Dimerlike positional correlation and resonant transmission of electromagnetic waves in aperiodic dielectric multilayers

R. W. Peng,[1,*] Y. M. Liu,[1] X. Q. Huang,[1] F. Qiu,[1] Mu Wang,[1] A. Hu,[1] S. S. Jiang,[1] D. Feng,[1] L. Z. Ouyang,[2] and J. Zou[2]
[1]*National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China*
[2]*Division of Materials and Centre for Microscopy and Microanalysis, The University of Queensland, Brisbane, Queensland 4072, Australia*
(Received 2 November 2003; published 8 April 2004)

In this paper, we investigate transmission of electromagnetic wave through aperiodic dielectric multilayers. A generic feature shown is that the mirror symmetry in the system can induce the resonant transmission, which originates from the positional correlations (for example, presence of dimers) in the system. Furthermore, the resonant transmission can be manipulated at a specific wavelength by tuning aperiodic structures with internal symmetry. The theoretical results are experimentally proved in the optical observation of aperiodic SiO_2/TiO_2 multilayers with internal symmetry. We expect that this feature may have potential applications in optoelectric devices such as the wavelength division multiplexing system.

DOI: 10.1103/PhysRevB.69.165109 PACS number(s): 61.44.Br, 42.25.Bs, 42.70.Qs

I. INTRODUCTION

Since the pioneer work of Yablonovitch[1] and John,[2] considerable attention has been paid to dielectric microstructures with photonic band gaps (PBG), i.e., photonic crystals. The propagation of photons is forbidden in a PBG. Similar to manipulating electrons in solid states, it is also possible to manipulate photons in microstructures.[3,4] Hence many potential applications have been suggested in optoelectrics and optical communications. Moreover, the concept of PBG has been extended to quasiperiodic structures.[5] Among many studies, the photonic localization in quasiperiodic microstructures is particularly attractive. The photonic localization in a dielectric microstructure bears an analogy to the electronic localization in crystal.[2] In 1958, Anderson studied the localization of electrons in one-dimensional (1D) disordered systems.[6] Later on the concept of localization was recognized as applicable to any waves, such as acoustical waves[7] and optical waves.[2,8] It has been pointed out that the localization of waves appears not only in disordered system, but in deterministic aperiodic system as well.[9] In 1987, Kohmoto *et al.* suggested that classical electromagnetic waves in a quasiperiodic layered medium is a suitable system to study the photonic localization. They proposed that Fibonacci dielectric multilayer[10] should be a good candidate in which photonic localization can be observed. This was indeed experimentally realized in 1994.[11] The interest has also been extended to Thue-Morse system, an intermediate between periodic and quasiperiodic systems. The propagation of light in Thue-Morse dielectric multilayers has been compared with the Fibonacci scenario.[12] In particular, it has been pointed out that the unattenuated transmission roots from the positional correlation in Thue-Morse system,[13] and the frequency trifurcation of optical resonant transmission indeed exists in this structure.[14] In addition to the Fibonacci and Thue-Morse structures, the photonic behavior in several other nonperiodic structures have also been investigated.[15,16]

It is noteworthy that a localization-delocalization transition of electron was predicted by Dunlap *et al.* initially in a 1D random-dimer model in 1990,[17] and has recently been found in random-dimer GaAs-AlGaAs superlattices in experiments.[18] Physically, the extended electronic states in this system are due to the symmetry of its internal structure.[19] Inspired by the localization-delocalization transition of electrons, we are interested to know whether an analog exists in the case of photons in dielectric microstructures. In this paper, by introducing an internal mirror symmetry intentionally to an aperiodic dielectric multilayer, we show that the internal symmetry produces ''dimer'' in the dielectric microstructure, and the dimerlike positional correlation induces a series of resonant transmissions. Furthermore, the resonant transmission can be manipulated at a certain frequency by tuning the aperiodic structures. The theoretical analysis is experimentally tested by the optical observation of aperiodic SiO_2/TiO_2 multilayers with mirror symmetry.

II. THEORETICAL ANALYSIS OF OPTICAL PROPAGATION IN NONPERIODIC DIELECTRIC MULTILAYERS WITH INTERNAL SYMMETRY

Consider the optical propagation through a dielectric multilayer

$$S_0=\{A_1A_2\ldots A_i\ldots A_m\},$$

where there are m dielectric layers A_1, $A_2,\ldots,A_i,\ldots,A_m$, with their refractive indices $\{n_i\}$ and thicknesses $\{d_i\}$, respectively. We use the transfer-matrix method, and follow the description of the electric field in the report of Kohmoto *et al.*[10] In the case of normal incidence and polarization parallel to the multilayer surfaces, the transmission through the interface $A_j \leftarrow A_i$ is given by the transfer matrix

$$T_{i,j}=\begin{pmatrix} 1 & 0 \\ 0 & n_i/n_j \end{pmatrix}. \tag{1}$$

The light propagation within the layer A_i is described by matrix T_i,

$$T_i=\begin{pmatrix} \cos\delta_i & -\sin\delta_i \\ \sin\delta_i & \cos\delta_i \end{pmatrix}, \tag{2}$$

where the phase shift $\delta_i = kn_i d_i$, k is the vacuum wave vector, and d_i is the thickness of the layer A_i. Therefore, the whole multilayer is represented by a product matrix M relating the incident and reflection waves to the transmission wave. The total transmission matrix M has the form

$$M=\begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}. \tag{3}$$

Using the unitary condition $\det|M|=1$, the transmission coefficient of the multilayer film can be written as

$$\check{T}=\frac{4}{\sum_{i,j=1}^{2} m_{ij}^2+2}. \tag{4}$$

Now we introduce a mirror symmetry into the dielectric multilayer. By defining

$$S_0^{-1}=\{A_m A_{m-1}\ldots A_i \ldots A_2 A_1\},$$

the dielectric multilayer with internal mirror symmetry S can be expressed as

$$S=S_0^{-1}\cup S_0=\{A_m A_{m-1}\ldots A_i \ldots A_2 A_1 | A_1 A_2 \ldots A_i \ldots A_{m-1} A_m\}. \tag{5}$$

