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Resonant photonic states of quasi one-dimensional photonic quantum well in a rectangular waveguide

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Abstract. We have demonstrated a calculation of the resonant photonic states of quasi one dimensional photonic quantum well for the transverse electric (TE) and transverse magnetic (TM) modes in a rectangular waveguide. The photonic crystal heterostuctures are composed of two different photonic crystals as $(AB)^m(CD)^n(AB)^m$. In order to solve the resonant photonic states, it is necessary to calculate the transmission functions of TE modes and TM modes. In this work, we consider the propagation of microwaves in photonic crystal heterostructures in our simulation model. The positions and number of the resonant photonic states can be adjusted by the widths of photonic quantum wells. The degenerate resonant photonic states are not existed for both the TE and TM modes, respectively. These results are useful applications in photonic quantum devices and nano technologies.

1. Introduction

Photonic crystals (PCs) are typically novel artificial materials and periodic structures. The propagation of electromagnetic waves can be manipulated and controlled in periodic media and exhibit many interesting phenomena [1-2]. Since the 1980s, the photonic band gaps (PBGs) have been studied with much attention, a range of frequencies (optical modes) for which are forbidden. The photonic band gap gives rise to a lot of useful properties, including frequency-selective mirrors, resonators, band-pass filter, the localization of light at the defects [1], suppression of spontaneous emission [3-4], and etc. In addition, the photonic band-gap materials have been studied intensively by many groups theoretically [1-2] and experimentally [5]. Therefore, the periodic dielectric structures for PBGs materials can be designed and fabricated to provide a desired the frequencies of electromagnetic waves are crucial.

PCs are composed of periodic media, in the same as the periodic potentials in an electronic crystal. For better understanding the photonic band structures have been calculated and based on the Maxwell's equations [1-2, 6-7]. The structures of that combined with two or more PCs into a single crystal, namely photonic crystal heterostructures, have been a number of studies [8-12]. Photonic crystal heterostructures are similar to the electrons in semiconductor quantum well structures. When the barriers are thin enough, the electron wave functions in the neighboring wells would be overlapped in multiple quantum wells. Eventually, the electrons will be confined inside the quantum well at their corresponding lifetime and quasi-eigenenergies (quasibound states or resonant states) [13-14]. For EM waves, the photons could be quantized in photonic crystal heterostructures owning to the photonic bands mismatch, well known as photonic quantum wells (PQWs). Many structures of PQWs are either two or above PCs in one, two, and three dimensions [11]. Recently, many useful applications in

microwave and millimetre wave of PBGs are especially important in slow wave structures and back-wave devices [15-16]. However, fabrication of the complete PBGs in this frequency region is quite challenging and difficult [17]. Consequently, the simpler method to realize is a one-dimensional PC in a microwave waveguide.

In this work, the resonant photonic states of quasi one-dimensional PCs in a rectangular waveguide are investigated using finite element method (FEM). Both the TE and TM modes in rectangular waveguide are considered in our simulation models can be designed using any shapes of microwave waveguides for the suitable usage. In order to solve the resonant photonic states, calculated of the transmission function is indeed. Our calculations have been carefully verified and tested the convergence. At the same time, we consider more crucial applications, for example, the thermal radiation, quasibound states, and switching control of spontaneous emission at high-order modes.

