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Analysis and engineering of coupled cavity waveguides based on coupled-mode theory*

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The analytical expression for the transmission spectra of coupled cavity waveguides (CCWs) in photonic crystals (PCs) is derived based on the coupled-mode theory (CMT). Parameters in the analytical expression can be extracted by simple numerical simulations. We reveal that it is the phase shift between the two adjacent PC defects that uniquely determines the flatness of the impurity bands of CCWs. In addition, it is found that the phase shift also greatly affects the bandwidth of CCWs. Thus, the engineering of the impurity bands of CCWs can be realized through the adjustment of the phase shift. Based on the theoretical results, an interesting phenomenon in which a CCW acts as a single PC defect and its impurity band possesses a Lorentz lineshape is predicted. Very good agreement between the analytical results and the numerical simulations based on transfer matrix method has been achieved.

Keywords: photonic crystals, coupled cavity waveguides, coupled-mode theory, phase shift
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1. Introduction

Optoelectronic devices based on photonic crystals (PCs) are attracting more and more attention because PCs act as a promising platform for the manipulation of photons.[1] One of the key components for future PC integrated circuits is the PC waveguides that can deliver optical signals from one place to another. Basically, PC waveguides can be classified into two types. They are line-defect waveguides and coupled cavity waveguides (CCWs). For CCWs, which were first proposed and investigated by Stefanou and Modinos,[2] the physical mechanism for waveguiding is the evanescent tunnelling of electromagnetic (EM) waves among the constitutional PC defects.[3,4] This novel characteristic makes CCWs more attractive than their counterparts. To date, many studies have been devoted to the physical properties of CCWs[2−9] and CCW-based devices.[10−14] Apparently, the transmission spectra of CCWs are very important for the design and operation of CCW-based devices. The transmission of ultrashort pulses through CCWs has been investigated by Lan *et al.*[5] They indicated that the physical mechanism for the formation of quasiflat impurity bands can be revealed through the discussion of the symmetry of constitutional PC defects and their coupling. By employing the design approach in thin-film optics, Ye *et al*[6] have successfully reduced the oscillation appearing in the transmission spectra of one-dimensional (1D) CCWs by optimizing the parameters of the matching layers at both ends. In most cases, the transmission spectra for the impurity bands of CCWs are obtained by numerical simulations. So far, many simulation tools such as transfer matrix method (TMM) and finite-difference time-domain (FDTD) technique are available for the simulation of PC structures.[15,16] While the simulations based on these techniques are convenient and direct, many physical phenomena and the corresponding mechanisms are usually smeared. Therefore, efficient analytical tools are absolutely necessary in the study of PCs. In recent years, temporal coupled-mode theory (CMT)[17] has been widely employed for the analysis of PC resonators coupled

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with waveguides.[7,18–22] It was first used by Reynolds *et al* in the investigation of CCWs. They developed an expression for the transmission of the corresponding impurity bands, showing that the analytical results can reflect the shape of the transmission spectra of CCWs.[7] However, they did not provide the connection between the involved parameters (e.g., the coupling coefficients) and the configuration of a CCW, which is very important for checking whether the analytical results are in good agreement with the numerical simulations. Very recently, Sanchis *et al* derived an expression for the transmission of ultrashort pulses through CCWs based on a Fabry–Perot model.[8] Although the theoretical calculation is in good agreement with the numerical simulation, a semi-analytical method is needed to extract the involved parameters.[8]

In this article, we present a clear analytical expression for the transmission spectra of CCWs in which the parameters can be easily extracted from simple numerical simulations. Based on the analytical results, we discuss in detail how to control the transmission characteristics of CCWs through the adjustment of the parameters. This paper is organized as follows. In Section 2, we establish the physical model for CCWs and analyse in detail the intrinsic physical properties by use of CMT. A peculiar phenomenon in which a CCW acts as a single PC defect is predicted and discussed. Then, the theoretical results derived in Section 2 are verified by comparing with the simulation results obtained by TMM in Section 3. The factor that determines the flatness of the impurity bands of CCWs is discussed in Section 4. As an application of CCWs, we propose a simple method to control the flatness of the impurity bands of CCWs in Section 5. Finally, a summary of our study is given in Section 6.

