Extreme narrow photonic passbands generated from defective two-segment-connected triangular waveguide networks*

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In this paper, we investigate the optical transmission properties of perfect and defective two-segment-connected triangular waveguide networks (2SCTWNs) and find that after introducing defects in networks, many groups of transparent extreme narrow photonic passbands (ENPPs) will be created in the middle of the transmission spectra, the number for each group and the group number of ENPPs can be adjusted by the matching ratios of waveguide length (MRWLs), the number of defects, and the number of unit cells of 2SCTWNs. The influences of MRWL, number of defects, and number of unit cells on the number, width, and position of these ENPPs are researched and a series of quantitative rules and properties are obtained. It may be useful for the designing of high-sensitive optical switches, wavelength division multiplexers, extreme-narrowband filters, and other correlative waveguide network devices.

Keywords: photonic band gap, defective waveguide network, narrow passband

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1. Introduction

Photonic band gap (PBG) and photonic localization are the two main characteristics of photonic crystals (PCs).[1,2] This provides researchers probabilities to control and confine the propagation of electromagnetic (EM) waves through PCs. Now, a number of scientists have paid much attention to PCs.[3–9]

Even though PCs possess significant optical properties, they are very difficult to fabricate, especially for three-dimensional (3D) PC structures. The network systems composed of one-dimensional (1D) optical waveguides are another kind of PBG structure and can be easily realizable in experiment because of their structural flexibility. The phase, amplitude, and wave function at each node in the network can also be easily accessible. Moreover, strong scattering can be easily introduced in a unit cell to reproduce large full gaps in any direction.[10] Therefore, just like PCs, scientists have also paid much attention to these optical waveguide networks.[10–24]

It is well known that PCs exhibit many novel properties after introducing defects, which are useful for the designing of optical devices, such as optical switches,[25] wavelength division multiplexers,[26] ultra-small filters,[27,28] low-threshold lasers,[29] splitters,[30] and so on. However, it is not easy to realize defective PCs experimentally and the fabricating difficulty increases with the increment of the dimensions of PCs. Fortunately, defects can be introduced easily in optical waveguide networks, the fabricating difficulty does not change with the increment of the networks' dimension, and the number, the position, and the type of defects can also be controlled conveniently. So, the interesting features of defective waveguide networks have attracted much attention.[10,13,16,18]

In this paper, we investigate the optical transmission properties of perfect and defective two-segment-connected triangular waveguide networks (2SCTWNs) and find that after introducing defects in networks, many groups of transparent extreme narrow photonic passbands (ENPPs) will be created in the middle of the transmission spectra, the band number for each group and the group number of ENPPs can be adjusted by the matching ratios of waveguide length (MRWLs), number of defects, and number of unit cells of 2SCTWNs. Just like defective PCs, the interesting characteristics of defective 2SCTWNs may be also useful for the designing of relevant all-optical devices, such as high-sensitive optical switches, wavelength division multiplexers, and extreme-narrowband filters, etc.

We organize this paper as follows. The models studied in this paper and the methods used for calculating optical transmissions are introduced in Section 2. Numerical results and discussion of perfect and defective 2SCTWNs are presented in Section 3. Finally, a brief summary is drawn in Section 4.

2. Models and methods

2.1. Models

In this paper we study the symmetric defective 2SCTWNs and compare the photonic properties of these networks with those of the perfect systems. As an example, figure 1 shows

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the finite 2SCTWNs without and with a defect. Here we define a defective (normal) side as two nearest-neighborhood nodes connected by two segments of 1D waveguides with the lengths of d_1 and d_3 (d_1 and d_2), respectively. The dash line in Fig. 1(b) represents a defect and all solid lines in Fig. 1 denote normal sides.

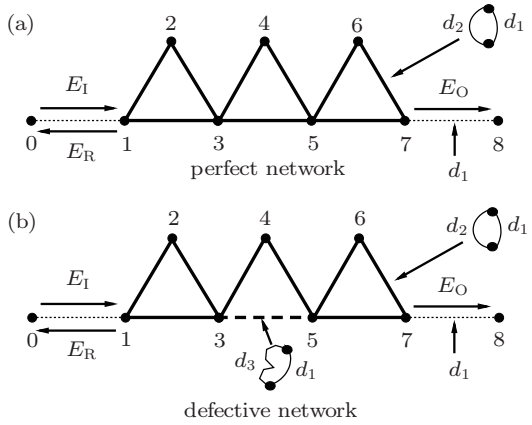


Fig. 1. The two-segment-connected triangular waveguide network with three unit cells, one entrance and one exit, where each solid line denotes two segments of one-dimensional waveguides with the lengths of d_1 and d_2, respectively, and each dot line expresses one segment of one-dimensional waveguide with the length of d_1. E_I, E_R, and E_O are the input, reflective, and output electromagnetic waves, respectively. (a) Perfect network. (b) Defective network with one defect, where the dash line represents a defect constructed from two segments of one-dimensional waveguides with the lengths of d_1 and d_3, respectively.