2. Formulation and physical model

Consider the rectangular waveguide and its cross section of sides a and b as shown in Figure 1. The heterostructures $(AB)^m(CD)^n(AB)^m$ consist of two different 1D PCs aligned in z direction are enclosed The dielectric functions are ε_a, ε_b, ε_c, and ε_d and the corresponding thicknesses are t_A, t_B, t_C, and t_D of A, B, C, and D layer, respectively. For microwave propagating in photonic crystal heterostructures in our calculations, the TE mode and TM mode are characterized by the H_z component of the magnetic field and the E_z component of the electric field in a rectangular waveguide, respectively.
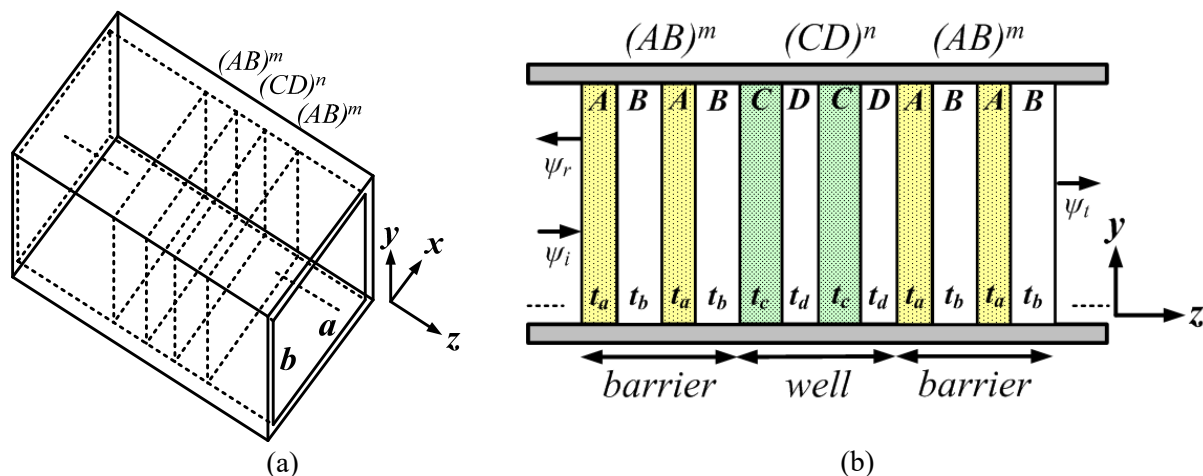

Figure 1. (a) Schematic of $(AB)^m(CD)^n(AB)^m$ along z direction enclosed in a rectangular waveguide (width a and height b) and (b) the corresponding heterostructures in the cross-sectional view.

The z components (H_z and E_z) of the Helmholtz's equations are TE and TM modes in our simulation model and assumed that the materials are homogeneous, linear, isotropic, and stationary:

$$\varepsilon(z)\vec{\nabla}\times\left[\frac{1}{\varepsilon(z)}\vec{\nabla}\times H_z\right]+\omega^2\varepsilon(z)\mu(z)H_z=0 \tag{1}$$

and

$$\mu(z)\vec{\nabla}\times\left[\frac{1}{\mu(z)}\vec{\nabla}\times E_z\right]+\omega^2\varepsilon(z)\mu(z)E_z=0. \tag{2}$$

Eqs. (1) and (2) can be separated the transverse parts and longitudinal parts, respectively. The cutoff frequencies of TE modes and TM modes in the waveguide are determined by the transverse parts. For the longitudinal parts, the Helmholtz's equation of p-layer with relative dielectric constant ε_{rp} and permeability μ_{rp} in a waveguide at z direction can be written as:

$$\frac{d^2}{dz^2}\psi_{H_z/E_z} + k_p^2 \psi_{H_z/E_z} = 0 \tag{3}$$

with

$$k_p = \frac{2\pi}{\lambda}\sqrt{\varepsilon_{rp}\mu_{rp} - \left(\frac{\lambda}{\lambda_c}\right)^2}, \tag{4}$$

where λ_c is the cutoff wavelength. The superposition of the traveling wave functions in each layer, the solutions are:

$$\psi_{H_z} = H_z(x,y)[\alpha_p \exp(-jk_p z) + \beta_p \exp(jk_p z)] \quad for \ \ TE \ \ modes \tag{5}$$

and

$$\psi_{E_z} = E_z(x,y)[\xi_p \exp(-jk_p z) + \zeta_p \exp(jk_p z)] \quad for \ \ TM \ \ modes \tag{6}$$

The $\alpha_p\ (\xi_p)$ and $\beta_p\ (\zeta_p)$ represent the amplitudes of the forward and backward propagating waves in the p-layer of $H_z\ (E_z)$, respectively. Calculated by matching the boundary conditions at normal components of each layer surfaces, the transmittance and reflectance in fig. 1 (b) can be obtained TE modes and TM modes represented as S-parameters:

$$S_{12}(dB) = 10\log\left|\frac{\psi_{t,H_z/E_z}}{\psi_{i,H_z/E_z}}\right|^2 \quad and \quad S_{11}(dB) = 10\log\left|\frac{\psi_{r,H_z/E_z}}{\psi_{i,H_z/E_z}}\right|^2 \tag{7}$$