The total transmission matrix through the multilayer S hence can be represented by

$$M=\{T_m T_{m-1,m} T_{m-1}\ldots T_{i,i+1} T_i T_{i-1,i}\ldots T_2 T_{1,2} T_1\}\cdot\{T_1 T_{2,1} T_2 \ldots T_{i,i-1} T_i T_{i+1,i}\ldots T_{m-1} T_{m,m-1} T_m\}. \tag{6}$$

In order to show that the mirror symmetry makes a "dimer" in the structure which finally induces the resonant transmission, we consider the simplest setting, i.e., the phase shift of wave through each layer is identical: $\delta_i=\delta(i=1,2,\ldots,m)$. This condition can be easily satisfied in experiments by tuning the thickness of each dielectric layer. Now looking at the center of M [shown in Eq. (6)], the pair of matrices related to the dimer "A_1A_1" [shown in Eq. (5)] is

$$M_1=T_1T_1=\begin{pmatrix} \cos(2\delta) & -\sin(2\delta) \\ \sin(2\delta) & \cos(2\delta) \end{pmatrix}. \tag{7}$$

Obviously in the case of $\delta=(n+1/2)\pi$, we have

$$M_1=-I,$$

where I is a unit matrix and n is an integer. Meanwhile, the most central part of M is simplified as the product of matrices $T_{1,2}\cdot T_{2,1}$, which is again an unit matrix, i.e., $T_{1,2}\cdot T_{2,1}=I$. On this basis, the second pair of matrices T_2T_2 [which corresponds to "A_2A_2" in Eq. (5)] comes to the center of M, as shown in Eq. (6). Again, if $\delta=(n+1/2)\pi$ is satisfied, $M_2=T_2T_2=-I$ holds. Repeating the same pairing procedure, and following the rules of $T_{i,j}\cdot T_{j,i}=I$ and $M_j=T_jT_j=-I$ (which corresponds to the jth pair of dimer "A_jA_j"), the total transfer matrix through the symmetric multilayer S is

$$M=(-1)^m I. \tag{8}$$

According to Eq. (4), the transmission coefficient is

$$\check{T}(S)=1 \tag{9}$$

in the case of $\delta=(n+1/2)\pi$. It can be clearly seen that the mirror symmetry in the multilayer S can indeed generate a series of dimers "A_jA_j" $(j=1,2,\ldots,m)$, and this kind of positional correlation eventually leads to the perfect transmission at the photonic frequencies corresponding to $\delta=(n+1/2)\pi$.

In general, considering the symmetry in the structure [shown in Eq. (5)] and using the unitary condition $\det|M|=1$, we can rewrite the transmission coefficient of the light wave through the multilayers with internal mirror symmetry as

$$\check{T}(S)=\frac{4}{(m_{12}+m_{21})^2+4}. \tag{10}$$

Obviously, under the condition

$$m_{12}+m_{21}=0, \tag{11}$$

resonant transmissions are expected in the dielectric multilayer with mirror symmetry.

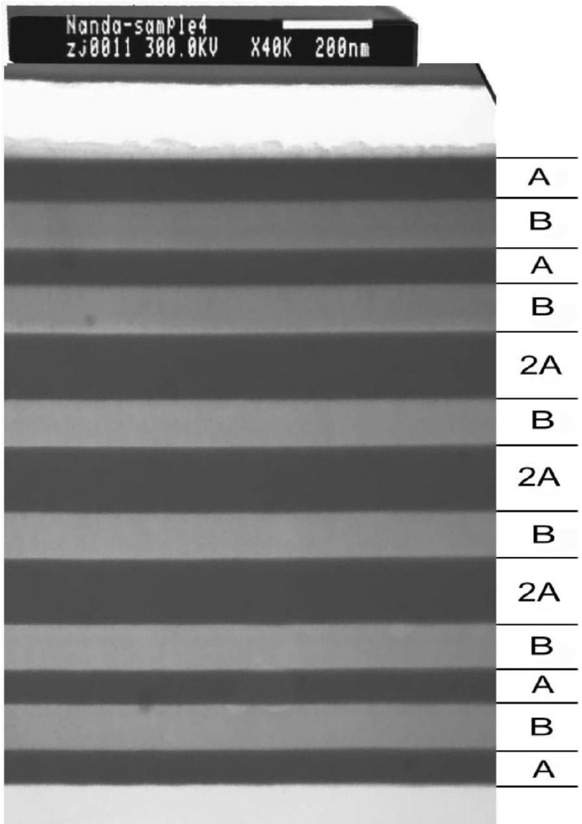

FIG. 1. Cross-sectional bright-field image of the symmetrical Fibonacci (SF) TiO_2/SiO_2 multilayer film with the fifth generation U_5. The SF sequence is marked to show the mirror symmetry.

