Finite-size effect on one-dimensional coupled-resonator optical waveguides

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We study the finite-size effect on the dispersion relation, group velocity, and transmission curves of one-dimensional finite-size coupled-resonator optical waveguide (CROW) structures. Both the dispersion relation and the group velocity curves of a finite-size CROW oscillate along those of the corresponding infinite-extended ones. The oscillations can be suppressed by matching the equivalent admittance of the surrounding medium to that of the unit cell. Thelen's method is used to find the parameters of the matching layer to reduce oscillations on the group velocity and transmission spectra, and to analyze the structure parameters that determine the bandwidth and the group velocity.

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I. INTRODUCTION

Photonic crystals (PCs) exhibit many unique features that are very attractive for photonic integrated circuits [1–3]. In addition to the well-known stop bands, recent experimental and theoretical works on the pass bands have revealed many interesting features. For example, there is a series of transmission resonances in the pass band, and the resonances near the band edge exhibit a low group velocity but a high transmittance, which can be used to build compact optical delay lines for ultrashort electromagnetic (EM) pulses [4]. The basic requirement for the delay lines is the transmission of ultrashort pulses with small attenuation and distortion. However, study on a one-dimensional (1D) and three-dimensional (3D), *N*-period, layered structure found that both the group velocity and the width of the resonance decrease exponentially with the number of period, and thus the small group velocity was found to be accompanied with distortion of the ultrashort pulse due to the group velocity dispersion [5–7]. An impurity pass band can be formed in the stop band by inducing a periodic arrangement of defects into a PC's period structure [8]. Although EM waves are tightly confined at each defect site, photons can hop between proximal defects due to overlapping of the confined modes, and a tight-binding (TB) approach was proposed to study such impurity pass band. Such a defective PC structure, the so-called coupled-resonator optical waveguide (CROW), exhibits some promising features over their conventional waveguide counterpart [8–11]. Yariv *et al.* proposed the possibility of making lossless and reflectionless bends in a CROW [8]. The effect of the defect size and the interval between neighboring defects was investigated to improve its behavior as delay lines [5].

The practical PCs, especially those in photonic integrated circuits, are always of finite-size (i.e., finite period) along the propagation direction, and their boundary conditions, i.e., the optical properties of the entry and exiting surfaces, will play an important role in their optical behaviors [12–15]. Olivier *et al.* observed oscillations in the transmission spectra of the impurity pass band due to the Fabry-Perot-type interference between the two ends of the CROW [12]. These oscillations will result in shape distortion of EM pulses transmitting through the CROW. In this paper, we study the finite-size effect on the dispersion relation and the group velocity of 1D CROW structures. The results of 1D photonic crystal can also provide a general understanding of the EM properties in two-dimensional (2D) and three-dimensional (3D) PCs [4], meanwhile avoiding an arduous task of the 2D and 3D computationally intensive eigenvalue problem. Our study shows that both the dispersion relation and the group velocity curves of a finite-size CROW will oscillate about those obtained from the TB method. Thelen's method is used to optimize the configuration of the CROW structure to reduce the oscillations on the transmission and group velocity curves. The structure parameters which determine the bandwidth and the group velocity are also analyzed.

II. CROW STRUCTURES

The *T*-matrix method, which was described in detail in Refs. [16–19], is used to calculate the transmission spectrum $[T(\omega)]$ and the dispersion relation $[\omega(K)]$ of the 1D CROW structure which is finitely extended along the wave propagation direction. On the other hand, the TB approximation approach has been successfully used to determine the CROWs dispersion relation, in which the CROW structure is tacitly considered to be infinitely extended [9,8]. For comparison, the TB approach is also used to calculate the dispersion relation of the infinitely extended 1D CROW. The group velocity v_g is obtained by differentiating the dispersion curve (i.e., $v_g = d\omega/dk$). The 1D (PC) structure we consider here is a quarter-wave Si_3N_4/air Bragg stack. Hereafter, the Si_3N_4 layer (high refractive index) and the air layer (low refractive index) are denoted as H and L, respectively. The optical thickness of both the H and L layers is $\lambda_0/4$, where λ_0 is the central wavelength of the first stop band of the PC. The central wavelength λ_0 is chosen to be 1.55 μm (i.e., the wavelength used in the fiber optical communication). Defects are introduced into the PC by periodically insetting air layers into the multilayer stack, forming a CROW structure. The inset layer is denoted as L_{in}. An example of the CROW structures discussed in this paper is illustrated in the inset of Fig. 1. Its unit cell is $LHLHLHLHL_{\mathrm{in}}$, i.e., consisting of four