2. Theoretical model for CCWs based on CMT

For the sake of simplicity, we discuss the CCWs that are formed by periodically introducing defects along one direction in PCs. The corresponding model that contains N identical PC defects is schematically shown in Fig.1. According to CMT, the equations describing the energy amplitude of the ith PC defect a_i $(i = 1, 2, \dots, N)$ can be written as

$$\frac{\mathrm{d}a_i}{\mathrm{d}t} = \left(\mathrm{j}\omega_0 - \frac{2}{\tau}\right) a_i + \sqrt{\frac{2}{\tau}} s_{+i} + \sqrt{\frac{2}{\tau}} s'_{+i}, \tag{1a}$$

$$s_{-i} = -s_{+i} + \sqrt{\frac{2}{\tau}} a_i, \quad s'_{-i} = -s'_{+i} + \sqrt{\frac{2}{\tau}} a_i, \tag{1b}$$

where ω_0 is the resonant frequency of the PC defects and $1/\tau$ denotes the external decay rate of a_i into one of its two adjacent defects. Here we ignore the internal loss of energy in PC defects. As shown in Fig.1, s_{+i} and s'_{+i} represent the EM waves entering into the ith PC defect from its left and right sides while s_{-i} and s'_{-i} represent the EM waves emerging from the left and right sides of the ith PC defect respectively. Obviously, the EM waves travelling between the ith PC defect and its two adjacent defects satisfy

$$s'_{+i} = \exp(-\mathrm{j}\varphi) s_{-(i+1)}, i = 1, 2, \dots, N-1; \tag{2a}$$

$$s_{+i} = \exp(-\mathrm{j}\varphi) s'_{-(i-1)}, \quad i = 2, 3, \dots, N, \tag{2b}$$

where φ represents the phase shift of the EM wave travelling between the two adjacent PC defects.

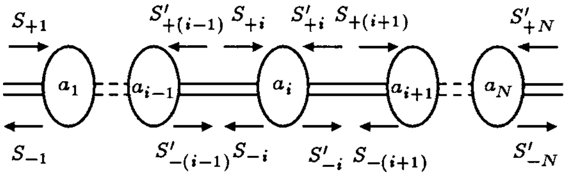

Fig.1. Schematic diagram for CCWs based on CMT.

First, we discuss the situations in which φ is not equal to $k\pi$, where k is an integer including zero. Based on Eqs.(1b) and (2), we have

$$s'_{+i} = \sqrt{\frac{2}{\tau}} \frac{[a_i - a_{i+1}\exp(-\mathrm{j}\varphi)]}{2\mathrm{j}\sin\varphi}, \quad i = 1, 2, \dots, N-1; \tag{3a}$$

$$s_{+i} = \sqrt{\frac{2}{\tau}} \frac{[a_{i-1} - a_i\exp(-\mathrm{j}\varphi)]}{2\mathrm{j}\sin\varphi}, \quad i = 2, 3, \dots, N. \tag{3b}$$

By substituting Eq.(3) into Eq.(1a), we obtain a series of coupled equations describing the time evolutions of a_i $(i = 1, 2, \dots, N)$

$$\frac{\mathrm{d}a_1}{\mathrm{d}t} = \left[\mathrm{j}\left(\omega_0 + \frac{1}{\tau\tan\varphi}\right) - \frac{1}{\tau}\right] a_1 - \mathrm{j}\frac{1}{\tau\sin\varphi} a_2 + \sqrt{\frac{2}{\tau}} s_{+1}, \tag{4a}$$

$$\frac{\mathrm{d}a_i}{\mathrm{d}t} = -\frac{1}{\tau\sin\varphi} a_{i-1} + \mathrm{j}\left(\omega_0 + \frac{2}{\tau\tan\varphi}\right) a_i - \frac{1}{\tau\sin\varphi} a_{i+1}, \quad i = 2, 3, \dots, N-1, \tag{4b}$$

$$\frac{\mathrm{d}a_N}{\mathrm{d}t} = \left[\mathrm{j}\left(\omega_0 + \frac{1}{\tau\tan\varphi}\right) - \frac{1}{\tau}\right] a_N - \mathrm{j}\frac{1}{\tau\sin\varphi} a_{N-1} + \sqrt{\frac{2}{\tau}} s'_{+N}. \tag{4c}$$