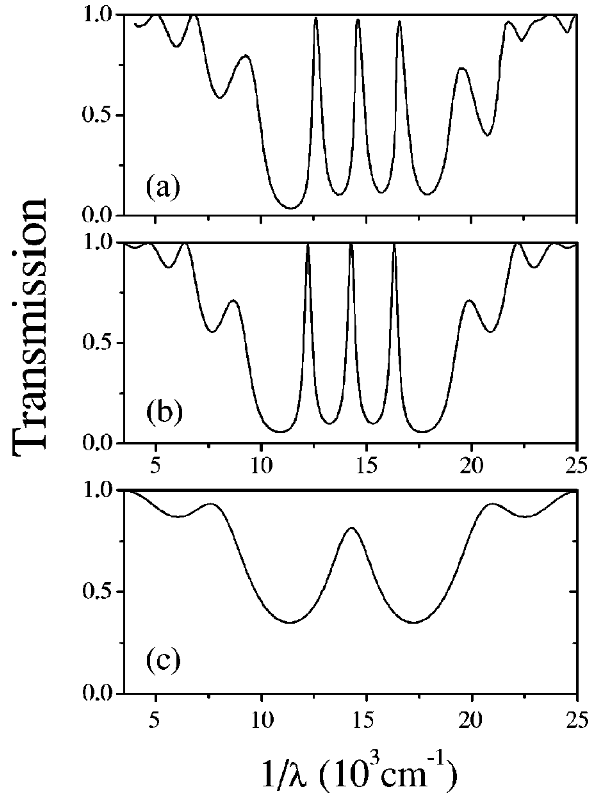

FIG. 2. The measured and calculated transmission coefficient T vs the wave number λ^{-1} for the symmetrical Fibonacci TiO_2/SiO_2 multilayers (SFM) with the fifth generation U_5. The SFM U_5 with 16 layers:(a) measured and (b) calculated, respectively.

III. OPTICAL OBSERVATION OF SYMMETRIC FIBONACCI DIELECTRIC MULTILAYERS

The above theoretical analysis can be tested by optical transmission measurements on the symmetric Fibonacci SiO_2/TiO_2 multilayer films. It is well known that the Fibonacci sequence, which contains two units A and B, can be produced by repeated application of the substitution rules $A \rightarrow AB$ and $B \rightarrow A$. Since Merlin *et al.* first reported the realization of Fibonacci superlattices in 1985,[20] much attention has been paid to the exotic wave phenomena of Fibonacci systems (without the mirror symmetry).[21] It opens a way for technological applications in several fields.[22] The symmetric Fibonacci sequence can be constructed in the following way.[23] The *j*-th generation of the sequence can be expressed as $U_j = \{G_j, H_j\}$, where G_j and H_j are Fibonacci sequences, and obey the recursion relations

$$G_j = G_{j-2} G_{j-1}, \tag{12}$$

$$H_j = H_{j-1} H_{j-2}$$

with $G_0 = H_0 = \{B\}$ and $G_1 = H_1 = \{A\}$. Therefore,

$$U_j = G_{j-2} G_{j-1} H_{j-1} H_{j-2}. \tag{13}$$

For example, the fifth sequence is

$$U_5 = \{ABABAABA|ABAABABA\}, \tag{14}$$

which indeed possesses a mirror symmetry.

In experiments, titanium dioxide (TiO_2) and silicon dioxide (SiO_2) were chosen as dielectric materials A and B. The refractive indices are $n_A = n_{TiO_2} = 2.30$ and $n_B = n_{SiO_2} = 1.46$ around the wavelength of 700 nm. By electron-gun evaporation method, the symmetric Fibonacci SiO_2/TiO_2 multilayer (SFM) films were fabricated on the substrate of $K9$ glass. Before the evaporation, the pressure of the chamber was lower than 2×10^{-5} Torr, and the films were formed in an oxygen atmosphere: the pressure is 2×10^{-4} Torr for TiO_2 deposition and 8×10^{-5} Torr for SiO_2. For simplicity, the thickness of these two materials were chosen to satisfy the condition $n_A d_A = n_B d_B$, which gives the same phase shift in two materials, i.e., $\delta_A = \delta_B = \delta$. The central wavelength was set around 700 nm. Therefore, $d_A = (700\text{ nm})/(4n_A) \simeq 76.1$ nm, and $d_B = (700\text{ nm})/(4n_B) \simeq 120.0$ nm. The structure of the SFM film was characterized by transmission electron microscope (TEM). Cross-sectional TEM specimens were prepared by ion beam thinning and investigated by Philips CM12 TEM operating at 120 KeV. Figure 1 shows a bright-field image of the SFM SiO_2/TiO_2 film with the 5th sequence U_5. TiO_2 and SiO_2 appear as bright and dark layers, respectively. The layered structure is perfectly flat and the symmetric Fibonacci sequence U_5 is clearly revealed as marked in Fig. 1.

Optical transmission spectra were measured by PerkinElmer Lambda 900 spectrophotometer in the range of wavelength from 175 nm to 3000 nm. During the measurement, the SFM film is sandwiched between the $K9$ glass. Figure 2(a) shows the experimentally measured transmission coefficients as a function of wave number for the symmetric Fibonacci SiO_2/TiO_2 multilayer (SFM) films with generation U_5. Obviously some perfect (or almost perfect) transmissions have been observed. The measurement transmission spectrum [shown in Fig. 2(a)] is in good agreement with the numerical calculation [shown in Fig. 2(b)]. It is quite interesting to compare the optical transmission of the SFM with that of the Fibonacci SiO_2/TiO_2 multilayers (FM) without symmetry. Figure 2(c) gives the calculated transmission coefficients of SiO_2/TiO_2 Fibonacci multilayer film (without mirror symmetry). Obviously, the poor transmission of the optical wave usually occurs in ordinary Fibonacci dielectric multilayers; while some resonant modes with perfect transmission indeed exist in symmetric Fibonacci multilayers. More experimental evidences can be found in Ref. 24.