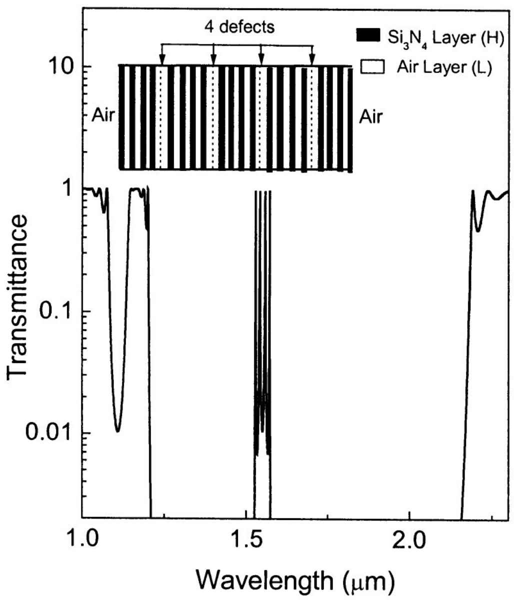

FIG. 1. The transmission spectrum of the CROW structure air/$(LHLHLHLHL)^5$/air calculated by the T-matrix method, where $H(L)$ represents the quarter-wave Si_3N_4 (air) layer. The inset shows the schematic sketch of the CROW air/$(LHLHLHLHL_{in})^5$/air.

H layers, four L layers, and one L_{in} layer. The CROW structure shown in Fig. 1 can be written as: air/$(LHLHLHLHL_{in})^N$/air (here, $N=5$).

The optical thickness of the L_{in} layer $(\chi\lambda_0/4)$ will determine the position of the impurity band. If L_{in} is the same as L (i.e., $\chi=1$), the central position of this impurity band will be located at the center of the stop band. Figure 1 shows the transmission spectrum of the CROW structure air/$(LHLHLHLHL)^5$/air, in which there are four defects. The refractive indexes of the H layer (n_H) and the L layer (n_L) are set to be 2.1 and 1.0, respectively. Figure 2(a) shows the enlarged view of the transmission and group velocity curves around the central wavelength. The impurity pass band shows large oscillations because it contains four resonances. The transmittance contrast, defined as $(T_{max}-T_{min})/(T_{max}+T_{min})$, where T_{max}/T_{min} is the maximum/minimum transmittance, around the center is near 97.9%. Similar to the normal pass bands of a PC the impurity pass band would normally consist of N resonances for a CROW composed of N defects [5–9]. These resonances exhibit nearly unity transmittance, and meanwhile a very low group velocity (smaller than $10^{-2}c$, where c is the light velocity in vacuum). Although each of these resonances can be independently used as a delay line of pulses, pulses shorter than 50 ps transmitting through it will be distorted because of the narrow width of the resonances ($\sim$1 nm). Therefore, in order to use the CROWs for ultrashort pulses, the oscillations on the group-velocity–transmission curves should be inhibited. For a finite-size CROW, the optical properties of the entry and exiting surfaces, can play an important role in their optical behaviors. Fortunately, the oscillations within the whole (or partial) impurity pass band can be suppressed by matching its surrounding environment to its unit cell. Figure 2(b) shows the transmission and group velocity curves of the

