Available online at www.sciencedirect.com
ScienceDirect
Optik 120 (2009) 736–740
Optik Optics
www.elsevier.de/ijleo

Transmission properties of photonic quantum well composed of dispersive materials

Tingting Bian, Yan Zhang*

Department of Physics, Capital Normal University, Xisanhuan Beilu 105, Beijing 100037, PR China

Received 1 October 2007; accepted 13 March 2008

Abstract

The transmission properties of one-dimensional photonic quantum well structure produced by inserting defect layers into dispersive photonic crystals have been investigated. These photonic crystals are stacked alternatively with two kinds of dispersive material layers. The inserted layers structure is another kind of dispersive photonic crystal. It has been turned out that the confined states are quantized.

Keywords: Photonic quantum well; Dispersive material; Photonic crystal

1. Introduction

In recent years, a new kind of artificial materials, photonic crystals (PCs), have attracted many attentions [1–3]. This kind of materials is composed of two mediums with different dielectric constants. By alternatively arranging these two mediums, the composed materials can present photonic band gaps (PBG) in which the propagation of the light with specific frequencies is forbidden. More recently, one-dimensional (1D) photonic quantum well (PQW) structures consisting of two different 1D PCs are investigated. The stacking of two constituent PCs can be expressed as $(ab)_N(cd)_M(ab)_N$, where N and M are the number of the ab and cd layers, respectively. When M is less than N, the cd PC can be considered as an inserted defect into the ab PC. It has been found that the number of the defect modes is just equal to the number of the cd layers [4]. Thus one can generate as many defect states as desired simply. This feature inspires us to try different materials to form dispersive PQW structures. To date, dispersive materials including positive index materials (PIMs), negative index materials (NIMs), negative μ materials (NMMs), and negative ε materials (NEMs) have been widely concerned because of their skeptical properties [5–11]. However, these dispersive materials have not been applied in the PQW structures. In this paper, six kinds of 1DPC with NMM–NEM, PIM–NIM, NMM–PIM, NMM–NIM, NEM–PIM, and NEM–NIM multi-layer structures are used to compose different PQW structures. The PQWs are formatted by inserting a layer or a kind of 1DPC into another 1DPC and have the form of $(ab)_N(c)(ab)_N$ or $(ab)_N(cd)_M(ab)_N$, where the layer c and the PC $(cd)_M$ can be viewed as the defects. The transmittances of the above PQW structures are investigated in the possible frequency ranges by using the transfer matrix method (TMM). The dependence of the position and number of defect modes on the incited defect is analyzed.

The paper is organized as follows. In Section 2, the disperse relations of materials used are given and the

*Corresponding author.
E-mail address: yzhang@mail.cnu.edu.cn (Y. Zhang).

0030-4026/$ - see front matter © 2008 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2008.03.003

TMM is also introduced. The transmission properties of different PQW structures are studied in Section 3. At last, a conclusion is drawn in Section 4.

2. Dispersion relations and TMM

In this paper, we employ A to denote the NMM material, B to NEM material, C to PIM material, and D to NIM material. The permittivity and permeability of A are

$$\varepsilon_A > 0, \quad \mu_A = 1 - \frac{\omega_{\mathrm{mp}A}^2}{\omega^2}, \tag{1}$$

where $\omega_{\mathrm{mp}A}$ is the magnetic plasma frequency and ε_A is a positive constant. Only when the relation $\omega < \omega_{\mathrm{mp}A}$ is satisfied, A is an NMM material. Correspondingly, the permittivity and permeability of B are

$$\varepsilon_B = 1 - \frac{\omega_{\mathrm{ep}B}^2}{\omega^2}, \quad \mu_B > 0, \tag{2}$$

where $\omega_{\mathrm{ep}B}$ is the electronic plasma frequency and μ_B is a positive constant. The condition $\omega < \omega_{\mathrm{ep}B}$ must be satisfied to ensure B is an NEM material. Since C is used to express the PIM material, both ε_C and μ_C are positive constants. Both permittivity and permeability of D are functions of the frequency:

$$\varepsilon_D = 1 - \frac{\omega_{\mathrm{ep}D}^2}{\omega^2}, \quad \mu_D = 1 - \frac{\omega_{\mathrm{mp}D}^2}{\omega^2}, \tag{3}$$

where $\omega_{\mathrm{mp}D}$ and $\omega_{\mathrm{ep}D}$ are the magnetic and electronic plasma frequency, respectively. When $\omega < \omega_{\mathrm{mp}D}$ and $\omega < \omega_{\mathrm{ep}D}$ are simultaneously satisfied, D is an NIM material.