3. Results and discussion

The periodic heterostructures $(AB)^m(CD)^n(AB)^m$ of dimensions 7.11 *mm* x 3.55 *mm* are along the z direction in a rectangular waveguide. In order to determine the stop band, the transmittance spectra by applying Eq. (7) is calculated as a function of normalized to cutoff frequency of TE_{10} for $(AB)^{10}$ and $(CD)^{10}$ of the lowest TE and TM modes and plotted in Figure 2, respectively. For this case, the dielectric constants and the thicknesses of the (AB) and (CD) double-layer stacks are as follows, ($\varepsilon_a = 11.4$, $t_a = 0.063a$, $\varepsilon_b = 1$, and $t_b = 0.937a$) and ($\varepsilon_c = 3.8$, $t_c = 0.167a$, $\varepsilon_d = 1$, and $t_d = 0.833a$), where a is a lattice constant. As one can see, we desired the much wider PBGs of the (AB) PC simultaneously for the TE_{10} and TM_{11} mode based on the multiple Bragg scattering. The way is easily to imbed the pass band of the second (CD) PC into the PBGs of the (AB) PC and constitute the quasi 1D PCs of the PQW structures $(AB)^m(CD)^n(AB)^m$ as shown in Fig. 1. Obviously, the EM waves within the overlapped frequencies that can be regarded as the photonic quantum well for the (CD) PC. In contrast, the (AB) PC is played as the photonic quantum barrier.
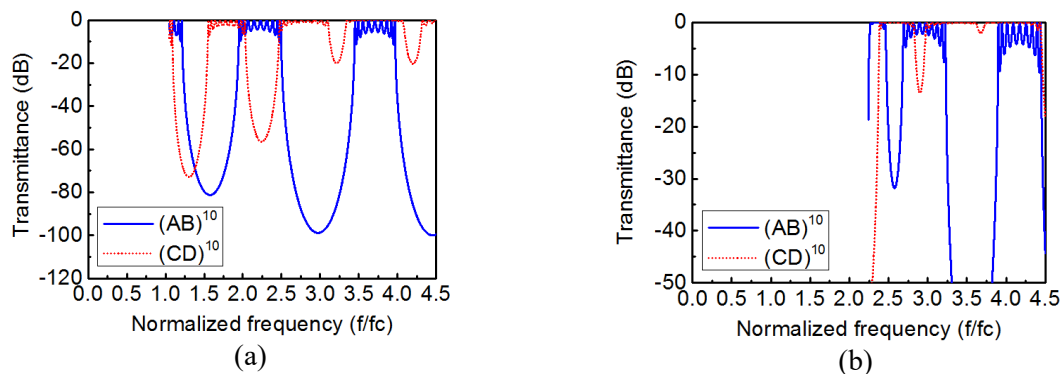

Figure 2. Calculated transmittance of 10 double-layer stacks of (AB) PC and (CD) PC for (a) TE_{10} and (b) TM_{11} modes, respectively.