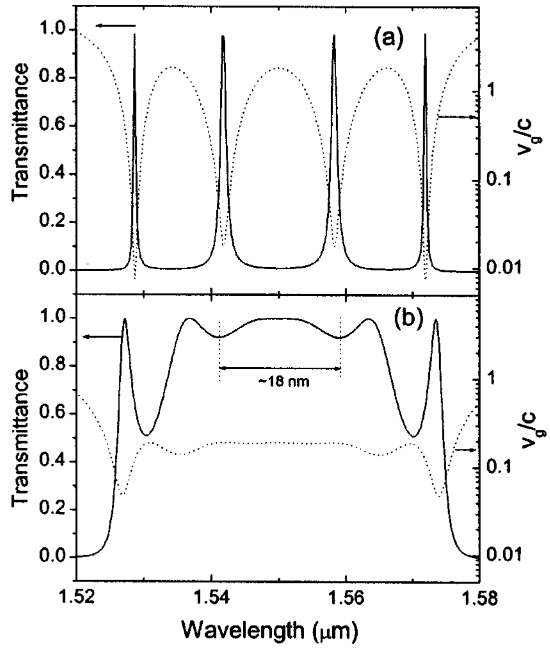

FIG. 2. (a) The enlarged view of the transmission (solid curve) and group velocity (dotted curve) curves around the central wavelength of the CROW structure air/$(LHLHLHLHL)^N$/air. (b) The transmission (solid curve) and group velocity (dotted curve) curves of the CROW structure air/$HLHL(LHLHLHLHL)^5LHLH$/air.

CROW structure air/$HLHL(LHLHLHLHL)^5LHLH$/air. The impurity band of this CROW is quasiflat around the central wavelength. The transmittance contrast around the central wavelength is lower than 4.1% within a 18-nm-wide range, as a result, a 0.3-ps pulse can transmit with almost no distortion and loss.

III. THE ORIGIN OF THE OSCILLATIONS: THE FINITE-SIZE EFFECT

Figure 3(a) shows the dispersion curves of ω (frequency) vs k (wave vector) of the CROW structures air/$(LHLHLHLHL)^N$/air, where N is 5 and 15, respectively, ω_0 is the central frequency of the impurity pass band (i.e., $\omega_0=(2\pi/\lambda_0)c$), and R is the distance between the two neighboring defects. For comparison, the dispersion curve calculated by the TB approach (i.e., $N\rightarrow\infty$) is also presented in Fig. 3(a). The curves of $N=5$, 15 exhibit steplike oscillations about the TB curve. The number of these steps is N-1 (equal to the number of defect), and with increasing N, its deviation from the TB curve decreases, and at large N, it becomes nearly the same as the TB curve. In fact, the experimental CROW samples are always of finite size along the wave propagation direction, and the measured dispersion relation presented by some experimental reports clearly shows this kind of steplike oscillation behavior [9].

The group velocity v_g is the differentiation of the dispersion relation ($v_g=d\omega/dk$). The differentiation of the oscillating dispersion curves of the finite-size CROWs shown in Fig. 3(a) will result in oscillations in the group velocity curves. Therefore the oscillations in the group velocity curve

