A Switching Mechanism Based on Photonic Quantum-well Effects

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Abstract Photonic quantum-well (QW) structures can be constructed by stacking 3 photonic crystals (PCs) with the same photonic band gap and different defect modes. On condition that the defect mode of the PC in the well region is located into nontransmission frequency ranges of the PCs in the barrier regions, the confined photonic state appears and can completely transmit through the structure by tunneling. However, its transmission will be strongly prohibited due to vanishing of the photonic QW induced by shifting the defect mode frequency of either of the PCs in the surrounded regions to that of the middle PC. Switching and narrow band filtering can be realized simultaneously with the structure. The theoretical calculation has been carried out by transfer matrix methods.

Keywords Photonic crystal; Defect mode; Quantum well; Optical switch; Filter
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0 Introduction

Photonic crystals (PCs) are composite structures with a periodic arrangement of refractive indices. In such materials, a photonic band gap (PBG)[1] exists in which the existence of photons is forbidden. They have been used in various applications[2~5].

It has been shown that the transmission properties of PCs can be tailored by using photonic quantum-well (QW) structure. One used different PCs to construct photonic QW, provided that the band of the PC in the middle region is just inside the PBGs of the PCs in the surrounded regions[6].

Different from Ref. [6], a new type of sandwiched structure is taken. It is constructed by 3 PCs each with a defect whose PBGs are identical but defect modes are different. When the defect mode of the PC in the middle region is located into the nontransmission frequency ranges of the PCs in the surrounded regions, the photonic QW structure is formed. As compared with the conventional photonic QW structure, it is easy to vanish by shifting the defect mode frequency of either of the PCs in the surrounded regions to that of the PC in the middle region. Therefore, the transmission properties of the structure are highly sensitive to a shift of defect modes of constituent PCs. This provides a mechanism for optical switches which can tune the transmission at resonance in the PBG. It is different from switching mechanisms based on a periodic modulation of defects in a PC[7], a shift of band edges[8] and a shift of defect modes[9].

1 Structure with 3 different defects

The calculated structure is a one-dimensional (1D) PC which is composed of SiO_2 and Si with three SiO_2 defects, as shown in Fig. 1. In Fig. 1, A $=\{(HL)^2 d_1 (LH)^2\}$, B$=\{L(HL)^3 d_2 (LH)^3 L\}$ and C$=\{(HL)^2 d_3 (LH)^2\}$ are 3 PCs each with a defect, where all superscripts are the period number of the unit, and d_1, d_2 and d_3 represent 3 different defects. Their thicknesses are d_1, d_2 and d_3 respectively. The lattice constant is Λ. The thicknesses of Si and SiO_2 layers are $d_H=0.2886\Lambda$ and $d_L=0.7114\Lambda$ respectively, and the refractive indices are $n_H=3.7$ and $n_L=1.5$ respectively. The ambient medium is air, and the incident angle is 0°.

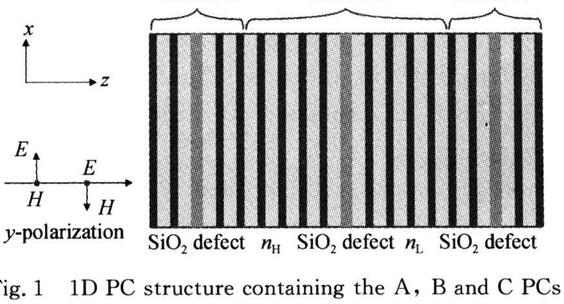

Fig. 1 1D PC structure containing the A, B and C PCs each with a defect

The thicknesses of d_1, d_2 and d_3 defect layers are chosen so that the defect mode frequency of the B PC is different from that of the A and C PCs. Fig. 2(a) shows spectra of the A, B, C PCs and the ABC structure for $d_1=1.7d_L$, $d_2=2.0d_L$ and $d_3=1.7d_L$. For the electromagnetic (EM) wave with frequency in the range of the defect mode of the B PC, the A and C PCs strongly prohibit its propagation and play roles of barriers, whereas the B PC sustains its propagation and acts as a well.

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The Photonic QW is formed. Consequently, the EM wave is highly confined to the B PCs for the confined photonic state. The confined state can completely transmit through the photonic QW owing to the fact that it pass through the structure by tunneling. It exhibits a complete transmission peak in the PBG as shown in (d) Fig. 2(a).

