Photonic quantum well composed of photonic crystal and quasicrystal

Shaohui Xu a,*, Yiping Zhu a, Lianwei Wang a, b, Pingxiong Yang a, Paul K. Chu b

a Key Laboratory of Polar Materials and Devices, Ministry of Education, and Department of Electronic Engineering, East China Normal University, 500 Dongchuan Road, Minhang District, Shanghai 200241, China
b Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China

1. Introduction

The concepts of superlattices and quantum wells [1,2] in semiconductor crystals were introduced to photonic-bandgap (PBG) materials in the late-1980s [3–5] and much progress has been made on photonic quantum-well structures (PQWSs) composed of one-, two-, and three-dimensional PBG materials [6–11]. A two- or three-dimensional PQWS can be constructed by inserting a photonic well (a uniform medium photonically different from the surrounding area) into the photonic barriers. Theoretical analysis by Jiang et al. [6,7] has predicted the presence of confined quantized states in these structures as a result of the photonic confinement effect similar to that in semiconductor quantum wells. They have shown that the transmission coefficient is unity for all the confined states similar to electronic tunneling in a semiconductor quantum well system. The resonant tunneling effect can be used to explain the phenomenon. Two types of one-dimensional (1D) PQWSs have been proposed, namely the homogenous dielectric slab [8] and photonic crystal (PC) [9]. It is difficult to observe the PBG and quantum well effects from the former but in the latter, the quantum well effect has been demonstrated and the number of confined photonic states can be tuned by adjusting the number of periods in the photonic well region. However, experimental realization is still difficult.

Photonic quasicrystals (PQCs) such as the typical quasiperiodic structure – Fibonacci multilayer have aroused interests due to possible optical applications and theoretical assessment of light transmission in quasi-periodic media [10–13]. It has been shown that photon propagation in quasi-periodic materials is different from that in periodic and disordered ones [13]. The PQCs exhibit long-range order but lack a translational symmetry and show the properties of self-similarity. In this case, the light wave can be localized in the quasiperiodic system, for instance, the Fibonacci quasicrystal (FQC) [11], and exhibits scaling properties in the transmission spectra. It is of interest to localize the light wave when the quasiperiodic structure as a photonic well is sandwiched by two barrier PCs. In this work, one-dimensional photonic quantum well structures are fabricated by PCs and FQCs by only adjusting the sequence of two materials with the proper dielectric properties and thickness. Our results indicate that the resonance frequency, frequency interval, and number of resonance modes can be tuned freely by adjusting the period number of the photonic well. The general understanding can be extended to 2D and 3D structures with some modifications.

The PQWSs with the photonic crystal and Fibonacci photonic quasicrystal are composed of two kinds of dielectric layers with the proper dielectric constant and layer thickness (large dielectric constant A and small dielectric constant B), as shown in Fig. 1a. The large dielectric constant and layer thickness are selected to 6 and the small dielectric constant and thickness are 1 (air). The thicknesses are L4 and L0, respectively and L0+L4=a, where a is the lattice constant. The dielectric constant and thickness of the large one (εA and L4) are used to set the parameters of the PCs and FQCs. A Fibonacci quasicrystal [10] is based on the recursive relationship Sj+1=Sj+Sj−1 for j ≥ 1 as well as S1={A} and S2={AB}. Hence, S3={ABAAB}, and so forth. For the PC and FQCs, the transmission (or reflectance) spectra and electric field distribution curves can be obtained by the transfer matrix method (TMM) [10] widely used.
for multilayered structures. Here, the electromagnetic (EM) waves are normal to the PCs and FQCs from the air medium.

At first, the quarter-wave stack \( (L_A=0.29) \) is selected to obtain the wide band-gap of the periodic PC. Fig. 1b depicts the transmission spectra of FQCs for S3 (II), S4 (III), S5 (IV), S6 (V), and S7 (VI). The small transmission coefficient appears between frequencies \( f=0.192 \) and 0.592 for FQC S3. The main part of the frequency region forms the band-gap of the PC as influenced by both the interference and coupling effects [14], as shown in the transmission spectrum of the periodic PC (I). Owing to the phase matching conditions for the quarter-wave stack structure, the transmission maxima (confined states) appear at the central region in the band-gap of the PC with increasing Fibonacci number. However, because of the quasiperiodic properties of FQCs, only parts of the peaks can approach unity. On the other hand, the confined states cannot be adjusted by the Fibonacci number. For example, one defect state appears when the Fibonacci number increases from 4 to 6 \( (S_4, S_5 \text{ and } S_6) \), but the three symmetrical defect states appear in the band-gap for FQC \( S_7 \). Quasilocalization of the light waves in the FQCs results in the small transmission intensity and uncontrolled defect modes by changing the Fibonacci number. The localization properties can be improved by sandwiching the FQCs with two periods of PCs. The transmission spectra of the PQWS fabricated with the PC and FQC are shown in Fig. 1c. The photonic wells are FQCs \( S_3 \) (II), \( S_4 \) (III), \( S_5 \) (IV), \( S_6 \) (V), and \( S_7 \) (VI). As a result of the increased localization effect, the sharp transmission peaks are shown in the middle of the band-gap when the FQC as the photonic well is sandwiched by two PCs. Even though it does not show the localized mode in the FQC \( S_3 \), a narrow transmission peak appears in PQWS when FQC \( S_3 \) is the photonic well (II). As the Fibonacci number changes from 4 to 7 (III–VI), the numbers of the narrow transmission peaks are 1, 2, 3 and 5. The enhanced localized effect in the PQWS makes the confined modes narrow showing spiculate peaks.