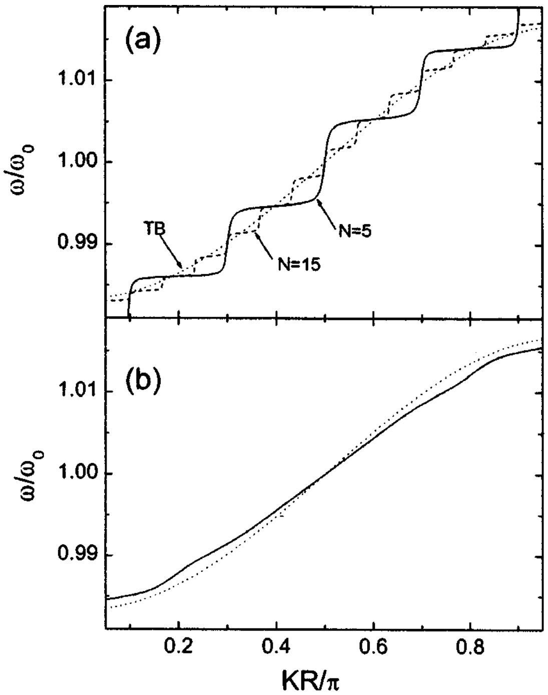

FIG. 3. (a) The $\omega(k)$ dispersion curves of the CROW structures air/$(LHLHLHLHL)^N$/air, where N is 5 (solid curve), 15 (dashed curve), and ∞ (dotted curve), respectively. (b) The $\omega(k)$ dispersion curves of the CROW structures air/$HLHL$ $\times(LHLHLHLHL)^5LHLH$/air (solid curve) and air/$(LHLHLHLHL)^\infty$/air (dotted curve), respectively.

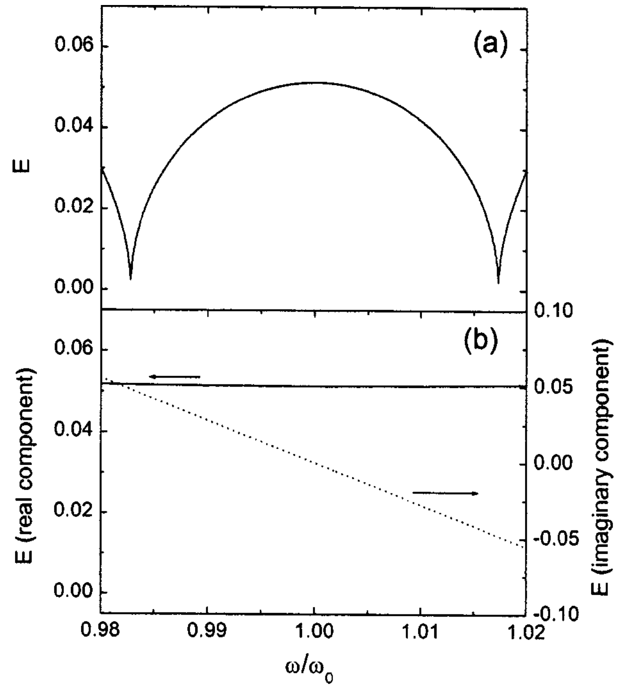

FIG. 4. (a) The equivalent admittance of the unit cell $LHLHLHLHL$. (b) The real component (solid curve) and the imaginary component (dot curve) of equivalent admittance of the matching layer stack air/$HLHL$.

shown in Fig. 2(a) originate from the finite-size effect. However, as shown in Figs. 2(b) and 3(b), the oscillations can be suppressed by adding matching layers at the CROW's two end surfaces to match the equivalent admittance of the environment to its unit cell. In the following, Thelen's method will be used to derive the parameters for the required matching layer.

IV. QUASIFAT IMPURITY BAND

A 1D infinitely extended CROW structure is periodic since defects contained in it are periodically arranged. The basis of Thelen's method is to divide the CROW structure into a series of symmetrical unit cells, and the properties of the CROW can be predicted by finding the equivalent admittance of the unit cell [20]. For example, a CROW

$$\cdots LHLHLHLHL_{\mathrm{in}}LHLHLHLHL_{\mathrm{in}}\cdots$$

can be divided into the arrangement

$$\cdots[(\chi+1)/2]L\ HLHLHLH[((\chi+1)/2)]L$$

$$[(\chi+1)/2]L\ HLHLHLH[(\chi+1)/2]L\cdots.$$

The unit cell $[(\chi+1)/2]LHLHLHLH[(\chi+1)/2]L$ is a symmetrical assembly. According to Epstein, any symmetrical assembly of film stacks can be replaced by a single layer [21]. Therefore this unit cell can be replaced by a single layer with an equivalent admittance (E) and optical thickness (a'), and the two parameters E and a' are functions of wavelength. Let us consider a simple example with $\chi=1$. The finite-periodic stack $(LHLHLHLHL)^N$ can be equivalent to a single layer with thickness $Na'(\lambda)$ and index $E(\lambda)$. Figure 4(a) shows the equivalent admittance E as a function of wavelength. The equivalent admittance E is a real and almost a constant around the center of the impurity pass band. At the central frequency ω_0, the equivalent admittance E is $n_L^5/n_H^4\approx 0.05$. At the edges of the impurity band, it tends towards zero.