2.2. Network equation

We use the network equation to numerically calculate the photonic properties of 2SCTWNs. It is known that in 1D waveguides, only monomode propagation of EM waves needs to be considered. The EM wave function with angular frequency ω in any segment between nodes i and j can be regarded as a linear combination of two opposite traveling plane waves:

$$\psi_{ij} = \alpha_{ij} e^{ikx} + \beta_{ij} e^{-ikx}, \tag{1}$$

where $k = \omega/c$ and c is the speed of the EM wave in the vacuum. Moreover, at any node i, the energy flux conservation gives

$$\sum_j \frac{1}{\mu\omega} \psi_{ij} \frac{\partial \psi_{ij}}{\partial x} A_{ij}\big|_{x=0} = 0, \tag{2}$$

where the summation is over all segments linked directly to node i. Based on Eqs. (1) and (2) one can deduce the following network equation:[31]

$$-\psi_i \sum_j \cot kl_{ij} + \sum_j \psi_j \csc kl_{ij} = 0, \tag{3}$$

where ψ_i and ψ_j are the wave functions at nodes i and j, respectively, and l_{ij} is the length of the segment between nodes i and j.

2.3. Generalized eigenfunction method

In this subsection, we introduce the generalized eigenfunction method by an example network as shown in Fig. 1(b). According to Eq. (1) one can obtain the normalized wave functions of the entrance (nodes 0 and 1) and the exit (nodes 7 and 8) in Fig. 1(b) as follows:

$$\begin{cases} \psi_0 = 1 + r, \\ \psi_1 = e^{ikd_1} + re^{-ikd_1}, \\ \psi_7 = t, \\ \psi_8 = te^{ikd_1}, \end{cases} \tag{4}$$

where r and t are the reflection and transmission coefficients, respectively. On the other hand, by means of Eq. (3) one can obtain the relationship among the wave functions of all the 9 nodes in Fig. 1(b):

$$\begin{cases} -\psi_1(2\Lambda + \cot kd_1) + (\psi_2 + \psi_3)\Theta + \psi_0 \csc kd_1 = 0, \\ -2\psi_2\Lambda + (\psi_1 + \psi_3)\Theta = 0, \\ -\psi_3(3\Lambda + \Xi) + (\psi_1 + \psi_2 + \psi_4)\Theta + \psi_5\Omega = 0, \\ -2\psi_4\Lambda + (\psi_3 + \psi_5)\Theta = 0, \\ -\psi_5(3\Lambda + \Xi) + (\psi_4 + \psi_6 + \psi_7)\Theta + \psi_3\Omega = 0, \\ -2\psi_6\Lambda + (\psi_5 + \psi_7)\Theta = 0, \\ -\psi_7(2\Lambda + \cot kd_1) + (\psi_5 + \psi_6)\Theta + \psi_8 \csc kd_1 = 0, \end{cases} \tag{5}$$

where

$$\begin{cases} \Lambda = \cot kd_1 + \cot kd_2, \\ \Theta = \csc kd_1 + \csc kd_2, \\ \Xi = \cot kd_1 + \cot kd_3, \\ \Omega = \csc kd_1 + \csc kd_3. \end{cases} \tag{6}$$

Obviously, in order to obtain the transmission coefficient t one has to solve the united equation sets (4)–(6). Evidently, this is very difficult. Here we make use of the generalized eigenfunction method[14] and treat the coefficients r and t in Eqs. (4)–(6) as the same as the wave functions. In this way, by means of Eqs. (4)–(6) one can obtain an $N+2$ order matrix equation $X\psi = Y$, where N is the number of the nodes in the network. Then the transmission coefficient is simply $t = (X^{-1}Y)_{N+2}$ and the transmissivity T can be defined as $T = |t|^2$.

3. Numerical results and discussion

In this section we numerically calculate the transmission spectra of perfect and symmetric defective 2SCTWNs and investigate the influences of defects on the properties of ENPPs in the middle of the transmission spectra.

3.1. Influence of MRWL

3.1.1. Networks with integral MRWLs

From our recent research[23] one knows that the 2SCTWNs with integer MRWL produce a large PBG in the middle of the transmission spectrum, so large PBGs will be generated in the middle of the spectra for the perfect networks with even MRWL (e.g., $d_2 : d_1 = 2 : 1$, see Fig. 2(a)) and odd MRWL (e.g., $d_2 : d_1 = 3 : 1$, see Fig. 2(b)). But for defective networks the cases change.

