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Omnidirectional and tunable symmetrical confined states in photonic quantum-well structures with single-negative materials

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ABSTRACT

The symmetrical confined states are found in photonic quantum-well structures with single-negative materials, in which the photonic barrier is based on the zero-effective-phase gap. The number and frequencies of the symmetrical confined states can be tuned by varying the period number and thicknesses of the well photonic crystal, respectively. Furthermore, the symmetrical confined states of the structures are less sensitive to the incident angle and polarization, compared with previous confined states of photonic quantum-well structures based on the Bragg or zero-average-index gap. The structures open a promising way to fabricate symmetrically tunable and omnidirectional multichannel filters for future dense wavelength division multiplexing applications.

1. Introduction

Since photonic crystals (PCs), which are photonic band gap (PBG) materials with periodically modulated dielectric constants, were suggested by Yablonovitch [1] and John [2], photonic quantum well (QW) has been attracting researchers' special interests in optics [3–9]. Similar to the idea of semiconductor QW structures [10,11], one can use different PCs to construct photonic QW structures provided the PBGs of the constituent PCs are aligned properly. Quantized photonic confined states have been observed in conventional QWs with positive-index materials [5–8]. However, in such conventional QW structures based on the Bragg gap, the confined states will just move from a higher passband to a lower passband by increasing the thickness of the well PC. Furthermore, the frequencies of the confined states will blueshift as the incident angle increases. So the applications of the confined states are restricted.

Recently, metamaterials including negative-index materials (NIMs) and single-negative (SNG) materials have been realized [12–16]. Some researchers have presented photonic QW structures containing NIMs with simultaneously negative permittivity and permeability [17]. The photonic barrier of the structures is based on the zero-average-index (zero-$\bar{n}$) gap [18–21] with weak dependance on the incident angle and polarization. Thus, the frequency shift of the confined states is small with the incident angle increasing. Nevertheless, these confined states are not strictly omnidirectional and can only be regard as large-incident-angle filtering.

In this paper, we study theoretically one-dimensional (1D) photonic QW structures containing SNG materials including the mu-negative (MNG) and epsilon-negative (ENG) materials, in which the photonic barrier is based on the zero-effective-phase (zero-φ_{eff}) gap [22–25]. The omnidirectional symmetrical confined states are found in the transmission spectra of the QW structures. The properties of such symmetrical confined states will lead to potential applications.

2. Computational model and mathematical method

In this section, we will first investigate the gap properties of 1D PCs containing SNG materials in order to design 1D photonic QW structures based on the zero-φ_{eff} gap. We use a transmission line model to describe the isotropic SNG materials [19,26] that is,

$$\varepsilon_a = \varepsilon_1, \quad \mu_a = \mu_1 - \frac{\omega_{mp}^2}{\omega^2} \tag{1}$$

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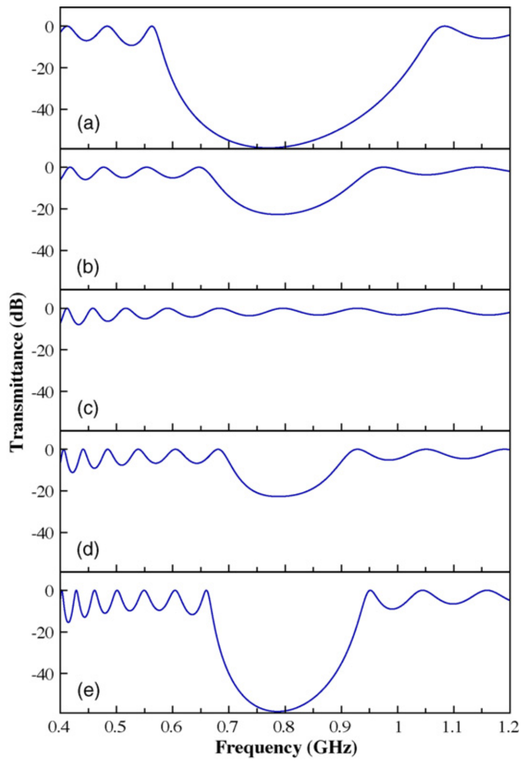

Fig. 1. Dependence of the PBGs of PC $(ab)_{12}$ on the thickness ratio of two SNG materials with d_a = 12 mm but the different thicknesses d_b of layer b (a) 6 mm, (b) 9 mm, (c) 12 mm, (d) 15 mm, and (e) 18 mm, respectively.

in MNG materials and

$$\varepsilon_b = \varepsilon_2 - \frac{\omega_{ep}^2}{\omega^2}, \quad \mu_b = \mu_2 \tag{2}$$

in ENG materials, where ω_{mp} and ω_{ep} are the magnetic plasma frequency and electronic plasma frequency, respectively. In Eqs. (1) and (2), ω is the angular frequency measured in GHz. We consider a situation where μ_a and ε_b are negative, that is to say, in the frequency range of $\omega^2 < (\omega_{mp}^2/\omega^2)$, $\omega^2 < (\omega_{ep}^2/\omega^2)$. we choose $\mu_1 = \varepsilon_2 = 1$, $\varepsilon_1 = \mu_2 = 3$, and $\omega_{ep} = \omega_{mp}$ = 10 GHz. A zero-φ_{eff} gap will be found in 1D PCs constituted by a periodic repetition of MNG and ENG layers with the thickness of d_a and d_b, respectively. In Fig. 1, we show the dependence of the gaps of PC $(ab)_{12}$ on the thickness ratio of two SNG layers d_b/d_a at normal incidence with d_a = 12 mm. It can be seen from Fig. 1 that the zero-φ_{eff} gap can be widened by enlarging the difference between d_a and d_b. However, the zero-φ_{eff} gap is closed with $d_a = d_b$. Such properties of the zero-φ_{eff} gap are useful for designing periodic structures with multiple resonance modes.

