Analysis of defect states in optical microcavities based on the photonic quantum well structure

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\begin{abstract}
The defect states in optical microcavities are demonstrated to be related to the different confinement states by analyzing the photonic band structure of the equivalent photonic quantum well structure consisted of a photonic well confined by photonic barriers. Our results indicate that the defect states in optical microcavities could be divided namely into the localized, pseudo-localized, and non-localized modes, and explain the relationship between the localized states in optical microcavities and confinement effects of the electric field in the defect layers.
\end{abstract}

1. Introduction

Photonic crystals (PC) composed of artificial structures with periodic dielectric constants have attracted much attention due to the versatile optical frequencies, confinement properties, and applications such as optical manipulation and engineering [1–5]. When an incident electromagnetic wave impacts a photonic crystal, propagation of the electromagnetic (EM) wave is forbidden if the frequency lies in the photonic band-gap (PBG) region and the wave behavior is similar to that of electrons in a solid crystal. If the perfect translational symmetry of PC is broken by a defect, the peaks associated with the defect is introduced into the photonic band-gap [1,6]. Always the defect mode can trap the EM wave because that the photonic crystal does not allow extended states at the defect frequency. Similar to semiconductor quantum wells, photonic quantum well structures (PQWS) composed of one-, two-, and three-dimensional PBG materials [7–10] can be constructed by inserting a photonic well into the photonic barriers. Theoretical analysis and experimental results have revealed the presence of confined quantized states in these structures as a result of photonic confinement and the transmission coefficient is unity for all the confined states similar to electronic tunneling in a semiconductor quantum well. The resonant tunneling effect can be used to explain the phenomenon.

Optical microcavities with a cavity size on the order of the photon wavelength can confine light in a small volume by resonant recirculation [11–22] and theoretically, the density of the optical modes in microcavities in comparison with free space can be modified. The density of the photon states (mode density) can be increased at some frequencies and reduced at other frequencies and the alteration is accompanied by spatial redistribution of the mode density. If a photon emitting medium is introduced to the cavity, the spontaneous emission rate and spatial emission intensity distribution are altered and is usually treated within the framework of Fermi’s golden rule in which the emission rate is proportional to the product of the mode density and matrix element of the atom-field interaction [11–14]. The unique properties of confined systems can lead to a smaller size and power requirement for integrated optical components. In fact, optical microcavities have been implemented in devices [21,22] such as ultra-small lasers with small power consumption and threshold-less lasing operation arises from efficient coupling of spontaneous emission with a single lasing mode while polariton lasing results from stimulated scattering of polaritons. In practice, the optical microcavities made of III–V semiconductors control the laser emission spectra to ensure a narrow spot-size laser such as the read/write beam for compact disks (CD) and digital versatile disks (DVD). Indeed, part of optical microcavities can be envisaged as defects introduced to periodic structures, especially one-dimensional (1D) ones such as Fabry–Perot (FP) planar microcavities [11,12]. However, there has been limited research on such defect states in optical microcavities based on the photonic crystal structure. In additional, there have been few studies on the properties of defect states, confined conditions of the defect states in optical microcavities at different frequencies, and classification of the defect states, but a better understanding of these issues is important to engineering and exploiting these defects in...
devices. In this work, photonic quantum well structures with the Fabry–Perot (FP) planar microcavities are designed adjusting the sequence of the periodic layers with the proper dielectric properties and thickness and investigated theoretically. Our results indicate that the defect states in the optical microcavities can be divided into localized, pseudo-localized, and non-localized ones and the general understanding can be extended to 2D and 3D structures with some modifications.

2. Structures and calculation method

Two- or three-dimensionally confined microcavities have been employed to produce large changes in the mode density but there is concomitant modification of the photonic state density pattern even for one-dimensional confinement structures with paired planar reflectors such as the FP planar microcavities. Herein, attention is paid to planar microcavities and one-dimensional photonic crystals theoretically calculated by transfer matrix method (TMM) that is widely used for multilayered structures. The electromagnetic (EM) waves are normal to the planar microcavities and PCs from the homogeneous medium (such as air medium with \( n_0 = 1 \)). Within the framework of the transfer matrix method, the distribution of the electric field in a particular layer within the stratified structure can be written as a sum of two plane waves traveling in opposite directions. In this case, the electric field in the \( n \)th layer of the stratified structure can be thus represented