Here we focus on the perfect transmission peaks, i.e., completely transparent states. Taking the SFM U_5 as an example, we will show that some completely transparent states are related to the "dimer" in the structure U_5. There are several kinds of dimers in U_5 contributing to resonant transmissions.

(i) According to Eqs. (5)–(9), the dimer "AA" or "BB" induces the resonant transmission at $\delta=(n+1/2)\pi$, i.e., at the central wavelength $\lambda_c=700$ nm.

(ii) There also are the dimers "CC"($C=ABA$) and "DD"($D=BAB$) in the multilayer U_5 sandwiched between the $K9$ glass (the refractive index of $K9$ glass is $n_{k_9}\simeq 1.5$). The sandwiched U_5 can be approximately expressed as

$$U_5^*=\{\underline{BAB}\ \underbrace{ABA}\ \underbrace{ABA}|\underbrace{ABA}\ \underbrace{ABA}\ \underline{BAB}\}. \tag{15}$$

The total transmission matrix through the multilayer U_5^* is

$$M(U_5^*)=\underbrace{\{M_v \underline{\underline{T_{A,B}}}\ \underbrace{M_u\ \underbrace{M_u\}\cdot\{M_u}\ M_u}\ \underline{\underline{T_{B,A}}}M_v\}}, \tag{16}$$

where

$$M_u=T_AT_{B,A}T_BT_{A,B}T_A,$$

$$M_v=T_BT_{A,B}T_AT_{B,A}T_B.$$

Now we apply the Cayley-Hamilton theorem for 2×2 unimodular matrices as[25]

$$NN=\mathrm{Tr}(N)(N-I), \tag{17}$$

where N is a unimodular matrix and its trace is $\mathrm{Tr}(N)$. Looking at the center of $M(U_5^*)$ [shown in Eq. (16)], the pair of matrices which corresponds to the dimer "CC" [$C=ABA$] can be expressed as

$$M_uM_u=\mathrm{Tr}(M_u)(M_u-I). \tag{18}$$

It is found that if

$$\delta=(n+1/2)\pi,$$

or

$$\delta=n\pi\pm\frac{1}{2}\arccos\left(\frac{r-1}{r+1}\right), \tag{19}$$

where $r=n_A/n_B+n_B/n_A+1$ and n is an integer, we have $\mathrm{Tr}(M_u)=0$. Therefore, the product of matrices is minus unit matrix, i.e., $(M_u)^2=-I$. On this basis, the second dimer "CC" [$C=ABA$, shown in Eq. (16)] comes to the center of $M(U_5^*)$. Obviously, $(M_u)^4=I$ in the case of Eq. (19). Now due to $T_{B,A}T_{A,B}=I$, the third pair of matrices M_vM_v is at the center of $M(U_5^*)$ [to see Eq. (16)]. The pair of M_vM_v corresponds to the dimer "DD" ($D=BAB$) in Eq. (15). Again, using the Cayley-Hamilton theorem, we have $M_vM_v=\mathrm{Tr}(M_v)(M_v-I)$. Interestingly, $\mathrm{Tr}(M_v)=0$ under the condition of Eq. (19). Therefore, the total transfer matrix through the symmetric multilayer U_5^* satisfies $M(U_5^*)=-I$, and the transmission coefficient is $\check{T}(U_5^*)=1$. That is to say, the dimers of both "CC" and "DD" in the sandwiched U_5^* film additionally induce the two perfect transmission peaks at the photonic frequencies corresponding to Eq. (19).

It is shown that the mirror symmetry has made several kinds of dimers in SFM U_5^*, and the dimerlike positional correlation has induced the resonant transmission. However, not all perfect transmission peaks come from the dimerlike correlation. In fact, the electronic delocalization has been found in both symmetric and nonsymmetric dimer, trimer, and n-mer models.[26] Therefore, the internal mirror symmetry is not a necessary condition for the presence of the electronic delocalization. Instead, it is the short-range spatial correlation that inhibits localization of electronic states in these correlated disorder systems. Similar to the case of electron, some perfect transmission of electromagnetic wave may originate from other positional correlations besides the dimer in the internal structure.

IV. MANIPULATION OF RESONANT TRANSMISSION OF ELECTROMAGNETIC WAVE BY TUNING NONPERIODIC STRUCTURE

According to above analysis, the perfect transmission definitely occurs if the mirror symmetry is introduced into the structure. Actually, the perfect transmission can be controlled at a specific wavelength if the special structure with an internal symmetry is achieved. Here we present a way to obtain the resonant mode at the specified wavelength in so-