From Eq.(4), we find that the coupling between two PC defects depends on two parameters. One is the leakage rate of energy amplitude into the adjacent defect ($1/\tau$), and the other is the phase shift between two adjacent defects (φ). For an external EM wave s_{+1} working at a frequency of ω, the steady form of Eq.(4) can be written as

$$(\alpha-\mathrm{j}\sin\varphi)\,a_1+a_2=-\mathrm{j}\left(\sqrt{\frac{8Q}{\omega_0}}\sin\varphi\right)s_{+1},\quad(5a)$$

$$a_{i-1}+\beta a_i+a_{i+1}=0,\quad i=2,3,\ldots,N-1,\quad(5b)$$

$$a_{N-1}+(\alpha-\mathrm{j}\sin\varphi)\,a_N=0,\quad(5c)$$

where

$$\alpha=4Q\,(\omega/\omega_0-1)\sin\varphi-\cos\varphi,$$

$$\beta=4Q(\omega/\omega_0-1)\sin\varphi-2\cos\varphi,$$

$Q=(\omega_0\tau)/4$. Obviously, Q is the quality factor of the PC defects. Based on Eq.(5), we have

$$a_N=\frac{\left(-\mathrm{j}\sqrt{8Q/\omega_0}\sin\varphi\right)s_{+1}}{\left[\left(\alpha^2-\sin^2\varphi\right)A_{N-2}-2\alpha A_{N-3}+A_{N-4}\right]+\mathrm{j}2\sin\varphi\left(-\alpha A_{N-2}+A_{N-3}\right)},\quad(6)$$

where A is a series function of β that satisfies A_{-1}=0, A_0=1, and A_m=$\beta A_{m-1}-A_{m-2}$ ($m=1,2,3,\ldots N$). Using Eqs.(6) and (1b), we obtain the transmission spectrum of a CCW

$$T_N=\left|\frac{s'_{-N}}{s_{+1}}\right|^2=\frac{4\sin^2\varphi}{\left[\left(\alpha^2-\sin^2\varphi\right)A_{N-2}-2\alpha A_{N-3}+A_{N-4}\right]^2+4\sin^2\varphi\left(-\alpha A_{N-2}+A_{N-3}\right)^2}.\quad(7)$$

Apart from the frequency ω of the incident wave, Eq.(7) shows that the transmission spectrum of a CCW also depends on three parameters, i.e. the resonant frequency of the PC defect (ω_0), the quality factor of the PC defect (Q) and the phase shift between the two PC defects (φ). We will show below that these parameters can be extracted from a simple numerical simulation. Therefore, it is easy to verify whether Eq.(7) correctly describes the transmission spectra of CCWs.

It is emphasized that Eq.(7) is suitable only for N is equal to or larger than 3. For N=2, i.e., a PC molecule, the equation describing the coupling of three PC defects (Eq.5(b)) does not exist. In this case, only two coupled equations 5(a) and 5(c) are needed to derive the transmission spectrum of a PC molecule T_2 which is given as follows:

$$T_2=\left[T_0^{-1}-8Q^2\cos^2\varphi\left(\frac{\omega}{\omega_0}-\frac{1}{4Q\tan\varphi}-1\right)^2+64Q^4\sin^2\varphi\left(\frac{\omega}{\omega_0}-\frac{1}{4Q\tan\varphi}-1\right)^4\right]^{-1},\quad(8)$$

where

$$T_0=4\left(2+\sin^{-2}\varphi+\sin^2\varphi\right)^{-1}.\quad(9)$$

In the following discussion, it is temporarily assumed that the phase shift φ is not sensitive to the frequency of the EM waves, at least in the narrow frequency range we considered. We will confirm later the validity of this assumption by comparing the transmission spectra of CCWs calculated by CMT with those obtained by TMM simulation. According to Eq.(8), it is easy to deduce that the two peaks in the transmission spectrum corresponding to the bonding and antibonding states of the PC molecule appear at ω=ω_0 and ω=ω_0 [1+$(2Q\tan\varphi)^{-1}$]. The transmissions at the two peaks (i.e., the maximum value of T_2) are equal to unity. Also, we find that T_0 is the transmission at the valley in between the two peaks. The corresponding frequency is ω=ω_0 [1+$(4Q\tan\varphi)^{-1}$]. From Eq.(9), it is remarkable that T_0 depends only on the phase shift φ and has nothing to do with the other two parameters (i.e. ω_0 and Q). Based on the discussion, we can extract the three parameters (ω_0, Q and φ) from the simulated transmission spectrum of the PC molecule. Of course, both ω_0 and Q can be also extracted easily from the simulated transmission spectrum of one PC defect.