The CROW structure air/$(LHLHLHLHL)^N$/air can be written as air/E,Na'/air. Like the case in a Fabry-Perot etalon, the transmittance will oscillate between 1 and $T_{\min}(\lambda)$, where $T_{\min}(\lambda)$ is given by

$$T_{\min}(\lambda)=T_S^2/(1+R_S)^2, \quad (1)$$

where $R_s=[(E-n_{\mathrm{en}})/(E+n_{\mathrm{en}})]\,[(E-n_{\mathrm{en}})/(E+n_{\mathrm{en}})]^*$, $T_s=4E\ \mathrm{Re}(n_{\mathrm{en}})/(E+n_{\mathrm{en}})\ (E+n_{\mathrm{en}})^*$, and n_{en} is the equivalent admittance of the surrounding medium. According to Eq. (1), if n_{en} is equal to E, $T_{\min}(\lambda)$ will be 1, and thus the impurity band will become flat and of unity transmittance. Figure 5 shows the transmittance spectrum and $T_{\min}(\lambda)$ of the CROW air/$(LHLHLHLHL)^{10}$/air. The surrounding medium is air ($n_{\mathrm{en}}=1.0$), whose refractive index is quite different from the admittance E(λ) shown in Fig. 4(a), so the transmittance spectrum shows large oscillations. Therefore, in order to have a quasiflat impurity pass band with high transmittance, the surrounding medium should be matched to the equivalent admittance $E(\lambda)$, which can be realized by adding a suitable number of quarter-wave

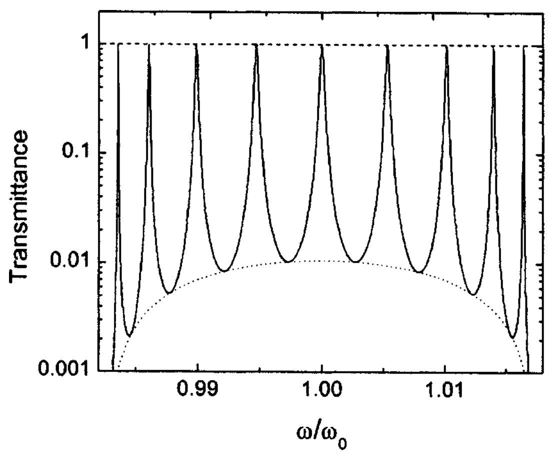

FIG. 5. The transmission spectrum (solid curve) and $T_{\min}(\lambda)$ curve (dotted curve) of the CROW air/$(LHLHLHLHL)^{10}$/air. The straight dashed line is the unity transmittance.