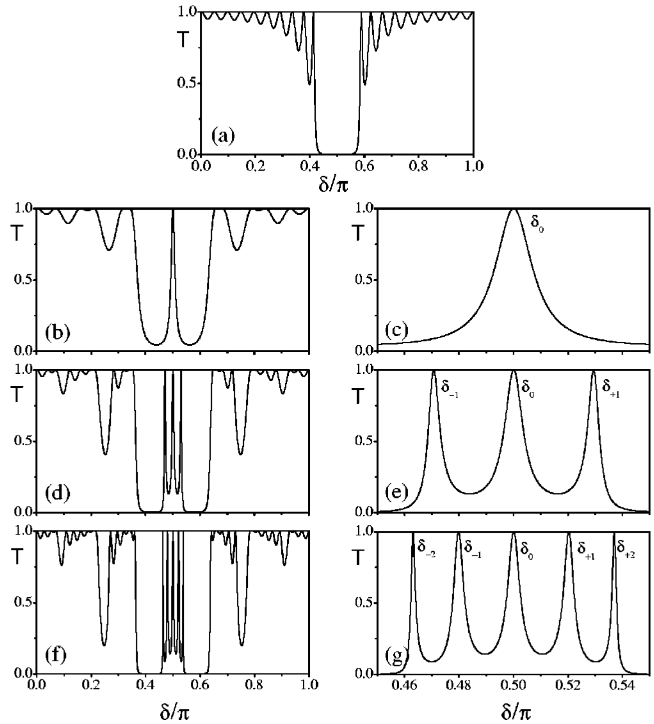

FIG. 3. The calculated transmission coefficient T as a function of the optical phase δ for the symmetric multilayer with defects (SMD): (a) the periodic multilayer; (b) the SMD as V_2; (c) the enlargement of (b) around $\delta_0=0.5\pi$; (d) the SMD as V_3; (e) the enlargement of (d) around $\delta_0=0.5\pi$, (f) the SMD as V_4; (g) the enlargement of (f) around $\delta_0=0.5\pi$, respectively. V_2, V_3, and V_4 are described in the text.

called symmetric multilayers with defects (SMD). For the simplification, we still choose two kinds of dielectric materials A and B with the thicknesses of two different layers satisfying $n_A d_A = n_B d_B$, therefore the phase shift corresponding to the two different layers is the same as $\delta_A=\delta_B=\delta$. Now we present the construction of the SMD and their optical transmission based on Eq. (10). First, it is well known[12] that there is a wide gap around $\delta_0=\pi/2$ [as shown in Fig. 3(a)] in the optical transmission spectrum of the periodic multilayer "$ABABAB$ . . . ." Here, we define a periodic structure as the base of the SMD, i.e., $V_1=\{ABABAB\}$. In the second, if the multilayer film is constructed as $V_2=V_1\cup V_1^{-1}$(where V_1^{-1} is defined as $V_1^{-1}=\{BABABA\}$), there will be one perfect transmission peak at the optical phase of $\delta_0=\pi/2$ within the central gap [shown in Figs. 3(b) and 3(c)]. Obviously, this perfect transmission comes from the prediction shown in Eqs. (5)–(9). Thirdly, if we construct the symmetric multilayer with defects (SMD) as $V_3=V_2\cup V_2$, three perfect transmission peaks occur in the central gap as shown in Figs. 3(d) and 3(e). The optical phases of these three resonant modes are distributed at δ_{-1}, δ_0, and δ_1, where $\Delta\delta=\delta_1-\delta_0=\delta_0-\delta_{-1}$. Furthermore, if the fourth SMD is formed as $V_4=V_3\cup V_2=V_2\cup V_2\cup V_2$, as can be seen in Fig. 3(f) and 3(g), five perfect transmission peaks occur at the central gap of the transmission spectrum. They locate at the optical phases δ_{-2}, δ_{-1}, δ_0, δ_1, and δ_2, respectively. Therefore, after k operations, the SMD possesses $k-1$ units of V_2, and there will be $2k-3$ perfect peaks around $\delta_0=\pi/2$ in the corresponding optical transmission spectrum, i.e., $2k-3$ resonant modes can be achieved at the specified phases. And if the two nearest peaks of perfect transmissions away from the central peak at $\delta_0=\pi/2$ are marked by "-1" and "$+1$," respectively, the corresponding phases δ_{-1} or δ_1 approximately satisfy the relation $\Delta\delta=\delta_1-\delta_0=\delta_0-\delta_{-1}\simeq 0.015+0.05\pi\exp(-k/2.66)$ as shown in Fig. 4, where $k-1$ is the number of V_2 in the SMD constructed by the above operation. Once the dielectric materials and their thicknesses in the multilayers are chosen, the phase in the optical transmission spectrum is directly related to the wavelength of the light. Therefore, it seems that the perfect transmissions can be controlled at certain wavelengths following this way.

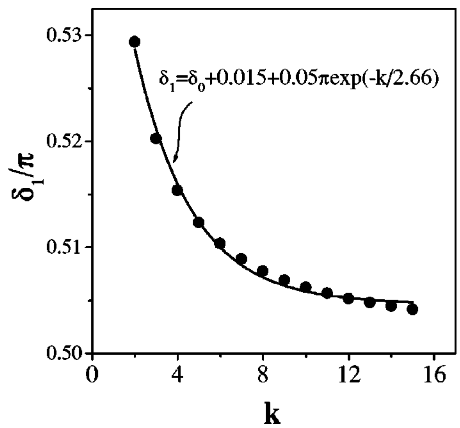

FIG. 4. The relation between the optical phase δ_1 of the nearest perfect peaks away from the central peak at $\delta_0=0.5\pi$ and the number of V_2, i.e., k in the SMD described in the text.