It is necessary to note that so far we have not made any approximations in the derivation of Eq.(7). Therefore, it provides a simple way to exactly calculate the transmission spectrum of a CCW consisting of N identical PC defects. Although the dependences of transmission spectrum on the involved parameters Q, ω_0, and φ are not apparent in Eq.(7), it is easy to discuss this issue by directly calculating the transmission spectra for various CCWs.

As mentioned above, Eqs.(3)–(7) are not suitable for the case when the phase shift φ happens to be $k\pi$, where k is an integer including zero. Thus, we wonder what the transmission spectra of CCWs look like under such a special condition. By substituting $\varphi=k\pi$ into Eq.(2) and combining with Eq.(1b), we find

$$s'_{+i} \pm s_{+(i+1)} = \sqrt{\frac{2}{\tau}} a_i = \pm\sqrt{\frac{2}{\tau}} a_{i+1}, \quad i = 1, 2, \ldots, N-1, \tag{10}$$

where "+" and "–" correspond to the situations in which k is even (including zero) and odd, respectively. For all of the equations that describe the time evolution of the energy amplitude of PC defects, i.e., Eq.(1a), we make a performance described as follows

$$\begin{aligned}&\left(\frac{\mathrm{d}a_1}{\mathrm{d}t} \pm \frac{\mathrm{d}a_2}{\mathrm{d}t}\right) + \left(\frac{\mathrm{d}a_3}{\mathrm{d}t} \pm \frac{\mathrm{d}a_4}{\mathrm{d}t}\right) + \cdots \\ &= \left(\mathrm{j}\omega_0 - \frac{2}{\tau}\right)[(a_1 \pm a_2) + (a_3 \pm a_4) + \cdots] \\ &\quad + \sqrt{\frac{2}{\tau}}[(s_{+1} + s'_{+1}) \pm (s_{+2} + s'_{+2}) \\ &\quad + (s_{+3} + s'_{+3}) \pm (s_{+4} + s'_{+4}) + \cdots],\end{aligned} \tag{11}$$

where $\pm$ have the same meaning mentioned above. Substituting Eq.(10) into Eq.(11), it turns out to be

$$\frac{\mathrm{d}a_i}{\mathrm{d}t} = \left(\mathrm{j}\omega_0 - \frac{2}{N\tau}\right) a_i + \frac{1}{N}\sqrt{\frac{2}{\tau}}\left(s_{+1} + s'_{+N}\right), \quad (i = 1, 2, 3, \ldots, N), \tag{12}$$

no matter whether k is even or odd. It is interesting to note that all PC defects are able to couple directly with the external input waves s_{+1} and s'_{+N}, showing that the coupling between adjacent PC defects are the strongest of all. Under the circumstances, the steady solution of Eq.(12) for a single input wave s_{+1} can be expressed as

$$a_i = \left(\frac{1}{N}\sqrt{\frac{2}{\tau}}\right)\frac{s_{+1}}{\mathrm{j}(\omega - \omega_0) + 2/(N\tau)}, \quad (i = 1, 2, 3, \ldots, N). \tag{13}$$

Accordingly, the transmission spectrum of the CCW can be obtained by using Eqs.(13) and (1b). It has the form

$$T_N = \left|\frac{s'_{-N}}{s_{+1}}\right|^2 = \left[1 + 4(NQ)^2(\omega/\omega_0 - 1)^2\right]^{-1}. \tag{14}$$

Obviously, the spectrum of the CCW in this case has a Lorentz lineshape. Comparing Eq.(14) with the transmission spectrum of a single PC defect, which is $\left[1 + 4Q^2(\omega/\omega_0 - 1)^2\right]^{-1}$, we find that the quality factor of the CCW appears to be N times that of the single PC defect. Therefore, it becomes clear that the CCW acts as a single PC defect when the phase shift φ happens to be $k\pi$. It is reasonable to consider Eq.(14) as the limit case of Eq.(7) under the condition of φ being close to $k\pi$ despite of the difficulty in derivation. Nevertheless, it is easy to be verified later by numerical simulation.