\[
E(x) = A_n e^{i k_n(x-ma)} + B_n e^{-i k_n(x-ma)},
\]

where wave-vector \( k_n = (\omega/c)n_\alpha \) and \( \alpha = 1 \) or 2 corresponding to the period dielectric layer. \( \omega \) is the angle frequency and \( c \) light velocity. The translation matrix can be obtained by solving the Maxwell’s equations with the boundary conditions properly which relates the complex amplitudes of EM in one layer to those of the next layer. The translation matrix of \( n \)th dielectric layer can be represented as

\[
M_n = \begin{pmatrix}
\cos(k_nh_n) & -i_n \frac{n_{n+1}}{n_n} \sin(k_nh_n) \\
-i_n \frac{n_{n+1}}{n_n} \sin(k_nh_n) & \cos(k_nh_n)
\end{pmatrix},
\]

where \( n_m \) and \( h_m \) are the refractive index and thickness of \( m \)th dielectric layer respectively, and wave-vector \( k_m = (\omega/c)n_m \). Then the transmission (or reflectance) spectra, electric field distributions and photonic band structures can be obtained from the transfer matrix method (TMM) [23–25].

The optical microcavity is designed by introducing a defect slab (W) into the periodic structure (photonic crystal) composed of two kinds of dielectric layers with a large refractive index A and small refractive index B as shown in Fig. 1a with the same thickness of \( L_A = L_B = 0.5a \), where \( a \) is the lattice constant. Since a refractive index of about 20 at some frequencies for special man-made structures have been demonstrated experimentally [26,27], the large refractive index \( n_A \) ranges from 3 to 10 and the small refractive index \( n_B \) is 1 (air). The defect slab (W) changes the optical parameters, that is, increasing or decreasing the refractive index and length. The typical calculated results are shown in Figs. 1 to 4 which include the photonic band structures, transmission spectra, and electric field distributions of the defect states.

3. Results and discussion

In the first case, the periodic structure with large and small refractive indexes of 3.5 and 1 (same thickness of 0.5a) is selected. The optical microcavity consists of a defect layer with a refractive index of 1.5 or 5.5 (thickness of 0.5a), which breaks the periodic structure (refractive index change of \( \Delta n = 2 \)). The photonic quantum well structure is composed of the triple-PC stacked structure (\( AB_{m} / (CD)_{p} \) / (EF)_q). Therefore, the photonic crystal (\( AB_{m} \)) is the front photonic barrier equal to the basic periodic structure (\( m \) is the period number of the photonic crystal). The photonic well is constructed by considering the influence of the defect layer and PC (CD)_p is prepared with a C layer equal to the defect layer \( W \). The D layer selects the background with \( n_C = 1.5 \) (or 5.5) and \( n_D = 1.0 \), the same thickness 0.5a, and period number \( p \) equal to 1. The back photonic barrier is considered based on the additional influence of the defect layer. The PC (EF)_q consist of the E layer equal to the additional refractive index of the defect layer \( \Delta n \), and D layer represent the background and \( n_B = 2.0 \) and \( n_B = 1.0 \) with the same thickness of 0.5a and period number of \( q \) equal to 1. As shown in Fig. 1b, the transmission spectra of the optical microcavity with decreasing (increasing) refractive indexes of the defect layer \( \omega_W = 1.5 \) (5.5) are shown in panel IV (VI) and the transmission spectra of the corresponding equivalent photonic quantum well structures are exhibited in panel V (VII). The defect peaks of the optical microcavities corresponding to the high transmission intensity of peaks (reaching unity) are shown in the PBG region of the basic periodic structure (\( AB_{m} \)). The overall consistency between the transmission spectra of the optical microcavities and PQWS is quite good, except that the calculated defect states of PQWS have shallower and wider dips than those of the optical microcavities. Some defect peaks overlap the high transmission region of the periodic structure (\( AB_{m} \)) when some of them are near the edges of the PBG region. However, the similar frequency position of the defect states in the transmission spectra indicates the suitability of the representative structure of PQWS.