The experiments of the SMD SiO_2/TiO_2 films have demonstrated the above calculation. The fabrication parameters and the optical observations are the same as those for the symmetric Fibonacci SiO_2/TiO_2 multilayer films given in Sec. III. Figure 5 shows the measured and the calculated transmission coefficients within the central gap as a function of wave number for SMD films with the symmetric sequence V_2, V_3, V_4, respectively. It is shown that after k operations, the SMD multilayers indeed give $2k-3$ resonant transmissions in the central gap of optical transmission spectra. Furthermore, it is found that the width among resonant modes can be tuned if we adjust the position of defect in the SMD. In the SMD V_3 with $k=3$, three resonant peaks within the central gap appear at $\lambda\simeq 740$ nm, 702 nm, and 658 nm, respectively [shown in Figs. 6(a) and 6(b)]. The width among resonant peaks is $\Delta\lambda\simeq 40$ nm. While adjusting the position of the defect "BB" in the same SMD structure ($k=3$), three resonant peaks within the central gap can appear at $\lambda\simeq 769$ nm, 700 nm, and 632 nm, respectively [shown in Figs. 6(c) and 6(d)]. Obviously, the width among resonant peaks is enlarged to $\Delta\lambda\simeq 68$ nm. The similar situation can happen in the SMD with $k=4$. Figure 7 presents the transmission spectra of the four different SMD films with $k=4$ in the central gap, the widths among five resonant peaks can be adjusted by changing the positions of defects "AA" and

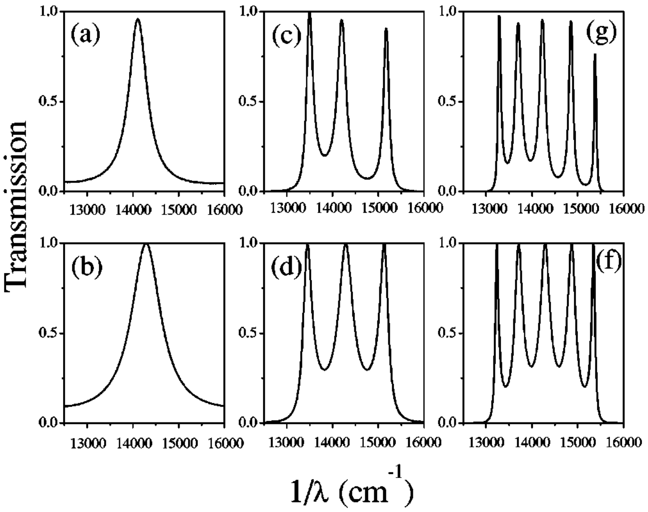

FIG. 5. The measured and calculated transmission coefficient T as a function of the wave number λ^{-1} for the symmetric TiO_2/SiO_2 mutilayers with defects in the central gap. The SMD V_2 with 12 layers: (a) measured and (b) calculated; The SMD V_3 with 24 layers:(c) measured and (d) calculated; The SMD V_4 with 36 layers: (e) measured and (f) calculated, respectively.

"*BB*" in the SMD with $k=4$. That is to say, the width among these five peaks can be tuned almost to be identity (as shown in Figs. 7(a)–7(d)]; The widths can also be quite distinguished (as shown in Figs. 7(e)–7(h)]. Generally speaking, the resonant modes, which are required in the optoelectronic devices, can be achieved by designing the dielectric multilayers with a specific symmetric structure. The SMD film is just one of examples.

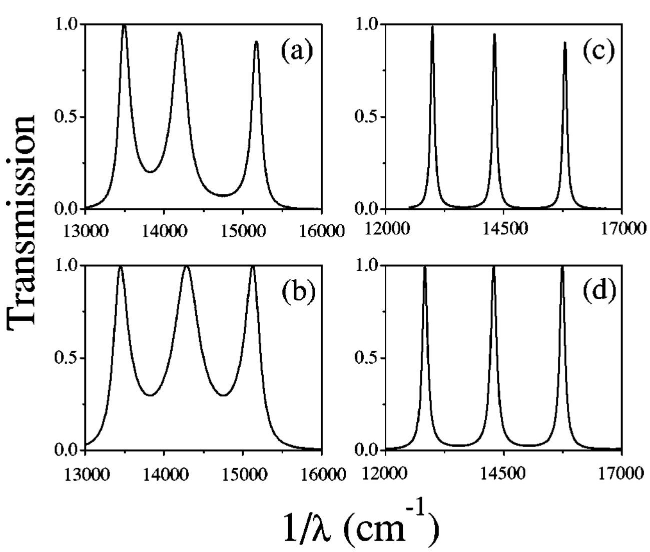

FIG. 6. The measured and calculated transmission coefficients T as a function of the wave number λ^{-1} for the third symmetric TiO_2/SiO_2 multilayers with defects (SMD) with 24 dielectric layers. The SMD $V_3=\{ABABABBABABAABABABBABABA\}$: (a) measured and (b) calculated; The SMD $V_3'=\{ABABABABBABAABABBABABABA\}$: (c) measured and (d) calculated, respectively.

It is obvious that in the SMD, the defects lead to the photonic localized states. As a result, the transmission peaks appear in the PBG. The number of transmission peaks depends on the number of defects. Further, the location and the width of these peaks are determined by the position of the defects in the structure. Similar phenomena can be found in other structures. For example, ten coupled microcavities of porous silicon in the Bragg mirror can produce ten propagation modes in the PBG.[27] Besides, in planar multiple-microcavity structures, the scattering states can form a series of discrete levels, the photonic Bloch oscillation and photonic Wannier-Stark ladder have been theoretically demonstrated.[28] It is an analog to electronic Bloch oscillations in crystal subjected to an electric field. For photons, however, the role of the electric field is played by a gradual variation of the crystal cell. In a SMD, there exists a gradient of the size of the elementary cell of the optical crystal. From this point of view, it is very interesting to know whether the photonic Bloch oscillation occur in a SMD or not. Certainly, the detection of the photonic Bloch oscillation requires time-resolved optical experiments.