3. Comparison of the results obtained by CMT and TMM

So far the dimensions of PCs and CCWs have not been mentioned, thus the analytical results we derived above are suitable for CCWs of any dimensions. For the sake of simplicity, we consider in this article CCWs based on 1D PCs. A typical example is shown in Fig.2. The 1D PC consists of an array of identical dielectric layers (n=3.4) embedded in air (n_0=1.0). The thickness of the dielectric layers is 0.50a, where a is the lattice constant. The first band gap of the 1D PC ranges from 0.150c/a to 0.270c/a, where c is the speed of light in vacuum. The PC defects forming the CCW are introduced periodically by modifying the thickness of the dielectric layers to a value of d. One of the PC atoms constituting the CCW is indicated by a dashed box in Fig.2. In order to derive the phase shift φ, we first simulate the transmission spectrum of a PC molecule by use of TMM and obtain the minimum transmission T_0 in between the two peaks. Then, the phase shift can be extracted by using Eq.(9). Thus, we can establish the relationship between the phase shift φ and the defect thickness d, as shown by the filled circles in Fig.3. It is found that φ decreases monotonically from 0.50π to 0.00π when d is increased from 0.00a to 0.50a. As d is further increased from 0.50a to 1.00a, φ experiences an increase and a decrease processes and its value ranges from 0.50π to 0.28π.

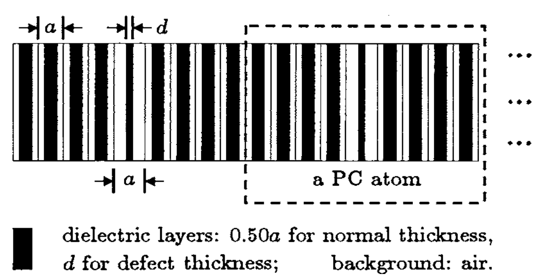

Fig.2. Schematic of the 1D CCW studied in this paper. One of the constitutional PC atoms is indicated by the dashed box.

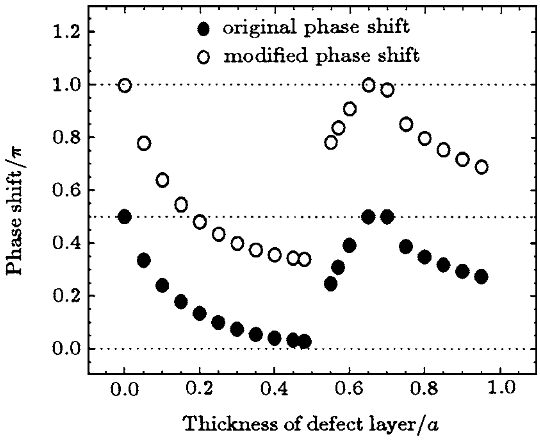

Fig.3. Relationship between the phase shift and the thickness of the defect layer for the original 1D CCW (filled circles) and the modified 1D CCW (empty circles).

Now we examine the transmission spectra of the CCWs constructed by three types of defects. The three PC defects are intentionally chosen to be located at the different frequency regimes in the band gap. They are defect A near the air band (d=0.00a, ω_0= 0.248c/a, Q=458, φ=0.50π), defect B in the middle of the band gap (d=0.90a, ω_0= 0.217c/a, Q=2525, φ=0.29π), and defect C near the dielectric band (d=0.30a, ω_0= 0.163c/a, Q=274, φ=0.07π).

Based on Eq.(7), we have calculated the transmission spectra of the three CCWs consisting of 10 defects. They are depicted by the solid curves in Figs.4(a)–(c), respectively. Meanwhile, the transmission spectra of the three CCWs simulated by TMM are also shown by dashed curves in Figs.4(a)–(c) for comparison. Despite of the ripples appearing in the spectra, it is observed that the spectra calculated by CMT are in good agreement with those simulated by TMM. It is remarkable that the two spectra shown in Fig.4(b) for d=0.90a are exactly the same. Of course, it is also noticed that there exists a discrepancy to some extent for the case of d=0.30a. While the two spectra are overlapped in the low-frequency region, some deviations appear in the high-frequency region. It is considered that the coupling between the defect mode and the continuum modes in the dielectric band is responsible for the deviations observed. Therefore, we can confirm that Eq.(7) is valid for quantitatively expressing the transmission spectra of CCWs. In addition, it is also confirmed that the phase shift is nearly independent of the frequency at least in the frequency range of the spectrum.