In order to understand the confinement states in the PQWS, the electric field distributions of the confined states are shown in Fig. 2. The magnitude of the incident electric field is unity and the two dashed lines indicate the region of the photonic well. The confined mode is an interfacial state with FQC \( S_3 \) being the photonic well, in which the electric field is localized in the interfacial region between the PC and FQC (Fig. 2a). The defect state shown as FQC \( S_4 \) is the photonic well and the electric field is localized in the well region (Fig. 2b). Although they are all confined states, the different localization properties influence the transmission intensity and the defect states yield the large transmission coefficient reaching unity. When FQC \( S_5 \) is the photonic well, the interfacial states appear again corresponding to the first and second confined modes (Fig. 2c). If QPC \( S_6 \) is the photonic well, the defect states appear and the electric field is localized in the well region (Fig. 2d). However, on account of the non-periodic properties of the Fibonacci quasicrystal, the electric field is localized in the different defect layers asymmetrical for the first, second, and third confined modes. In this case,
the confined states of the PQWS can be divided into the interfacial state and defect state for odd and even Fibonacci number, respectively. In the interfacial state case in which the electric field is localized at the interface between the PC and FQC, the unfilled localized properties reduce the transmission in the confined states. In the defect state, the electric field is localized in the photonic well and the EM waves may travel from an evanescent defect state to a neighboring one in the hopping mode which is similar to electron hopping in semiconductor with defects [15]. However, owing to the non-periodic properties of the photonic well, the transmission of defect states decreases with increasing photonic well thickness (increasing Fibonacci number) and it is difficult to reach unity.

To control the confined states, the coupled cavity waveguide (CCW) can be chosen as the photonic well. When introducing a series of defects A in the periodic structure of the PC, a coupled cavity waveguide is fabricated and the defect band can be formed in the band-gap of the periodic PC due to the coupling effects of the defect states [16–18]. Comparing the schematic structures of the Fibonacci quasicrystal and coupled cavity waveguide (CCW), the CCW structure is a suitable replacement for the Fibonacci quasicrystal to increase the symmetry. The similar frequency regions of the pass band and band-gap in the transmission spectra (Fig. 2c) between the Fibonacci quasicrystal and CCW support the argument.

Because of the phase matching condition, the second pass band of CCW which is formed by the coupled defect states remains in the band-gap region of the periodic PC, as shown by the photonic band structures of the PC and CCW in Fig. 3a. The photonic quantum-well structure can be fabricated by the PC and CCW structures and the CCW acts as a well with the two PCs being the barriers. As shown in Fig. 3b, the defect band of CCW (VII) stays in the middle of band-gap of PC (VIII). If the photonic quantum-well structure is fabricated by \((AB)^n(AAB)^n(AB)^n (n = 1–6)\), very sharp transmission peaks appear in the band-gap of the PC since EM wave can be localized in the CCW structure and photon confinement leads to quantization of frequencies to satisfy the multiple Bragg scattering condition. The confined states can tunnel through the PQWS. Hence, the number of confined states is equal to the period number of the CCW and the desired confined state can be obtained simply by adjusting the period number of the CCW.

To study how EM waves are confined in the PQWS, the electric field distribution patterns of \((AB)^n(AAB)^n(AB)^n\) PQWs are shown in Fig. 3c. The incident EM waves are the confined states in the transmission spectra from low to high frequencies (I–V). The two dashed lines indicate the region of the photonic well. The electric field is mainly confined in the CCW although there are attenuated wings penetrating into the adjacent PC layers. The defect like states in the photonic band-gap region of the PC is caused by
Photon confinement in the photonic well. Moreover, different incident lights produce different electric field distributions, namely, one, two, three, four and five envelope oscillation peaks as the incident light frequencies change from low to high. The different confined photonic states are associated with the different electric field oscillation modes. That is, the symmetrical field distribution modes are observed from the CCW structure as the photonic well when the period increases. The periodic distribution of the defect states in the CCW enables the photon to transmit through the photonic structure by resonance tunneling and the transmission of the confined states can reach unity.