Owing to the similar transmission spectra between the optical microcavities and PQWS, the photonic band structure of PQWS can be used to analyze the defect modes in the optical microcavities. The photonic band structure of the front photonic barrier (\( AB_{m} \)) is shown in panel I (\( n_D = 3.5, n_B = 1.0, L_A = L_B = 0.5a \)) in Fig. 1b, panel II is the photonic band structure of the photon well (CD), composed of the defect layer (\( n_C = 1.5 \) red line or 5.0 blue line, \( L_C = 0.5a \)) and background dielectric (\( n_D = 1.0, L_A = 0.5a \)), and panel III shows the photonic band structure of the back photonic barrier (EF)_q with an additional defect layer (\( n_B = 2.0, L_B = 0.5a \)) and background dielectric (\( n_B = 1.0, L_A = 0.5a \)). Compared to the photonic band structure and transmission spectra, the transmission spectra of the optical microcavities are mainly determined by the photonic band structure of the front photonic barrier (\( AB_{m} \)) and the low transmission regions of optical microcavities are consistent with the PBG region of the front photonic barrier (\( AB_{m} \)). The positions of the defect peaks in the transmission spectra are mainly determined by the passbands in the photonic band structure of the photonic well (CD). The defect peaks in the optical microcavities can be attributed to the confinement of photonic well passbands by the photonic band gap region of the photonic barriers. With regard to the optical microcavity with a small refractive index defect layer \( \omega_W = 1.5 \) (panel IV), there are four defect peaks in each PBG region of the front photonic barrier in the transmission spectra and only three passbands appear from the photonic band structure of the photonic well (panel II). According to the photonic band structure of PQWS, the first defect peak at the frequency \( f = 0.2175 \) stems from confinement of the first passband of the photonic well by PBG of the front photonic barrier. As a result of the wide frequency region of the second passband of the photonic well, the second and third defect states arise from confinement of the second passband of the photonic well by the front photonic barrier (\( AB_{m} \)) and/or the back photonic barrier (EF)_q. The second defect state (\( f = 0.5116 \)) stays in the PBG region of the front photonic barrier (\( AB_{m} \)) and third defect state (\( f = 0.6347 \)) is in both the PBG region of the photonic barriers (\( AB_{m} \)) and (EF)_q. The fourth defect state at the frequency of 0.9102 is produced by the third passband of the photonic well and mainly confined by PBG of the front photonic barrier. Concerning the optical microcavity comprising the defect layer with a large refractive index of \( \omega_W = 5.5 \), there are four defect states (panel VI) in each PBG region of the front photonic barrier. There are six passbands in the photonic band structure of the photonic well (panel II). The first (fourth) passband of the photonic well overlaps the first (third) passband of the front photonic barrier and the related defect peaks disappear from the transmission spectra of the
Fig. 1. (a) Schematic of the one-dimensional optical microcavity and equivalent photonic quantum well structure composed of a triple photonic crystal (PC) with a front photonic barrier (AB) and back photonic barriers (EF) and photonic well (CD). The periodic structure has high and low refractive indexes of 3.5 and 1 (same thickness of 0.5). (b) Transmission spectra of the optical microcavity (panel IV) with decreasing refractive index of the defect layer ($n_W = 1.5$, $L_W = 0.5$) and equivalent photonic quantum well structure (panel V) are shown. Panels I, II, and III are the photonic band structures of PCs (AB), (CD), and (EF) respectively. (c) Electric field distributions of the defect states of the optical microcavities with a defect layer by (d) decreasing ($n_W = 1.5$) and (d) increasing ($n_W = 5.5$) the refractive index. The defect states are marked by the Roman numerals from low frequencies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

optical microcavities. The first defect peak ($f = 0.2040$) is related to the second passband of the photonic well confined by the photonic bandgap of the front photonic barrier and the second (third) defect peak at the frequency $f = 0.3792$ (0.7093) is the confined state of the third (fifth) passband of the photonic well by the PBG of the photonic barriers. The fourth defect peak ($f = 0.8862$) represents the confined state of the sixth passband of the photonic well by PBG of the front photonic barrier.