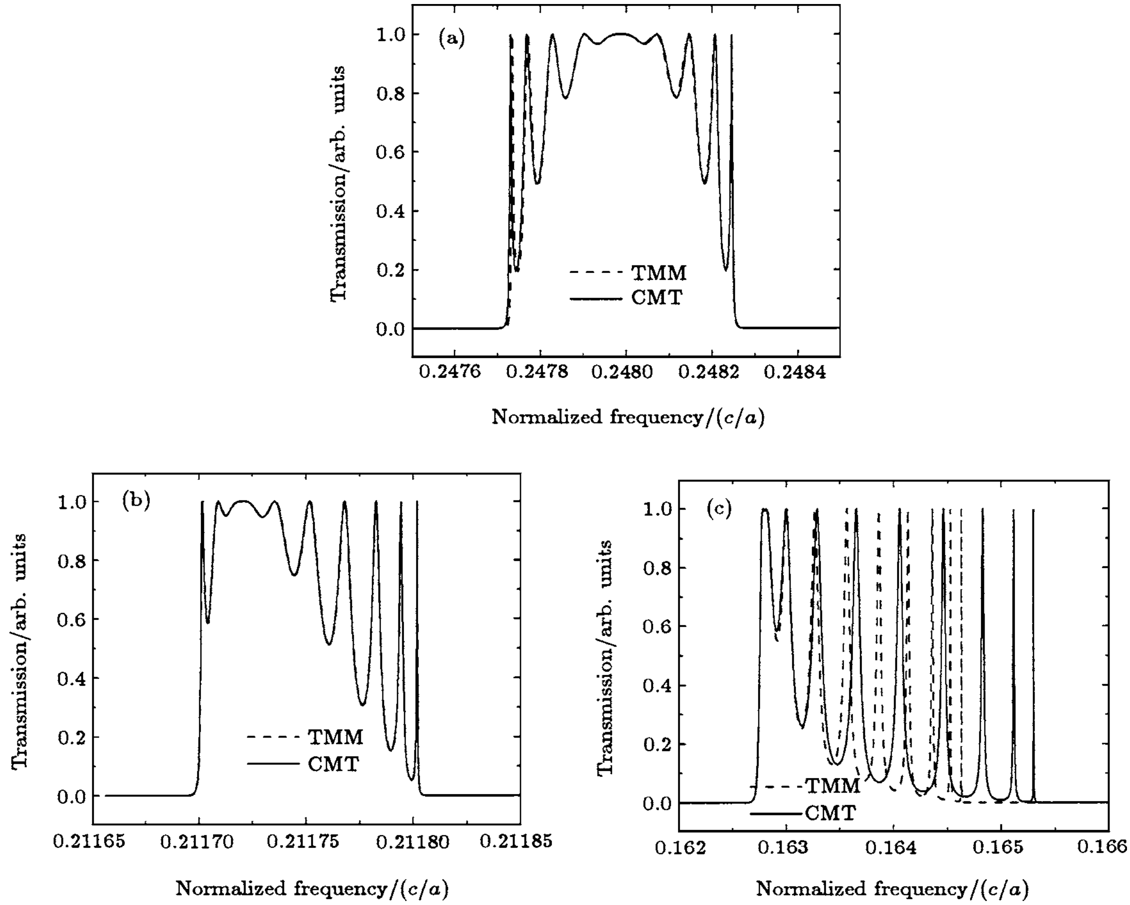

Fig.4. Comparison of the transmission spectra calculated by CMT (solid curves) and those simulated by TMM (dashed curves) for three 1D CCWs. (a) d=0.00a; (b) d=0.90a; (c) d=0.30a.

By carefully inspecting Figs.4(a)–(c), it is suggested that the ripples appearing in the impurity bands are closely related to the phase shift φ. For φ=0.50π (see Fig.4(a)), the spectrum is dominated by a central quasi-flat part with only very small ripples at both sides. As φ drops to 0.29π (see Fig.4(b)), it is observed that the quasi-flat part shrinks and moves to a lower frequency. Meanwhile, the ripples in the spectrum become bigger. When φ is further reduced to 0.07π, the quasi-flat part almost disappears and the big ripples begin to dominate the spectrum, as shown in Fig.4(c).