In Figure 3, the transmittance spectra of varying the $m = 1, 2$, and 3 of the $(AB)^5(CD)^n(AB)^5$ for the fundamental mode, TE_{10} are calculated in a rectangular waveguide. For these cases, the EM waves will be confined in the (CD) PC caused by PBGs that prohibit the EM waves propagated in the (AB) PCs. Consequently, the EM waves with the corresponding energies consistent with the photonic resonant states of the PQWs will transmit through the barriers that of the transmittance approaching unity. As one can see, the resonant photonic states are approximately proportional to the (CD) stacks increased for the TE_{10} mode in the first PBG of the (AB) PC. In our calculations, the transmitted peaks are changed extremely sensitive for the thickness of each layer. In general, the resonant photonic states can be designed by tuning the number of the (CD) stacks at indicated frequencies for the PQWs structures. Figure 4 shows the $(AB)^5(CD)^3(AB)^5$ in a rectangular waveguide that of the degenerate states are not existed for higher order modes, even cutoff frequencies are the same in the hollow rectangular waveguide. One should note the transmitted peaks due to the wave impedance $Z_{TE} > Z_{TM}$, those of TE_{11} and TE_{21} are shifted higher frequency than the corresponding to TM_{11} and TM_{21} modes, respectively. Conventionally, all of the polarization modes are nearly independent of the PQWs structures in a rectangular waveguide.
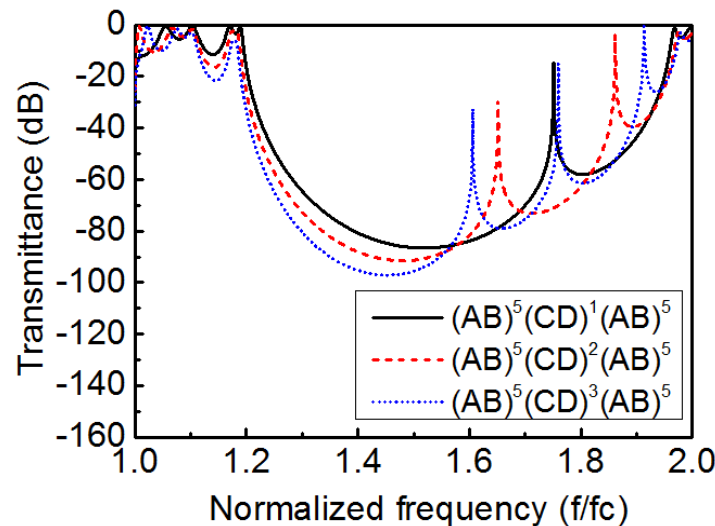

Figure 3. Calculated transmittance of varying the $m = 1, 2$, and 3 of the $(AB)^5(CD)^n(AB)^5$ for (a) TE_{10} and (b) TM_{11} mode in a rectangular waveguide.
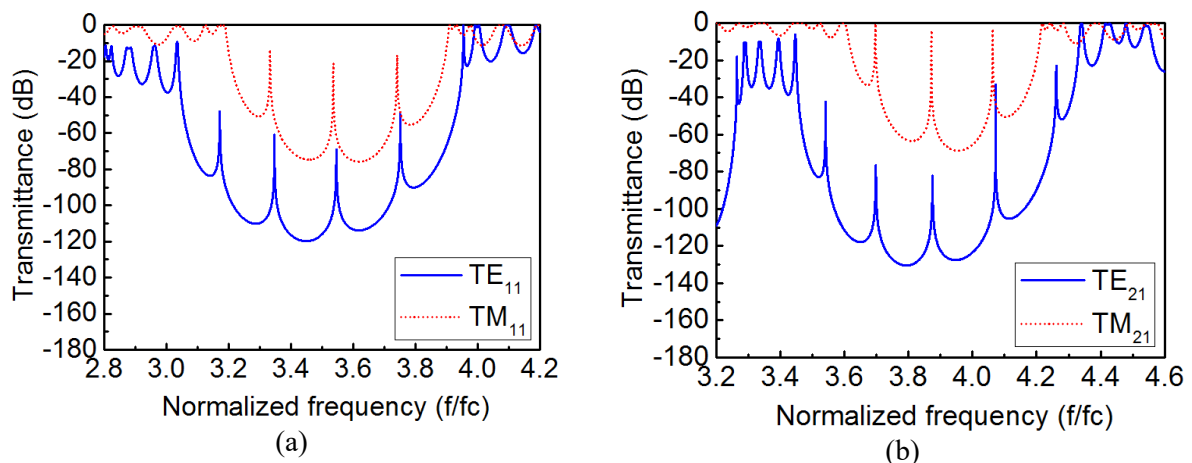

Figure 4. Comparisons of the transmitted peaks of (a) TE_{11} and TM_{11} modes, (b) TE_{21} and TM_{21} modes for $(AB)^5(CD)^3(AB)^5$ in a rectangular waveguide. The degenerate states are not existed for the same cutoff frequency of the TE and TM modes.

4. Conclusions

In this work, we have presented the calculations of the resonant photonic states of $(AB)^m(CD)^n(AB)^m$ for the TE and TM modes in a rectangular waveguide. We have examined the quantitative analysis of the transmission functions and resonant photonic states in our simulation models. Due to the change of impedance of TE waves and TM waves, the degenerate resonant photonic states are not existed. As a result, it is quite different from the traditional 1D PQWs. Additionally, the positions and number of the resonant photonic states are approximately proportional to the (CD) stacks increased. We believe these results are useful applications in photonic quantum devices and nano technologies.

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