V. SUMMARY

To summarize, we have investigated the propagation of electromagnetic wave in aperiodic dielectric multilayers with internal symmetry. It is shown that the mirror symmetry imposes positional correlation to the structure, for example, creates a series of "dimers." The dimerlike positional correlation induces the resonant effect of electromagnetic wave, which is characterized by perfect transmissions. We demonstrate that this property is generic for the multilayer films with an internal symmetry. We have also presented a way to manipulate the resonant transmission at a specific wave-e

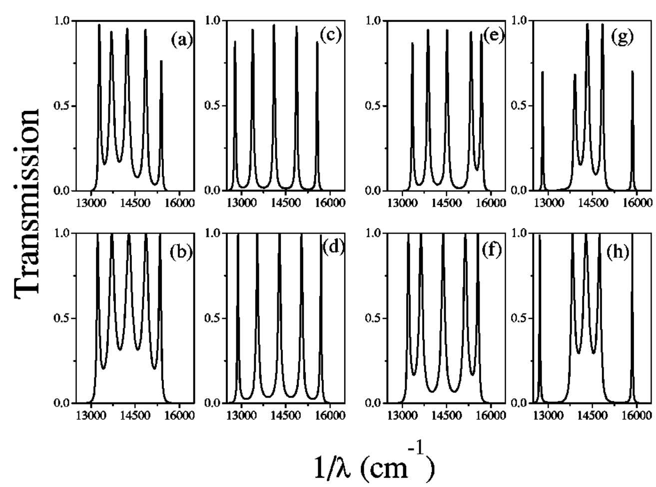

FIG. 7. The measured and calculated transmission coefficients T as a function of the wave number λ^{-1} for the fourth symmetric TiO_2/SiO_2 multilayers with defects (SMD) with 36 dielectric layers. The SMD V_4: (a) measured and (b) calculated; the SMD V_4': (c) measured and (d) calculated. The SMD V_4'': (e) measured and (f) calculated; the SMD V_4''': (g) measured and (h) calculated, respectively.

length by designing the symmetric multilayer with defects (SMD). The theoretical analysis has been experimentally checked in the aperiodic SiO_2/TiO_2 multilayer films. Due to the existence of resonant transmission modes and to the rich structure of transmission spectra, we suggest that the aperiodic dielectric multilayer with internal symmetry may have potential applications in the multiwavelength narrow band optical filters and the wavelength division multiplexing systems.

ACKNOWLEDGMENTS

This work was supported by grants from the National Natural Science Foundation of China (Grant Nos. 90201039, 10274029, 10021001, 10374042), the State Key Program for Basic Research from the Ministry of Science and Technology of China, NSF of Jiangsu (Grant No. BK2002408), and partly by the Ministry of Education of China and Fok Ying Tung Education Foundation.

*Email address: rwpeng@nju.edu.cn

[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987); E. Yablonovitch, T.J. Gmitter, and R. Bhat, *ibid.* **61**, 2546 (1988); E. Yablonovitch and T.J. Gmitter, *ibid.* **63**, 1950 (1989).

[2] S. John, Phys. Rev. Lett. **58**, 2486 (1987); S. John, Phys. Today **44**, 32 (1991).

[3] J.D. Joannopoulos, P.R. Villeneuve, and S. Fan, Nature (London) **386**, 143 (1997).

[4] K.M. Leung and Y.F. Liu, Phys. Rev. Lett. **65**, 2646 (1990); Z. Zhang and S. Satpathy, *ibid.* **65**, 2650 (1990); M. Plihal and A.A. Maradudin, Phys. Rev. B **44**, 8565 (1991); R. Meade, K. Brommer, A. Rappe, and J. Joannopoulos, *ibid.* **44**, 13 772 (1991); A.Z. Genack and N. Garcia, Phys. Rev. Lett. **66**, 2064 (1991); A.A. Maradudin and A.R. McGurn, J. Opt. Soc. Am. B **10**, 307 (1993); P.L. Gourley, Nature (London) **371**, 571 (1994); J.B. Pendry, J. Mod. Opt. **41**, 209 (1994).

[5] Y.S. Chan, C.T. Chan, and Z.Y. Liu, Phys. Rev. Lett. **80**, 956 (1998); S.S.M. Cheng, L. Li, C.T. Chan, and Z.Q. Zhang, Phys. Rev. B **59**, 4091 (1999); M.E. Zoorob, M.D.B. Charlton, G.J. Parker, J.J. Baumberg, and M.C. Netti, Nature (London) **404**, 740 (2000).

[6] P.W. Anderson, Phys. Rev. **109**, 1492 (1958).

[7] S. He and J.D. Maynard, Phys. Rev. Lett. **57**, 3171 (1986); D.T. Smith, C.P. Lorenson, R.B. Hallock, K.R. McCall, and R.A. Guyer, *ibid.* **61**, 1286 (1988).

[8] L. Tsang and A. Ishimaru, J. Opt. Soc. Am. A **2**, 2187 (1985); M.P. van Albada, M.B. van der Mark, and A. Lagendijk, Phys. Rev. Lett. **58**, 361 (1987); P.E. Wolf and G. Maret, *ibid.* **55**, 2696 (1985).