4. Factor that determines the flatness of an impurity band

In practical applications, the flatness of the impurity bands of CCWs is very important for the transmission of ultrashort pulses with negligible attenuation and distortion. According to Eq.(7), it is found that the parameters ω_0 and Q affect only the location and bandwidth of CCWs. In other words, they have nothing to do with the flatness of the impurity bands. On the other hand, we have observed that the flatness of the impurity bands varies as φ is changed, as shown in Fig.4. Therefore, it is necessary to discuss the role of φ in determining the spectral shape.

Without losing generality, we consider again a CCW consisting of 10 identical defects with a resonant frequency of ω_0 and a Q factor of 500. To systematically show the dependence of the impurity band on the phase shift φ, we present the evolution of the impurity band of the CCW with the increase of φ in Fig.5 by using Eq.(7). It can be seen that the flatness and bandwidth of the impurity band vary periodically with the increase of φ. When $\varphi = (k+1/2)\pi$, the flattest impurity band, which is only a quasi-flat one, can be achieved. The filled circles in Fig.3 indicate that the condition of $\varphi = (k+1/2)\pi$ is fulfilled for d=0.00a and d = 0.65a − 0.70a in the 1D CCW we studied. Therefore, the CCW shown in Fig.4(a) possesses a quasi-flat impurity band. In Fig.5, we also observed that the impurity band appears to have a Lorentz lineshape when φ is close to 0 or π. This phenomenon is in good agreement with what we have predicted in Sec.2. In Fig.3, we find that φ is close to 0 when d is close to 0.50a, i.e., the thickness of the normal dielectric layer in our 1D CCW model. Unfortunately, such a defect mode actually links to the continuum modes of the dielectric band in frequency domain, making Eq.(1a) no longer valid. Accordingly, the impurity band is not a true Lorentz shape when d is very close to 0.50a for the 1D CCW we studied.

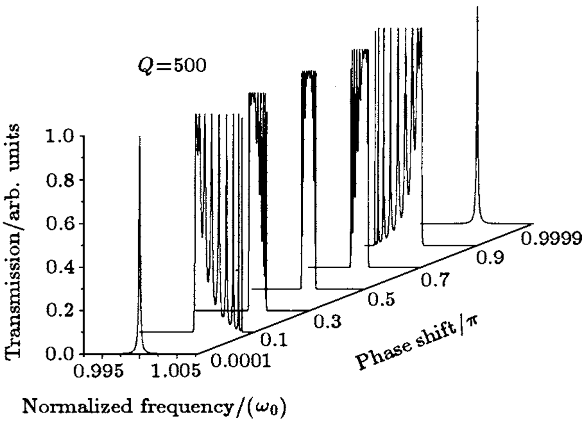

Fig.5. Evolution of the impurity band of a 1D CCW (Q=500) with the increase of the phase shift based on the calculation of CMT.

5. Control of the impurity bands of CCWs

Having known the physical mechanism of defect coupling in CCWs, we suggest a simple way to control the flatness of the impurity bands of CCWs through the adjustment of phase shift φ. It is apparent that we can increase the phase shift by intentionally separating the adjacent PC atoms by a distance of L. To do so, the other parameters ω_0 and Q remain unchanged. As a result, the phase shift is increased to (φ +2$\pi L/\lambda$), where λ is the resonant wavelength of the PC defects. We can achieve a quasi-flat impurity band when (φ +2$\pi L/\lambda$) = $(k+1/2)\pi$ or we can obtain an impurity band with a Lorentz lineshape when (φ +2$\pi L/\lambda$)=$k\pi$. Of course, new PC defects will be created when we intentionally separate the adjacent PC atoms by a distance of L. Therefore, we must avoid the situation in which the frequency location of the new defect mode is too close to the defect mode used for the construction of CCWs. Otherwise, some unexpected couplings may occur.

Consider the situation of $L = a$. The relationship between the modified phase shift (φ +2$\pi L/\lambda$) and the defect layer thickness d is shown in Fig.3 by empty circles. It is deduced that the condition φ +2$\pi L/\lambda$=$(k+1/2)\pi$ is satisfied when d=0.19a. Similarly, the condition φ +2$\pi L/\lambda$=$k\pi$ is fulfilled when d=0.65a. Therefore, impurity bands of quasi-flatness and of Lorentz lineshape are expected for $d \sim 0.19a$ and $d \sim 0.65a$, respectively.