The confined states of the PQWS are within the frequency region of the defect band of CCW when the period number of the CCW changes from 1 to 5 or larger, as shown in Fig. 3b. The confined states are the results of localized defect states of the CCW. It is believed that the confined states can shift in the band-gap region of the periodic PC when the defective band of the CCW shifts and it only limits the defect band in the band-gap of the PC. The shift of the defect band can be realized by only varying the thickness of the two stacking layers A and B. In order to obtain the thickness ratio of the stacking layers A and B to make the defect band of the CCW to be within the band-gap of the PC quantitatively, two parameters $\Delta E$ and $\delta E$ are introduced. $\Delta E$ represents the average width of the defect band in the CCW and band-gap of PC and can be expressed by the following:

$$\Delta E = \frac{2(\omega_{\text{CCW}} - \omega_{\text{PBG}})}{2},$$

where $\omega_{\text{CCW}}$ and $\omega_{\text{PBG}}$ represent the frequency widths of the defect band in the CCW and first band-gap of PC, respectively and $\delta E$ is the frequency difference between the mid frequencies of the defect band in the CCW and band-gap of PC which can be expressed by:

$$\delta E = \frac{[(\omega_{\text{CCW}})^{\text{max}} + (\omega_{\text{CCW}})^{\text{min}}]/2 - [(\omega_{\text{PBG}})^{\text{max}} + (\omega_{\text{PBG}})^{\text{min}}]/2],$$

where $(\omega_{\text{CCW}})^{\text{max}}$ and $(\omega_{\text{CCW}})^{\text{min}}$ are the largest and smallest frequencies of the defect band in the CCW, respectively and $(\omega_{\text{PBG}})^{\text{max}}$ and $(\omega_{\text{PBG}})^{\text{min}}$ are the largest and smallest frequencies of the band-gap of the PC obtained from the transmission spectra of the 1D CCW and PC structures. The absolute value is shown here because the defect band can shift to high or low frequencies. Fig. 4a shows the two parameters, $\Delta E$ and $\delta E$, versus the thickness of layer A. The two curves intersect at two points and the small and large values are $L_A = 0.24$ and 0.42, respectively. The defect band in the CCW will move out of the band-gap of PC when the thickness $L_A$ is less (more) than these values.

The photonic band structure calculated by the TMM for the PC and CCW are shown in Fig. 4 for $L_A = 0.24$ (b) and 0.42 (c). The second band of the CCW is inside the first PBG of the PC in the two cases and the band approaches the large (small) frequency edge of PC’s PBG for a short (long) length $L_A$. Even part of CCW’s second band is out of the frequency region of PC’s PBG, for example, $L_A = 0.42$, and the confined states can be formed by fabricating the PQWS with PC and FQ in which the confined states can only be formed at certain frequencies in order to satisfy the multiple Bragg scattering condition.

Fig. 5a shows the transmission spectra of the PC and CCW structure with $L_A = 0.24$. The lower bound frequency of the defect band in the CCW is correctly linked to the lower bound frequency of the band-gap of the PC, as shown in the photonic band structure in Fig. 4b. When the CCW is the photonic well in the PQWS, one and five confined states appear in the band-gap of the PC and only move towards the low frequencies. When $L_A = 0.42$, the transmission spectra of the PC and CCW structures are shown in Fig. 5b. The higher bound frequency of the defect band in the CCW is correctly linked to the higher bound frequency of the band-gap of the PC, as shown in the photonic band structure in Fig. 4c. One and five confined states are shown in the PBG of PC clearly and only move to high frequencies when the CCW is the photonic well in
the PQWS. A part of CCW’s second band is out of the frequency region of the PC band-gap and the transmission peaks of the confined states are hardly influenced. The confined states remain in the band-gap when the period number of the CCW increases. This is due to the overlap between the band-gap of the PC and CCW can enlarge the band-gap of the PQWS.

In summary, the confined states of one-dimensional photonic quantum well structure composed of photonic crystal and quasi-crystal fabricated by two kinds of stacking layers are investigated. The photons traverse the photonic quantum well structure via resonance tunneling. The frequency and number of confined states can be tuned by adjusting the thickness ratio and period number of the photonic well. These features are useful to optical devices and lead to more potential applications.

Acknowledgments

This work was jointly supported by Shanghai Natural Sciences Foundation No. 11ZR1411000, Shanghai Foundamental Key Project no. 11JC1403700, 10JC1404600, PCSIRT, and China NSFC Grant number 61176108, 60990312 and 61076060. The work is also supported by Guangdong–Hong Kong Technology Cooperation Funding Scheme (TCFS) GHP/015/12SZ.

References