An optical microcavity can also be constructed by introducing a defect slab (W) into the periodic structure with increasing or decreasing length (same refractive index). Since the optical length can be used to describe the optical characteristics of the dielectric layer (defined as refractive index times length), the different lengths of the defect layer can be translated into different refractive indexes with the same optical length. In the first group, the periodic structure with large
and small refractive indexes of 3.5 and 1 is chosen. When the defect layer is introduced by decreasing (or increasing) the length $\Delta L = 0.2$, that is, the thickness of the defect layer is 0.3$a$ (or 0.7$a$) with a refractive index of 3.5. To keep the same optical length of 0.5$a$, similar optical microcavities are designed by introducing a defect layer with a refractive index of 2.1 (or 4.9) corresponding to a change in the refractive index of $\Delta n = 1.4$. The equivalent photonic quantum well structure has the triple-PC stacked structure $(AB)_{m}/(CD)_{p}/(EF)_{q}$, as described before. Fig. 2a depicts the photonic band structure of the photonic well and the photonic barriers are shown in panels I, II, and III. The transmission spectra are acquired from the optical microcavities comprising defect layers with decreasing thickness 0.3$a$ (panel IV) and increasing thickness 0.7$a$ (panel VI) (same refractive index of $n_{W} = 3.5$) and the transmission spectra of the related equivalent photonic quantum well structures are displayed in panels V and VII, respectively. Except that the defect states have shallower and wider dips than those of the optical microcavities, the transmission spectra of the optical microcavities with different thicknesses to different refractive indexes in the design of the triple-PC stacked PQWS.

For the optical microcavity with a defect layer thickness of $L_{W} = 0.3$a, photonic defect states are observed from the transmission spectrum (panel IV) in the first, second, and fourth PBG regions of the front photonic barrier corresponding to the three passbands of the photonic well (panel II). The defect peak is not clear in the third PBG region of the front photonic barrier due to the limited third passband of photonic well into the third PBG region of the front photonic barrier. The first (third) defect peak at a frequency of $f = 0.1662$ (0.8803) arises from the first (third) passband of the photonic well confined by PBG of the front photonic barrier and the second defect state at the frequency of $f = 0.4711$ stems from the second passband of the photonic well confined by both PBG of the photonic barriers. With regard to the optical microcavity with a defect layer thickness of $L_{W} = 0.7$a, there are six passbands (panel II) and only four defect states appear from the transmission spectrum (panel VI), which stay in each PBG region of the front photonic barrier. The first (fifth) passband of the photonic well overlaps the first (fourth) passband of the front photonic barrier and the defect peaks disappear from the transmission spectrum of the optical microcavities. The first (third, fourth) defect peak is due to the second (fourth, sixth) passband of the photonic well confined by PBG of the front photonic barrier and the second defect peak ($f = 0.4198$) shows confinement of the third passband of the photonic well by both PBG of the photonic barriers.

To further investigate the defect peaks in the optical microcavities, the electric field distributions of the defect states of the different optical microcavities are shown in Figs. 1–2. The incident EM waves are the defect peaks in the transmission spectra and the magnitude of the incident electric field is unity. The same electric field intensities are selected in order to compare the confinement properties of different defect peaks of the optical microcavities. The two dashed lines indicate the region of the defect layer in the optical microcavities. The electric fields are mainly confined in the defect layer of the optical microcavities, although the attenuated wings penetrate the adjacent PC layers indicating that the defect peaks in the transmission spectra originate from confinement of EM in the defect layer. Localization of defect states in the optical microcavities enables the photons to be transmitted in the photonic structure by resonance tunneling and the transmission of the defect states can reach unity [9,10]. Different incident EM waves of the defect peaks can result in different electric field distributions and the various defect peaks in the optical microcavities are associated with the different electric field oscillation modes. Fig. 1c shows the electric field distributions of the optical microcavities with a small refractive index of the defect layer ($n_{W} = 1.5$). There is one envelope oscillation peak for the first defect state (panel I, no cross-point in the defect layer) corresponding to the confined state of the first passband.