Figure 6(a) shows the simulation result of a modified CCW in which d=0.188a.Apparently,a quasi-flat impurity band is realized. As a comparison, the impurity band for the original CCW is presented in Fig.6(b). We can observe that this spectrum is dominated by deep ripples and only a small part is of quasi-flatness. We must emphasize here that the values of ω_0 and Q remain unchanged in the modified CCW. Therefore, it is the change of the phase shift that modifies the flatness of the impurity band. It is also noticed that the bandwidth becomes narrower when the spectral shape becomes quasi-flat. The variation of the shape and bandwidth of the impurity band is in good agreement with the theoretical result shown in Fig.5.

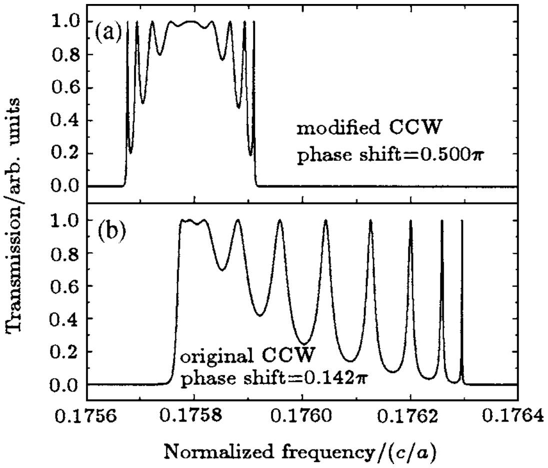

Fig.6. Comparison of the transmission spectra of two 1D CCWs in which d=0.188a. (a) Modified CCW in which the PC atoms are intentionally separated by a distance of a; (b) original CCW without any modification.

Similarly, the impurity band of the modified CCW in which d=0.653a is also simulated and depicted in Fig.7(a) by the solid curve. It possesses a Lorentz lineshape similar to the simulated spectrum of a single PC defect shown by the dashed curve. However, the linewidth is much narrower than that of the PC defect. The impurity band of the original CCW is shown in Fig.7(b) for comparison. Again, we can see the effects of the phase shift on the shape and width of the impurity band. A remarkable feature in Fig.7(a) is that the linewidth of the modified CCW is exactly one-tenth of that of the single PC defect. In other words, its Q factor is ten times that of the single PC defect. This verifies the validity of Eq.(14).

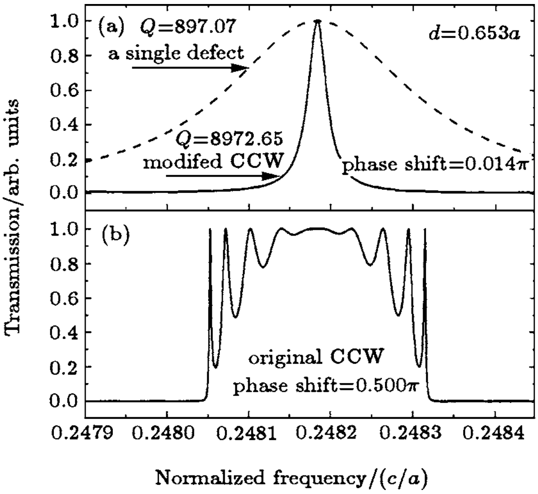

Fig.7. Comparison of the transmission spectra of the 1D CCWs in which d=0.653a. (a) Modified CCW in which the PC atoms are intentionally separated by a distance of a. The spectrum of a single PC defect (a single PC atom) is presented by the dashed curve for comparison. (b) Original CCW without any modification.

6. Conclusion

In summary, we have derived the analytical expression for the transmission spectra of CCWs in the framework of CMT. It is revealed that the flatness of the impurity bands of CCWs is uniquely determined by the phase shift of the EM waves travelling between two adjacent PC defects. An interesting phenomenon in which a CCW consisting of N PC defects acts as a single PC defect and its Q factor is N times that of the single PC defect has been predicted and demonstrated. Based on the theoretical results, we have suggested a simple way to control the impurity bands of CCWs through the adjustment of phase shift. All the theoretical results derived by CMT are in good agreement with the simulation results obtained by TMM.

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