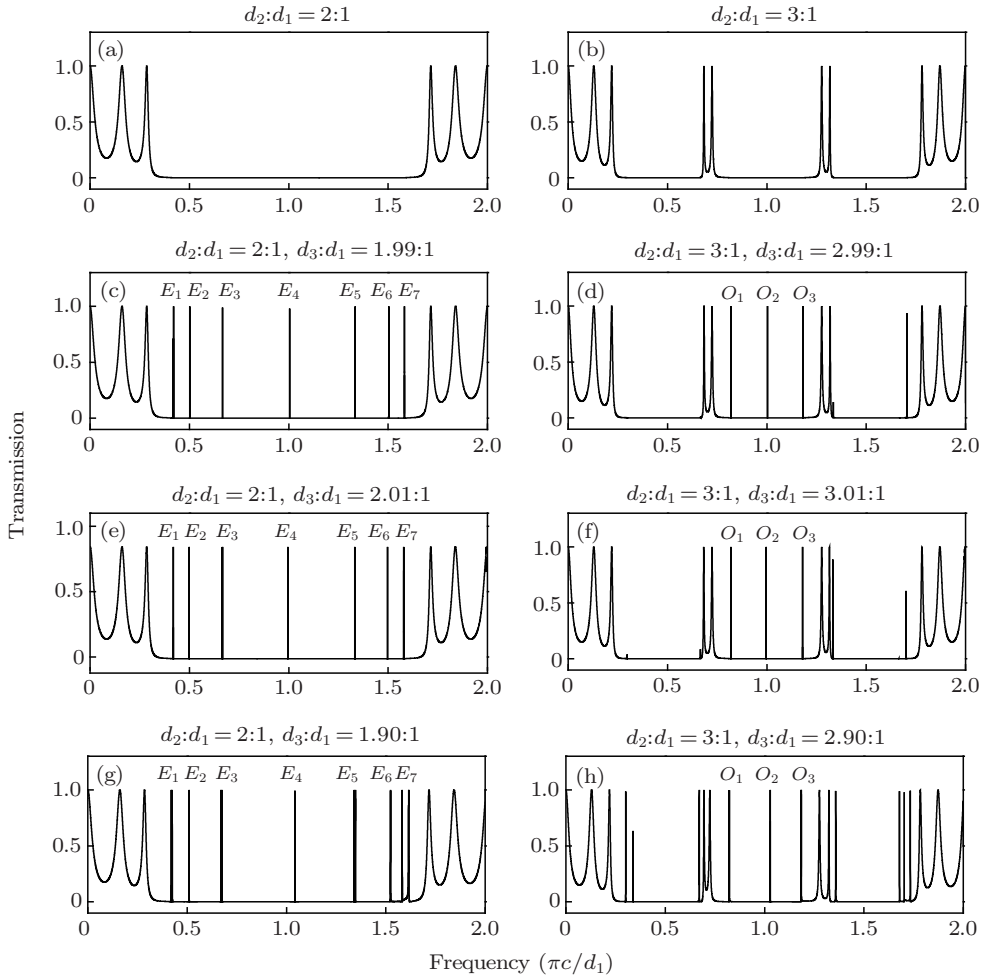


Fig. 2. Transmission spectra of the networks shown in Fig. 1, where panels (a) and (b) are the results of perfect systems and panels (c)–(h) are those of defective networks, E_i ($i = 1,2,\ldots,7$) denotes the i-th group of centric narrow passbands of defective networks with even MRWL, and O_i ($i = 1,2,3$) denotes the i-th group of centric narrow passbands of defective networks with odd MRWL. The MRWLs of the 8 subfigures are, respectively, as follows: (a) $d_2 : d_1$= 2 : 1. (b) $d_2 : d_1$=3 : 1. (c) $d_2 : d_1$=2 : 1 and $d_3 : d_1$=1.99 : 1. (d) $d_2 : d_1$=3 : 1 and $d_3 : d_1$=2.99 : 1. (e) $d_2 : d_1$=2 : 1 and $d_3 : d_1$=2.01 : 1. (f) $d_2 : d_1$=3 : 1 and $d_3 : d_1$=3.01 : 1. (g) $d_2 : d_1$=2 : 1 and $d_3 : d_1$=1.90 : 1. (h) $d_2 : d_1$=3 : 1 and $d_3 : d_1$=2.90 : 1.

We have calculated 6 symmetric defective networks with the defect of $d_2 : d_1 = n : 1$ and $d_3 : d_1 = (n + \Delta d) : 1$, where $-0.1 \leq \Delta d \leq 0.1$. The numerical results are plotted in Figs. 2(c)–2(h). From these subfigures and our numerical results we find the following three points of properties.