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**Fig. 2.** Structure with large and small refractive indexes 3.5 and 1 (same thickness of 0.5): (a) The transmission spectra of the optical microcavity fabricated by inserting a defect layer with decreasing ($L_{W} = 0.3$, panel IV) and increasing thickness ($L_{W} = 0.7$, panel VI) (refractive index 3.5) are shown. Panels V and VII are the transmission spectra of the equivalent PQWSs. The photonic band structures of PCs $(AB)m/(CD)q/(EF)p$ are shown from panels I to III. Electric field distributions of the defect states are shown for optical microcavities for (b) decreasing ($L_{W} = 0.3$) or (c) increasing ($L_{W} = 0.7$) thickness defect layer (refractive index of 3.5). The defect states are marked by the Roman numerals from low frequencies.
of the photonic well. For the second and third defect states (panels II and III), there is one cross-point in the defect layer and they are produced from the second passband of the photonic well confined by the photonic barrier. There are two envelope oscillation peaks where the electric field distribution is symmetrical about the middle point of defect layer. Similarly, for the fourth defect peak (panel IV), there are two cross-points in the defect layer (three envelope oscillation peaks) and the fourth defect peak is associated with confinement of the third passband of the photonic well by the photonic barrier. Since the electric field distribution of the defect peaks is similar to the energy level model in quantum physics [28], the defect peaks in the optical microcavities originate from different level defect states corresponding to the related passband of the photonic well. For the optical microcavity with a small refractive index \( n_{\text{w}} = 1.5 \), the first (fourth) defect peak in the transmission spectrum is the first (third)-level defect state corresponding to confinement of the first (third) passband of the photonic well by the photonic barriers. The second and third defect peaks are both second-level defect states associated with confinement of the second passband of the photonic well by the photonic barriers. The third defect state \( f = 0.6347 \) shows the maximum electric field intensity and the passband of photonic well is confined by both PBG of the photonic barriers. Fig. 1d depicts the electric field distributions of the optical microcavities with a large refractive index of the defect layer \( n_{\text{w}} = 5.5 \). Owing to omission of the first passband of the photonic well, the first defect peak (panel I) shows the confinement of the second passband of the photonic well by the photonic barrier PBG. There is one cross-point in the defect layer corresponding to two envelope oscillation peaks and second-level defect state. The third-, fifth-, and sixth-level defect states corresponding to the related passband of the photonic well confined by the photonic barrier PBG are shown in panels II, III, and IV, respectively. The fourth-level defect state disappears due to the overlap of the fourth passband of the photonic well with that of the front photonic barrier. Compared to the intensity of the electric field, the third defect state (panel III, \( f = 0.7093 \)) shows the maximum EM intensity that is almost 3 times larger than that of the first defect state because the fourth passband of the photonic well is confined by both PBG of the photonic barriers. However, it is noted that the interface effect is important when the electric fields are localized at the interface between the periodic structure and defect layer. The high frequency EM waves enhance the decay mode along the interface and so the complex decay modes of the band structure should be considered [29–32].

Similar electric field distributions are observed from the optical microcavities with defect layers of different thicknesses. Fig. 2b shows the electric field distributions of the defect peaks with a defect layer thickness of \( L_{\text{w}} = 0.3a \). The first, second, and third-level defect states can be observed from the electric field distributions based on the related passband of the photonic well confined by the photonic barriers. The second-level defect state (panel II, \( f = 0.47711 \)) shows the maximum localization electric field intensity which is almost 15 times that of the first defect state corresponding to the confinement of the second passband of the photonic well by both PBG of the photonic barriers. Fig. 2c shows the electric field distribution of the defect peaks in the optical microcavity with a defect layer thickness of \( L_{\text{w}} = 0.7a \). Because of overlapping between the first and fifth passbands of the photonic well by the front photonic barrier, the first-level and fifth-level defect states disappear. The second, third, fourth, and sixth-level defect states can also be observed from the electric field distribution (from I to IV). The third-level defect state (panel II, \( f = 0.4198 \)) shows the maximum electric field intensity in the defect layer and it is almost 10 times that of the first defect state corresponding to the defect states, where the passband of photonic well is confined by both PBG of the photonic barriers. Based on these results, there are three kinds of defect states according to the confinement effect of the passband of the photonic well by the photonic barrier. The first one is the localized state in which the passband of the photonic well is confined by both PBG of the two photonic barriers and it shows the maximum confinement effect in the optical microcavity. The second one is the pseudo-localized state in which the passband of photonic well is confined only by the front photonic barrier. Only the localized and pseudo-localized states show the defect peaks in the transmission spectra of the optical microcavities. The third one is the non-localized mode in which the passband of photonic well overlaps that of the front photonic barrier and the defect peaks disappear from the transmission spectra.