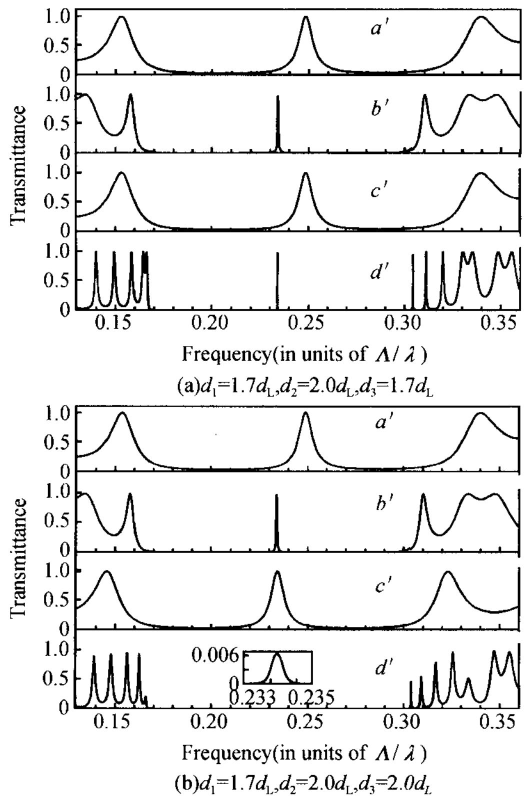

Fig. 2 Calculated transmission spectra of the A (a), the B (b), the C (c) PC and the ABC structure (d)

Now by adjusting the thickness of the defect in the C PC, the defect mode frequency of the C PC is shifted to that of the B PC. In this case, only the A PC prohibits the propagation of the EM wave with frequency of the defect mode in the B PC, while the C PC sustains its propagation and no longer acts as a barrier. The QW structure completely vanishes. Consequently, its transmission approaches the minimum, i. e. 0. 63%. Fig. 2(b) shows their spectra for $d_1=1.7d_L$, $d_2=2.0d_L$ and $d_3=2.0d_L$.

To clearly see how the EM waves are confined. It displays in Fig. 3 the electric field distributions of the confined state in the ABC structure, which are obtained by the transfer matrix method (TMM). The magnitude of the incident electric field is set to be 1. From the field distributions, it is obvious that the field is highly confined to the defect site in the B PC in the photonic QW structure although there are some minor penetration into the nearby A and B PCs, as shown in Fig. 3(a). The confined state appears and can completely transmit through the photonic QW by tunneling. Therefore, a complete transmission is observed in the PBG. When the defect mode frequency of the C PC is equal to that of the B PC, the photonic confinement is greatly weakened, as shown in Fig. 3(b), leading to a large decrease in the transmission at resonance in the PBG.

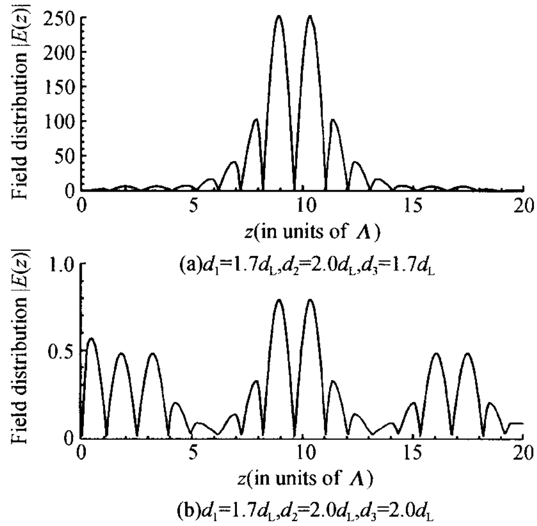

Fig. 3 Calculated electric field distributions of the confined states

It is found that the minimum value of the transmission at resonance depends on the defect separation in the structure. With increasing the defect separation below $5\Lambda+d_L$, which makes defect modes degenerate, the minimum value decreases. However, increasing the defect separation above $5\Lambda+d_L$ only reduces the band width of the resonant transmission peak, but can not change its minimum height. A further reduction of the minimum transmission at resonance can be caused by increasing thickness of A and C PCs and correspondingly increasing thickness of the B PC for defect modes to degenerate.

d_3 ranging between d_1 and d_2, the transmission at resonance varies from 1 to its minimum value. Therefore, decreasing the difference between d_2 and d_1 can improve the sensitivity of the transmission at resonance to d_3. But it causes an increase in the minimum transmission. To avoid this, thicknesses of A, C and B PCs should be increased.