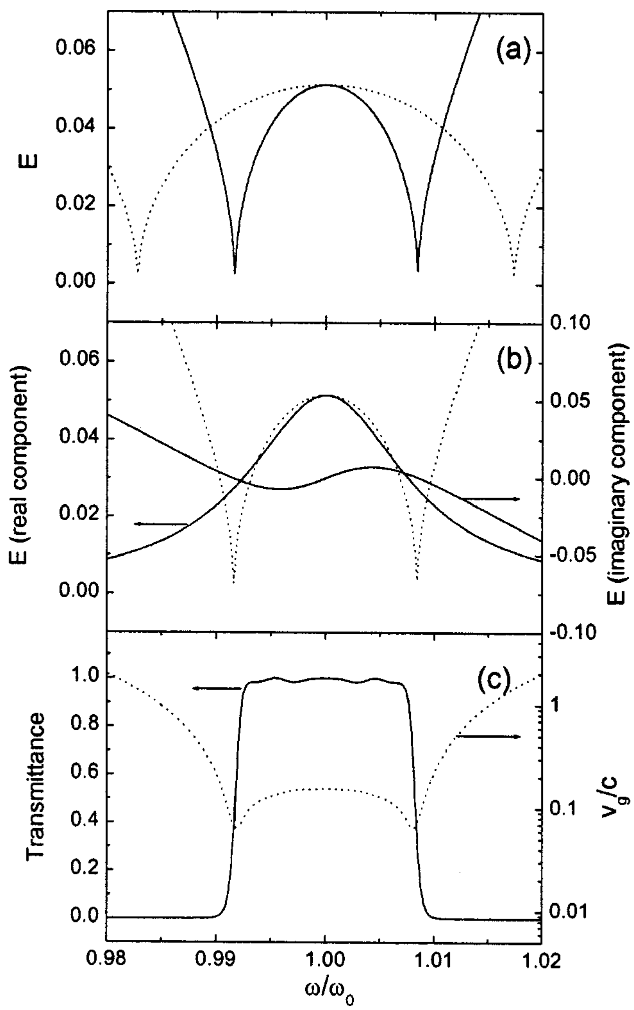

FIG. 6. (a) The equivalent admittances of the symmetrical assemblies *LLLHLHLHLHLLL* (solid curve) and *LHLHLHL* (dotted curve). (b) The real and imaginary components of equivalent admittance of the matching layer stack air/*HLHL LHLHLHLHL* (solid curve). For comparison, the equivalent admittance of the unit cell *LLLHLHLHLHLLL* (dotted curve) is also shown. (c) The transmittance (solid curve) and the group velocity (dotted curve) of the CROW air/*HLHLLLHLHLHLHL* $(LLLHLHLHLHLLL)^5$ *LHLHLHLHL LHLH*/air.

matching layers to the two end surfaces of the CROW structures [22,23]. In the case of air/$(LHLHLHLHL)^N$/air, adding the matching layer stack *HLHL* can improve the CROW's properties. The equivalent admittance of air/*HLHL* is shown in Fig. 4(b). At ω_0, the equivalent admittance is $(n_L^4/n_H^4)\, n_{\text{air}}=n_L^5/n_H^4$, which is the same as that of the CROW's unit cell. Away from ω_0, the equivalent admittance is a complex. Within the range of the impurity pass band, the real component does hardly change, and the imaginary one varies between $\sim\pm0.05$. Obviously, the CROW air/*HLHL* $(LHLHLHLHL)^N$ *LHLH*/air has smaller difference of the equivalent admittances between the unit cell and its environment than that of the CROW air/$(LHLHLHLHL)^N$/air, so its impurity band [Fig. 2(b)] should exhibit much smaller oscillations than that of the later. Around ω_0, the two equivalent admittances are close, so both the transmittance and group velocity are quasiflat in the central part of the impurity band.

As shown in Fig. 4, the equivalent admittance of the unit cell varies considerably within the impurity pass band. The equivalent admittance dispersions are not similar between the unit cell and the air/$HL\cdots HL$ matching stack. Although it is possible to make the two equivalent admittances be equal at a certain point, it is difficult to match the unit cell to its environment within the whole impurity pass band. Consequently, oscillation suppression only occurs in the band regions in which the two admittances are very close, as shown in Fig. 2(b). One optimization way is to inset between the unit cell and the matching stack with a symmetrical multilayer assembly whose dispersion is similar to that of the unit cell. In the following, the CROW structure air/*HLHL LHLHLHLHL* $(LLLHLHLHLHLLL)^5$ *LHLHLHLHL LHLH*/air is taken as an example. Figure 6(a) shows the equivalent admittances of *LLLHLHLHLHLLL* and *LHLHLHLHL*. The two equivalent admittances have the same value at the central frequency ω_0 and all exhibit a gradually deceasing admittance as the values of frequency moves away from ω_0. Figure 6(b) shows the equivalent admittance E of air/*HLHL LHLHLHLHL*. At ω_0, the equivalent admittance is the same as that of the CROW's unit cell *LLLHLHLHLHLLL*. The dispersion of its real component is similar to that of the unit cell, and the variation of its imaginary component is reduced, which is less than ±0.01 within the range of the impurity pass band. Because the equivalent admittances of the unit cell and the surrounding medium are matched well within the whole band, the whole impurity pass band becomes quasiflat, as shown in Fig. 6(c). The oscillations in the transmittance within the whole band are suppressed well, and the transmittance contrast is reduced to below 0.7% in the whole 23-nm-wide impurity band.