For further investigation, a refractive index of 6.0 is selected to construct the optical microcavities (small refractive index of 1.0 and the same thickness of 0.5a). The optical microcavity is designed by breaking the periodic structure with a change in the refractive index of \( \Delta n = 1.5 \) (same thickness of 0.5a), corresponding to introducing a defect layer with smaller \( (n_{\text{w}} = 4.5) \) or larger refractive indexes \( (n_{\text{w}} = 7.5) \). A similar method is adopted to design the triple-PC stacked PQWS (\( \text{AB}_{\text{w}}/(\text{CD})_{\text{w}}/\text{EF}_{\text{w}} \)). The calculated photonic band gap and transmission spectra of the optical microcavities and PQWSs are displayed in Fig. 3a and the related electric field distributions of the defect states are presented in Fig. 3b and c. Comparing the transmission spectra of the optical microcavities and PQWSs in Fig. 3a, there is good consistency between the transmission spectra of the optical microcavities and related PQWS, except that the defect states have shallower and wider dips than those of the optical microcavities. For the optical microcavity composed of a smaller refractive index defect layer \( (n_{\text{w}} = 4.5) \), the five defect peaks (panel IV) are the defect states from the first to five-level, which can be judged from the electric field distributions (from panel I to V in Fig. 3b) corresponding to the related passband of the photonic well confined by the photonic barriers. The third-level defect state (panel III, \( f = 0.4465 \)) shows the maximum localization electric field intensity in the defect layer that is almost 100 times that of first defect state, corresponding to the confinement of third passband of the photonic well by both PBG of the photonic barriers. For the optical microcavity with the large refractive index defect layer \( (n_{\text{w}} = 7.5) \), there are eight passbands (panel II) and only six defect peaks appear from the transmission spectrum (panel VI). The first-level and sixth-level defect states disappear from the transmission spectrum due to the overlap of the first and sixth passbands of the photonic well by the front photonic barrier. In this case, according to the number of envelope oscillation peaks in the electric field distributions of the defect states from panel I to VI (Fig. 3c), the defect peaks are the second, third, fourth, fifth, seventh and eighth-level ones corresponding to the confinement effect of the related passband in the photonic well by the photonic barrier. The third (fifth) defect state with a frequency of \( f = 0.4042 \) (0.7798) is the localized state corresponding to the fourth (seventh) passband of the photonic well confined by both PBG regions of the photonic barriers. The third defect state (panel III) shows the maximum electric field intensity in the defect layer and it is almost 100 times that of the first defect state. The electric field intensity is smaller (almost the same as that of the first defect state) in the defect layer for the fifth defect peak (panel V). It may arise from the interface effect that the electric fields are mainly localized at the interface between the defect layer and periodic structure as shown by the electric field distribution (panel V).

Defect layers with a smaller (or larger) length of \( \Delta L = 0.2 \) are introduced, that is, thickness of the defect layer being 0.3a (or 0.7a) and refractive index being 6.0. To keep the same optical length, new optical microcavities are designed by incorporating defect layer with a refractive index of 3.6 (or 8.4) with \( \Delta n = 2.4 \) (thickness of 0.5a). The equivalent PQWSs can also be fabricated with triple-PC stacked structure (\( \text{AB}_{\text{w}}/(\text{CD})_{\text{w}}/\text{EF}_{\text{w}} \)). Fig. 4a shows the results of the photonic band gap and transmission spectra of the optical microcavities and PQWSs and the related electric field distributions of the defect states are shown in Fig. 4b and c. The consistency between the transmission spectra of the optical microcavities and PQWSs is quite good except that the defect states exhibit shallower and wider dips than those of the optical microcavities. For the optical microcavity with a thinner defect layer \( (L_{\text{w}} = 0.3a) \), the confinement effects of the four passbands of...
The transmission spectra of optical microcavities with decreasing periodic structure with large and small refractive indexes of 6 and 1 (same Fig. 3. L. Shi, S. Xu, D. Xiong et al. Optics Communications 458 (2020) 124880 states are marked by the Roman numerals from low frequencies.

(b) decreasing ($n = 4.5$, panel IV) and increasing refractive index ($n = 7.5$, panel VI) are shown. Panels V and VII show the related transmission spectra of PQWSs. The photonic band structures of PCs (AB) $p$ and (CD)$q$ are also shown from panels I to III. The electric field distributions of the defect states (Fig. 4c) verify localization of the defect states. The fifth defect state (panel V, $f = 0.5911$) is the localized state of the sixth passband of the photonic well confined by both PBG regions of the photonic barriers. It shows a maximum EM wave intensity that is almost 40 times that of the first defect state. The second defect state (panel II, $f = 0.2512$) is also the localized state related to the third passband of the photonic well confined by both PBG regions of the photonic barriers with an EM wave intensity that is almost 15 times that of the first defect state, suggesting that the localized states have different degree of localization and more localized states near the center of the front photonic barrier PBG.