This provides a mechanism for optical switches, whose efficiency can be improved by decreasing the difference between d_1 and d_2 to improve its sensitivity and increasing the thicknesses of A, C and B PCs to decrease the minimum value of transmission at resonance. Even though the frequencies of the input light extend throughout the PBG, the intensity of the output light can be tuned by using the ABC structure. In contrast, switches realized by a shift of defect modes[8] or a periodic modulation of defects[7] require that the frequencies of the input light must be limited in narrow ranges around the defect modes or at the center of the impurity band. As compared with optical switches using two defects in series[2], the transmission at resonance for the structure with 3 defects can reach 1 due to the photonic QW effect.

2 Dependence of the transmission at resonance on voltage

The refractive index of nematic liquid crystal (LC) is tunable by an external electric field along z-axis. The nematic LC 5BC is introduced instead of the SiO_2 defect in the C PC because of its low critical voltage $V_C = 0.71$V. The refractive indices of nematic LC 5BC are $n_o = 1.54$ and $n_e = 1.75$ at room temperature. In the absence of an external electric field, the long molecular axis of the LC is aligned parallel to x-axis. The direction of LC molecules is affected by the external electric field only when the voltage V is larger than V_C. The transmission properties of the structure with a nematic LC defect and 2 SiO_2 defects are calculated by a 4×4 TMM[10,11].

The thickness of the LC defect is $d_{LC} = 3.429 d_L$. When V is less than the critical voltage V_C, the defect mode frequency of the C PC for the x-polarized light is just equal to that of the B PC and then the transmission at resonance is 0.63%, namely, approaches the minimum. An increase in V above V_C can cause an increase in the transmission at resonance due to forming of the photonic QW induced by shifting of the defect mode of the C PC. Fig. 4 shows dependence of the transmission at resonance on V. When V exceeds $1.5\ V_C$, it approaches 1.

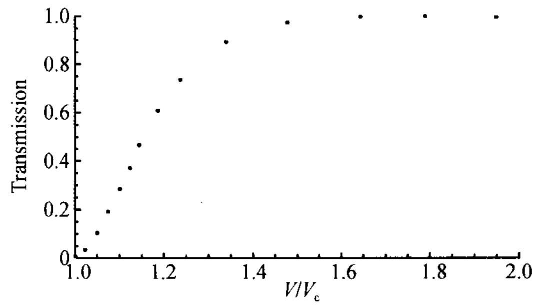

Fig. 4 Voltage dependence of the transmission at resonance of the structure for incident x-polarized wave at $d_{LC} = 3.429 d_L$

If stronger dependence of the transmission at resonance on the voltage V is expected, it will be necessary to decrease the difference between d_1 and d_2 and increase the thicknesses of A, C and B PCs.

In addition, the transmission for the y-polarized light is independent of the external electric field because the y-polarized light propagating through the LC defect feels n_o, which dose not change with molecular reorientation of the LC.

3 Conclusions

The transmission properties of the structure with 3 different defects have been studied. A change in the transmission at resonance originates from the forming and vanishing of the photonic QW induced by shifting the defect mode in either of the A and C PCs. The structure with a LC defect is taken as an example. The calculated results show that a channel in the PBG can be opened based on the photonic QW effects induced by an external electric field. The mechanism may be extended to multiple channeled optical switches.

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基于量子阱效应的光开关

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摘 要 把三块各带有一个缺陷的光子晶体结合起来,如果中央晶体的缺陷模处在两侧晶体的禁带中,缺陷模内的光波会受到两侧晶体的阻碍并被局域在中央晶体内,形成量子阱结构;若一侧晶体的缺陷模被移动到中央晶体缺陷模处,则只有一侧晶体阻碍在中央晶体缺陷模内传播的光波,量子阱效应完全消失,光的传输受到最大程度的阻碍.这种结构可同时具有窄带滤波器和光开关的功能,据此提出了一种高效的、灵敏的光开关的设计.采用传输矩阵法计算了一维光子晶体的透射谱和场分布.

关键词 光子晶体;量子阱;缺陷态;光开关;滤波

Liu Dandong was born in 1968. He received M. S. degree from Xi'an Institute of Optics and Precision Mechanics of Chinese Academy of Sciences in 1995. His main research interests are in the field of photonic crystals.