Based on the above results, we may propose 1D photonic QW structures described by $(AB)_n(CD)_m(BA)_n$, where $(AB)_n$ and $(CD)_m$ are two different 1D PCs, and $m(n)$ is the period number. Specifically, $A(C)$ and $B(D)$ indicate MNG and ENG materials, respectively. The thicknesses of the layers A, B, C and D are d_A, d_B, d_C and d_D, respectively. In the following calculations, we choose d_A = 12 mm, d_B = 6 mm and $d_C = d_D$ = 12 mm. According to Fig. 1, the zero-φ_{eff} gap exists in $(AB)_n$, but not in $(CD)_m$. Similar to the idea of previous QW structures, $(AB)_n$ plays a role of photonic barrier PC, and $(CD)_m$ can be regarded as a well PC.

We use the transfer-matrix method [19,27] to identify the transmittance spectra of the structures. Let a plane wave be injected from vacuum into the structures containing MNGs and ENGs at an incident angle θ with +z direction. Suppose wave vectors $k(\omega)$ lie in the xz plane. For the TE wave, the electric field E is in the y direction.

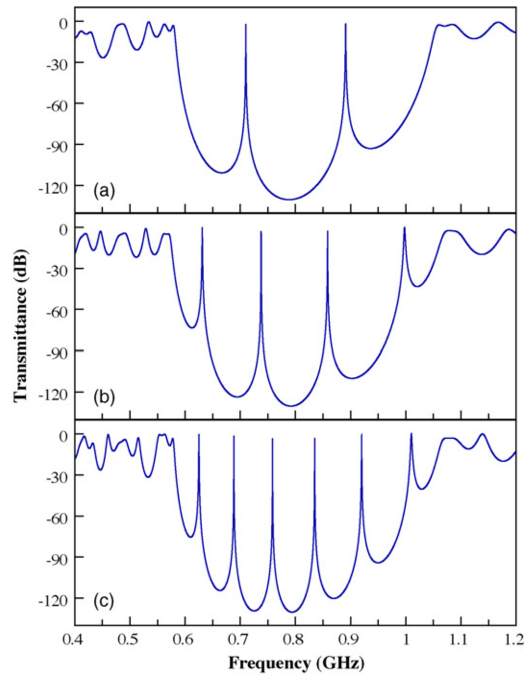

Fig. 2. Transmittance of photonic QWs (a) $(AB)_{12}(CD)_4(BA)_{12}$, (b) $(AB)_{12}(CD)_8(BA)_{12}$ and (c) $(AB)_{12}(CD)_{15}(BA)_{12}$ at normal incidence. The sharp peaks in transmission spectra correspond to the quantized confined photonic states.

The electric component and magnetic component in z and $z + \Delta z$ can be related via a transfer matrix:

$$\begin{pmatrix} \cos(k_z\Delta z) & -i\dfrac{\mu\omega}{k_z c}\sin(k_z\Delta z) \\ -i\dfrac{k_z c}{\mu\omega}\sin(k_z\Delta z) & \cos(k_z\Delta z) \end{pmatrix}, \tag{3}$$

where $k_z = \omega/c\sqrt{\varepsilon}\sqrt{\mu}\sqrt{1-\sin^2\theta/(\varepsilon\mu)}$ is the components of the wave vector along the z axis in the medium, and c is the speed of light in the vacuum. Supposed that the matrix connecting the incident end and exit end is $X_N(\omega)$, the transmission coefficient of the monochromatic plane wave can be written as [27]

$$t(\omega) = \frac{2\cos\theta}{(x_{11}+x_{22})\cos\theta + (x_{12}\cos^2\theta + x_{21})}, \tag{4}$$

where $x_{ij}(i, j = 1, 2)$ are the matrix elements of $X_N(\omega)$. The treatment for a TM wave is similar to that for a TE wave.

3. Numerical results and discussion

We first calculate the transmission spectra of 1D photonic QWs $(AB)_{12}(CD)_m(BA)_{12}$ with different period numbers of the well PC by the transfer-matrix method, as shown in Fig. 2. It can be seen that the confined states in the transmission spectra appear in the frequency region from 0.589 to 1.082 GHz, which corresponds to the zero-φ_{eff} gap. From Fig. 2(a), we can see that two confined states appear at frequencies 0.727 and 0.871 GHz, which are located in each side of central frequency of the band gap, respectively. As the period number of the well PC increases, four and six confined states will emerge inside the zero-φ_{eff} gap, as shown in Fig. 2(b) and (c). Such a phenomenon can be explained as follows. It is demonstrated that the zero-φ_{eff} gap of $(AB)_{12}$ corresponds to the phase mismatch ($k_Ad_A \neq k_Bd_B$) [22]. As the well PC $(CD)_4$ being inserted, the phase thickness of $(CD)_4$ can compensate the phase difference ($k_Ad_A - k_Bd_B$) partially, so that the phase-match condition of the whole structure can be satisfied at two symmetric frequencies that are lower and higher than central frequency of the zero-φ_{eff} gap