In the 1D layer structure, the electromagnetic fields at two surfaces z and $z + \Delta z$ of the ith layer medium can be related via a transfer matrix [12,13]:

$$M_i(\Delta z, \omega) = \begin{pmatrix} \cos[k_z^i \Delta z] & i\frac{1}{q_i}\sin[k_z^i \Delta z] \\ iq_i \sin[k_z^i \Delta z] & \cos[k_z^i \Delta z] \end{pmatrix}, \tag{4}$$

where $k_z^i = \omega/c\sqrt{\varepsilon_i}\sqrt{\mu_i}\sqrt{1-(\sin^2\theta/\varepsilon_i\mu_i)}$ is the component of the wave vector k^i along the z direction, θ is the incident angle of the light, c is the speed of light in the vacuum and Δz is the thickness of the layer. For the TE wave, $q_i = \sqrt{\varepsilon_i}/\sqrt{\mu_i}\sqrt{1-(\sin^2\theta/\varepsilon_i\mu_i)}$ and for the TM wave, $q_i = \sqrt{\mu_i}/\sqrt{\varepsilon_i}\sqrt{1-(\sin^2\theta/\varepsilon_i\mu_i)}$. Then the transmission coefficient $t(\omega)$ for a 1D cascading layer structure can be obtained by the TMM

$$t(\omega) = \frac{2\cos\theta}{\cos\theta(x_{22}(\omega) + x_{11}(\omega)) - [\cos^2\theta\, x_{12}(\omega) + x_{21}(\omega)]}, \tag{5}$$

where x_{ij} $(i,j = 1,2)$ are the matrix elements of $x_N = \prod_{i=1}^{2N} M_i(d_i, \omega)$, which represents the total transfer matrix connecting the amplitude of the incident wave with that of the transmitted and reflected waves.

3. Transmission properties of PQWs

In this section, the transmission of various PQWs composed of dispersive materials are studied by using TMM. For simplification, only the cases of the normal incidence are considered. The PQWs have the form of $(ab)_N(c)_M(ab)_N$ and $(ab)_N(cd)_M(ab)_N$, M and N represent the period number of the layers. In simulations, the permittivity of the NMM A is chosen as $\varepsilon_A = 1.5$ and the magnetic plasma frequency is $\omega_{\mathrm{mp}A} = 12\,\mathrm{GHz}$. The parameters for NEM B are chosen as $\omega_{\mathrm{ep}B} = 12\,\mathrm{GHz}$ and $\mu_B = 1.5$. The parameters of the PIM C are $\varepsilon_C = 1.5$ and $\mu_C = 1.5$. The magnetic and electronic plasma frequencies of the NIM D are $\omega_{\mathrm{ep}D} = 12\,\mathrm{GHz}$ and $\omega_{\mathrm{mp}D} = 12\,\mathrm{GHz}$, respectively. The thicknesses of all four layers A, B, C, and D are 12 mm. The finite number $N = 8$ is chosen because it is big enough compared with $M = 1-3$ for computing the transmission spectrum of the PQW. The mentioned parameters are employed in all the calculations hereafter except specific annotations.

The transmission spectra of the PQWs $(AC)_8(D)_M(AC)_8$, $(BC)_8(D)_M(BC)_8$, $(AC)_8(BD)_M(AC)_8$, and $(BC)_8(AD)_M(BC)_8$ have the nearly same patterns. Fig. 1 shows the transmission spectra of the PQW $(AC)_8(BD)_M(AC)_8$ in which (a), (c), and (e) are for the TE waves and (b), (d), and (f) for the TM waves when $M = 1-3$, respectively. Due to the introduction of the defect layers, some confined modes appear in the band gap of the perfect AC structure. It can be seen that the cases of TE and TM modes are similar. With the number of the

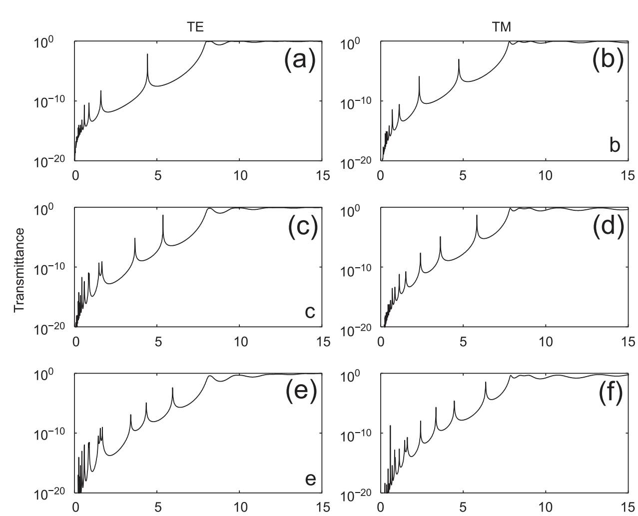

Fig. 1. Calculated transmittance spectra for $(AC)_8(BD)_M(AC)_8$ $(M = 1-3)$ PQWs.