The above example indicates that the surrounding medium plays an important role in the optical properties of the CROW structures, and a quasiflat impurity band with unity transmission can be obtained when the equivalent admittance of its surrounding medium is matched to that of the unit cell.

For the CROWs with defect layers of $\chi \neq 1$ i.e., the thickness of the layers not of quarter wave), the method presented here will also work though the central frequency of the impurity band will be tuned within the band gap and the matching layers will not be simply of quarter-wave thickness.

V. DEPENDENCE OF BANDWIDTH AND GROUP VELOCITY ON STRUCTURE CONFIGURATION

As has been shown, the surrounding medium has a decisive effect on the oscillations in the impurity pass band. On the other hand, the configuration of the unit cell plays a major role on the group velocity and the bandwidth of the impurity pass bands. The group velocity and the bandwidth are the two important properties for the applications related to CROWs such as optical delay lines. Assuming that the unit cell is $LH\cdots LHL$, which consists of m periods of the HL stacked layers and one defect layer same as the L layer, according to Thelen's design approach [20,23], the bandwidth of the impurity pass band is given by

$$\left|\frac{\delta \lambda_B}{\lambda_0}\right| = \frac{4}{\pi}\left(\frac{n_L}{n_H}\right)^m \frac{(n_H - n_L)}{n_H}. \quad (2)$$

The smaller the ratio of the refractive index between the L and H layer (n_L/n_H) is, and the larger the m number is, the narrower the impurtiy band is. A larger m number means a longer distance between the two neighboring defects (R). According to Eq. 7 in Ref. [8], the group velocity (ν_g) is given by

$$\nu_g = d\omega(k)/dk = \frac{\pi c R}{\lambda_0}\left(\frac{\delta \lambda_B}{\lambda_0}\right)\sin(kR), \quad (3)$$

where k is the wave vector along the propagation direction, which spans the region of $[0, \pi/\mathrm{R}]$. Since the matching process can make the portion of the impurity pass band around λ_0 be quasiflat, let us consider the ν_g value at λ_0, which is equal to $(\pi c R/\lambda_0)/(\delta \lambda_B/\lambda_0)$. Apparently, the narrower the impurity is, the lower the $v_g(\lambda_0)$ value is.

For the unit cell $LH\cdots LHL$, the m-periodic LH multiplayer stack forms a reflector, so the CROW structure can be written as

$\cdots$reflector/defect layer/reflector/defect layer/reflector$\cdots$.

The defect layer between two reflectors forms a microcavity. The larger the m number is, the higher the reflection of the reflector is [22,23], and consequently the higher the Q factor of the microcavity will be. For the case in which the EM wave is highly confined in the cavity, the group velocity of the EM modes will become very small. On the other hand, with the increase of the m number, the distance between two neighboring cavities is also larger, and thus the overlap between the evanescent EM modes will be small. In solid-state physics, it is well known that the expansion of the energy level due to the overlap of atomic wave functions is narrow if the overlap is weak. Analogously, the width of the impurity band will be narrower if the coupling between the neighboring cavities is weaker. Therefore both the bandwidth and the group velocity will decrease with the increase of the period number (m) of the HL layers in the unit cell. In addition, very small group velocity can be obtained if the two materials composed for the CROWs have a high refractive index contrast. For example, silicon is optical transparent around 1.55 μm, and has a high refractive index ($\sim$3.4). If the H and L layers are chosen to be silicon and air, and the unit cell is $LLLHLHLHLHLLL$, the CROW structure air/$HLHL$ $LHLHLHLHL$ $(LLLHLHLHLHLLL)^5$ $LHLHLHLHL$ $LHLH$/air is with a group velocity lower than 0.025c. Its bandwidth is $\sim$4 nm, and thus 3-ps EM pulses can transmit it without distortion.