[9] K. Machida and M. Fujita, Phys. Rev. B **34**, 7367 (1986); P. Hu and C.S. Ting, *ibid.*, **34**, 8331 (1986); Y. Liu and R. Riklund, *ibid.*, **35**, 6034 (1987); M. Dulea, M. Johansson, and R. Riklund, *ibid.*, **45**, 105 (1992); S. Aubry and G. Andre, Ann. Isr. Phys. Soc. **3**, 133 (1980).

[10] M. Kohmoto, B. Sutherland, and K. Iguchi, Phys. Rev. Lett. **58**, 2436 (1987).

[11] W. Gellermann, M. Kohmoto, B. Sutherland, and P.C. Taylor, Phys. Rev. Lett. **72**, 633 (1994).

[12] R. Riklund, and M. Severin, J. Phys. C **21**, 3217 (1988); M. Dulea, M. Severin, and R. Riklund, Phys. Rev. B **42**, 3680 (1990).

[13] S. Chattopadhyay and A. Chakrabarti, J. Phys.: Condens. Matter **12**, 5681 (2000).

[14] N.H. Liu, Phys. Rev. B **55**, 3543 (1997); F. Qiu, R.W. Peng, X.Q. Huang, Y.M. Liu, Mu Wang, A. Hu, and S.S. Jiang, Europhys. Lett. **63**, 853 (2003).

[15] K. Iguchi, Mater. Sci. Eng., B **15**, L13 (1992); K. Iguchi, Jpn. J. Appl. Phys., Part 1 **61**, 922 (1992); L. Chow and K.H. Guenther, J. Opt. Soc. Am. A **10**, 2231 (1993); X.Q. Huang, Y.Y. Liu, and M. Do, Solid State Commun. **87**, 601 (1993); T. Hattori, N. Tsurumachi, S. Kawato, and H. Nakatsuka, Phys. Rev. B **50**, 4220 (1994).

[16] R.W. Peng, M. Wang, A. Hu, S.S. Jiang, G.J. Jin, and D. Feng, Phys. Rev. B **57**, 1544 (1998); X.B. Yang, Y.Y. Liu, and X.J. Fu, *ibid.* **59**, 4545 (1999).

[17] D.H. Dunlap, H.L. Wu, and P.W. Philips, Phys. Rev. Lett. **65**, 88 (1990).

[18] V. Bellani, E. Diez, R. Hey, L. Toni, L. Tarricone, G.B. Parravicini, F. Domínguez-Adame, and R. Gómez-Alcalá, Phys. Rev. Lett. **82**, 2159 (1999).

[19] H.L. Wu, W. Goff, and P. Phillips, Phys. Rev. B **45**, 1623 (1992).

[20] R. Merlin, K. Bajema, R. Clarke, F.-Y. Juang, and P.K. Bhattacharya, Phys. Rev. Lett. **55**, 1768 (1985).

[21] J. Todd, R. Merlin, R. Clarke, K.M. Mohanty, and J.D. Axe, Phys. Rev. Lett. **57**, 1157 (1986); A. Hu, C. Tien, X. Li, Y. Wang, and D. Feng, Phys. Lett. A **119**, 313 (1986); K. Bajema and R. Merlin, Phys. Rev. B **36**, 4555 (1987); C. Wang and R.A. Barrio, Phys. Rev. Lett. **61**, 191 (1988); J.-P. Desideri, L. Macon, and D. Sornette, *ibid.* **63**, 390 (1989); K. Kono, S. Nakada, Y. Narahara, and Y. Ootuka, J. Phys. Soc. Jpn. **60**, 368 (1991).

[22] R.W. Peng, A. Hu, and S.S. Jiang, Appl. Phys. Lett. **59**, 2512 (1991); E. Die, F. Dominguez-Adame, E. Macia, and A. Sanchez, Phys. Rev. B **54**, 16 792 (1996); E. Macia, Appl. Phys. Lett. **73**, 3330 (1998).

[23] X.Q. Huang, S.S. Jiang, R.W. Peng, and A. Hu, Phys. Rev. B **63**, 245104 (2001).

[24] R.W. Peng, X.Q. Huang, F. Qiu, Mu Wang, A. Hu, and S.S. Jiang, Appl. Phys. Lett. **80**, 3063 (2002).

[25] S. Sil, S.N. Karmakar, and R.K. Moitra, Phys. Rev. B **48**, 4192 (1993); A. Chakrabarti, S.N. Karmaker, and R.K. Moitra, Phys. Rev. Lett. **74**, 1403 (1995).

[26] D. Giri, P.K. Datta and K. Kundu, Phys. Rev. B **48**, 14 113 (1993); R. Farchioni and G. Grosso, *ibid.*, **56**, 1170 (1997); F.C. Lavarda, M.C. dos Santos, D.S. Galvão, and B. Laks, Phys. Rev. Lett. **73**, 1267 (1994); Y.M. Liu, R.W. Peng, X.Q. Huang, Mu Wang, A. Hu, and S.S. Jiang, Phys. Rev. B **67**, 205029 (2003).

[27] M. Ghulinyan, C.J. Oton, Z. Gaburro, P. Bettotti, and L. Pavesi, Appl. Phys. Lett. **82**, 1550 (2003).

[28] G. Malpuech, A. Kavokin, G. Panzarini, and A. Di Carlo, Phys. Rev. B **63**, 035108 (2001).