG materials, respectively.