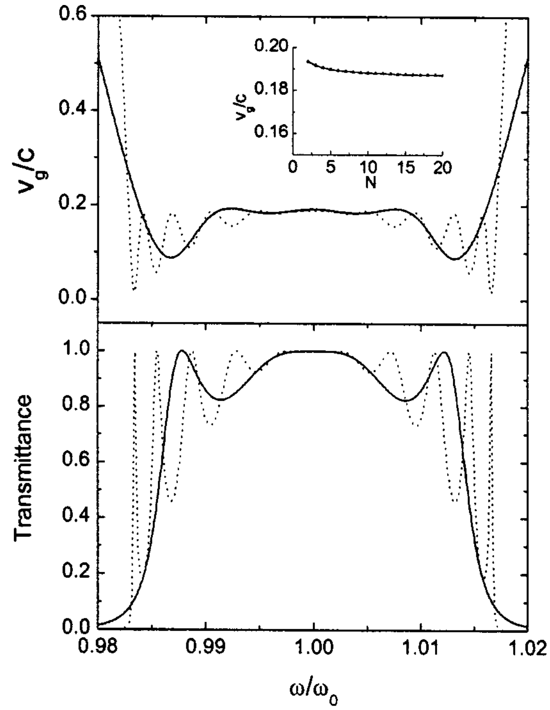

FIG. 7. The group velocity and the transmittance curves of the CROW air/$HLHL$ $(LHLHLHLHL)^N$ $LHLH$/air with N=3 (solid curve) and 10 (dotted curve). The inset shows $v_g(\lambda_0)$ versus the number of unit cell N.

Moreover, the number of the unit cell (N) of the CROWs does not significantly affect the group velocity and the bandwidth of the impurity pass band. Figure 7 shows the group velocity and the transmittance spectra of the CROW air/$HLHL$ $(LHLHLHLHL)^N$ $LHLH$/air with N=3 and 10, while the inset showing $v_g(\lambda_0)$ versus N, which is calculated by the T-matrix method. With increasing N, there is no big change in both the group velocity and the bandwidth though the impurity band becomes more sharply defined. This is in contrast to the case of pulse propagation at the photonic band-edge resonance of a prefect PC [4], where both the group velocity and the width of the band-edge resonances decrease exponentially with the period number. Although a perfect PC has also been proposed for applications of optical delay lines, the delay time and the width threshold of pulses through it are two directly correlated and conflicting factors. In the case of a CROW, the delay time and the width threshold are independent of each other and hence can be adjusted independently. For example, additional delay time can be gained by just increasing the cell number of the CROW, while the width threshold does not change.

VI. CONCLUSION

The dispersion relation of a finite-size CROW oscillate about that of the corresponding infinite-extended one, which results in oscillations in the group velocity and transmission curves. It is shown that such an oscillation originates from the finite-size effect. To reduce or even remove the oscillations on the transmission and group velocity curves, Thelen's method is utilized to find the parameters of the matching layer to match the equivalent admittance of the surrounding medium to that of the unit cell. As the photonic band-edge resonance of a prefect PC, the CROW structures have potential application in optical delay line. As an example, an optimized CROW structure air/$HLHL$ $LHLHLHLHL$ $(LLLHLHLHLHLLL)^5$ $LHLHLHLHLHL$ $LHLH$/air, where the H and L layers are silicon and air, a 3-ps electromagnetic pulse operating at 1.55 μm can transmit it at a group velocity lower than 0.025 c without distortion. Furthermore, it is shown that the bandwidth and the group velocity in the impurity pass band depend on the structure configuration of the unit cell, but not on the number of the unit cell, which is in contrast to the case of the photonic band-edge resonance of a perfect PC.

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