For the optical microcavity with a thicker defect layer ($L_0 = 0.7$), there are nine passbands (panel II) and seven defect peaks in the transmission spectrum (panel VI). The first-level and eight-level defect states disappear due to the overlap of the first and eighth passbands of the photonic well by the front photonic barrier. The first and fourth defect peaks stay at the same third PBG region of the front photonic barrier. In this case, the defect peaks are the second, third, fourth, fifth, sixth, seventh, and ninth-level ones corresponding to the confinement effect of the related passband in the photonic well by the photonic barrier. The number of envelope oscillation peaks in the electric field distributions of the defect states (Fig. 4c) verify localization of the defect states. The fifth defect state (panel V, $f = 0.5911$) is the localized state of the sixth passband of the photonic well confined by both PBG regions of the photonic barriers. It shows a maximum EM wave intensity that is almost 40 times that of the first defect state. The second defect state (panel II, $f = 0.2512$) is also the localized state related to the third passband of the photonic well confined by both PBG regions of the photonic barriers with an EM wave intensity that is almost 15 times that of the first defect state, suggesting that the localized states have different degree of localization and more localized states near the center of the front photonic barrier PBG.

Fig. 5 depicts the electric field intensity of the two different structures: (a) large refractive index of 3.5 and small refractive index of 1.0 and (b) large refractive index of 6.0 and small refractive index of 1.0. The electric field intensity of the localized states varies from 100 to 400 for the first case (Fig. 5a) and 1000 to 5000 for the second case (Fig. 5b) indicative of different extent of localization. The degree of localization of the defect states is determined by not only the defect peak position in the PBG of the front photonic barrier, but also the structural parameters of the periodic structure. The different localization degree can also be found from the pseudo-localization states in the optical microcavity. The electric field intensity of the pseudo-localized states varies from 10 to 100 for the first case and 20 to 2000 for the second case. The electric field intensities of some pseudo-localization states are larger than those of the localized states. However, the EM intensities of the localized states are larger than those of the pseudo-localization states totally and so the defect states should be divided into localized and pseudo-localized states. In this case, the model structure of photonic quantum well related to optical microcavities can be used to analysis the experiment results of 1D optical microcavities based on Si/air structure [34–36] and try to design the new optical microcavities with high-Q localized states to realize the low-threshold or threshold-less laser or high-quality filter.
Fig. 4. Periodic structure with large and small refractive indexes of 6 and 1 (same thickness of 0.5): (a) The transmission spectra of optical microcavity with decreasing ($L_\text{W}=0.3$, panel IV) and increasing thickness defect layer ($L_\text{W}=0.7$, panel VI) are shown. Panels V and VII show the related transmission spectra of PQWSs. The photonic band structures of PCs (AB)$^m$, (CD)$^p$ and (EF)$^q$ are shown from panel I to III. The electric field distributions of the defect states are shown for optical microcavities with a defect layer for (b) decreasing ($L_\text{W}=0.3$) and (c) increasing ($L_\text{W}=0.7$) thickness. The defect states are marked by Roman numerals from low frequencies.

Fig. 5. Localized electric field intensity of the defect states in optical microcavities for the periodic structures with large and small refractive indexes (a) 3.5 and 1.0 and (b) 6.0 and 1.0. The localized modes in the defect states are marked by arrows and the interface states are shown with non-solid symbols.

4. Conclusion

In summary, the defect states in optical microcavities are investigated theoretically based on the photonic band structure of the equivalent photonic quantum well structure. The defect states have different levels corresponding to the passbands of the photonic well confined by the photonic barrier depending on the electric field distributions in the defect layer. There are three kinds of defect states, namely the localized, pseudo-localized, and non-localized ones. The localized states show the maximum electric field intensity in the defect layer corresponding to the passbands of the photonic well confined by the photonic band gap of both photonic barriers. Our analysis provides insights into the roles of localized defect states in optical microcavities and design of optical devices such as optical filters and lasers.

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