(i) Many groups of transparent ENPPs are created from the middle PBG of the perfect networks and the narrowest ENPP is the centric one. The widths of ENPPs decrease with the decrement $|\Delta d|$. For example, in Fig. 2(c), $\Delta d = -0.01$, the frequency range of the 4th ENPP is $1.0040827\pi c/d_1 \sim 1.0040837\pi c/d_1$ and the width $\Delta E_4 \approx 1.0 \times 10^{-6}\pi c/d_1$. In Fig. 2(g), $\Delta d = -0.1$, the frequency range of the 4th ENPP is $1.04222\pi c/d_1 \sim 1.04233\pi c/d_1$ and the width $\Delta E_4 \approx 1.0 \times 10^{-4}\pi c/d_1$. This property may be useful for the designing of narrow passband filters or switches.

(ii) The group number of ENPPs is 7 when n is even, which we label as E_i ($i = 1,2,\ldots,7$), respectively. For each group E_i, the number of ENPPs is 2, 1, 2, 1, 2, 1, and 2, respectively. On the other hand, the group number of ENPPs will be 3 when n is odd, which we label as O_i ($i = 1,2,3$), respectively. For each group O_i, the number of ENPPs is 2, 1, and 2, respectively. Further, from Subsubsection 3.2.1 one can deduce that the integers 2 and 1 here will be changed into the defect number plus one and defect number, respectively. For example, for a defective system with 3 defects there exist 4, 3, 4, 3, 4, 3, and 4 ENPPs for even n and 4, 3, and 4 ENPPs for odd n, respectively. In order to distinguish the fine structure of each group ENPP, we enlarge Figs. 2(c) and 2(d) in Figs. 3 and 4. From Figs. 3 and 4 one can demonstrate the rule of the number of ENPPs clearly.

(iii) The ENPPs will shift with the change of Δd. When $\Delta d < 0$ ($\Delta d > 0$), the ENPPs will all shift to the right (left) slightly and the shifting degree increases with the increment of $|\Delta d|$. For example, in Fig. 2(g), $\Delta d = -0.1$, the frequency range of E_4 is $1.04222\pi c/d_1 \sim 1.04233\pi c/d_1$. Obviously, the total ENPP E_4 shifts to the right slightly and the shifting length is about $0.04228\pi c/d_1$ (where the centric position is $\pi c/d_1$). In Fig. 2(e), $\Delta d = 0.01$, the frequency range of

E_4 is $0.995949\pi c/d_1 \sim 0.995950\pi c/d_1$ (E_4). So, the total ENPP E_4 shifts to the left and the shifting length is about $0.004051\pi c/d_1$. Comparing the result of Fig. 2(g) with that of Fig. 2(e) one can see that the shifting degree does increase with the increment of $|\Delta d|$.

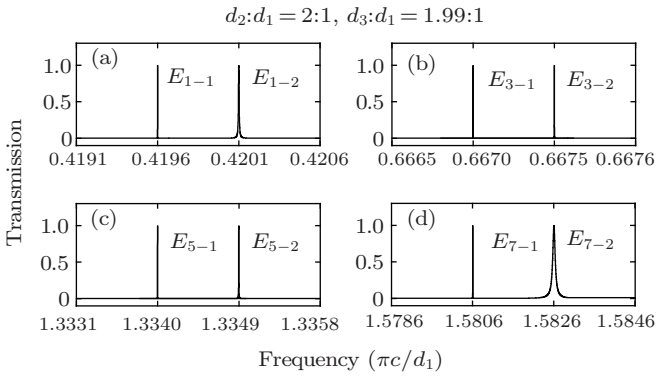


Fig. 3. Enlarged drawing of Fig. 2(c). Fine structures of (a) E_1, (b) E_3, (c) E_5, and (d) E_7.

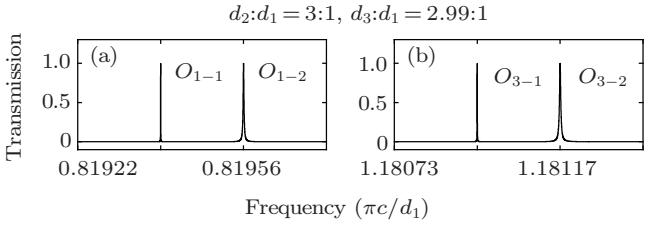


Fig. 4. Enlarged drawing of Fig. 2(d). Fine structure of (a) O_1 and (b) O_3.

3.1.2. Networks with non-integer MRWLs

From the numerical results of the perfect 2SCTWNs with non-integer MRWL $d_3 : d_1 = n : 1$ and $d_2 : d_1 = (n + \Delta d) : 1$, where $-0.1 \leq \Delta d \leq 0.1$, we find that when n is even, a narrow passband is created at the center of the transmission spectrum (see Figs. 5(a) and 5(b)); when n is odd, a large stopband is reproduced in the middle of the transmission spectrum (see Figs. 5(e) and 5(f)).

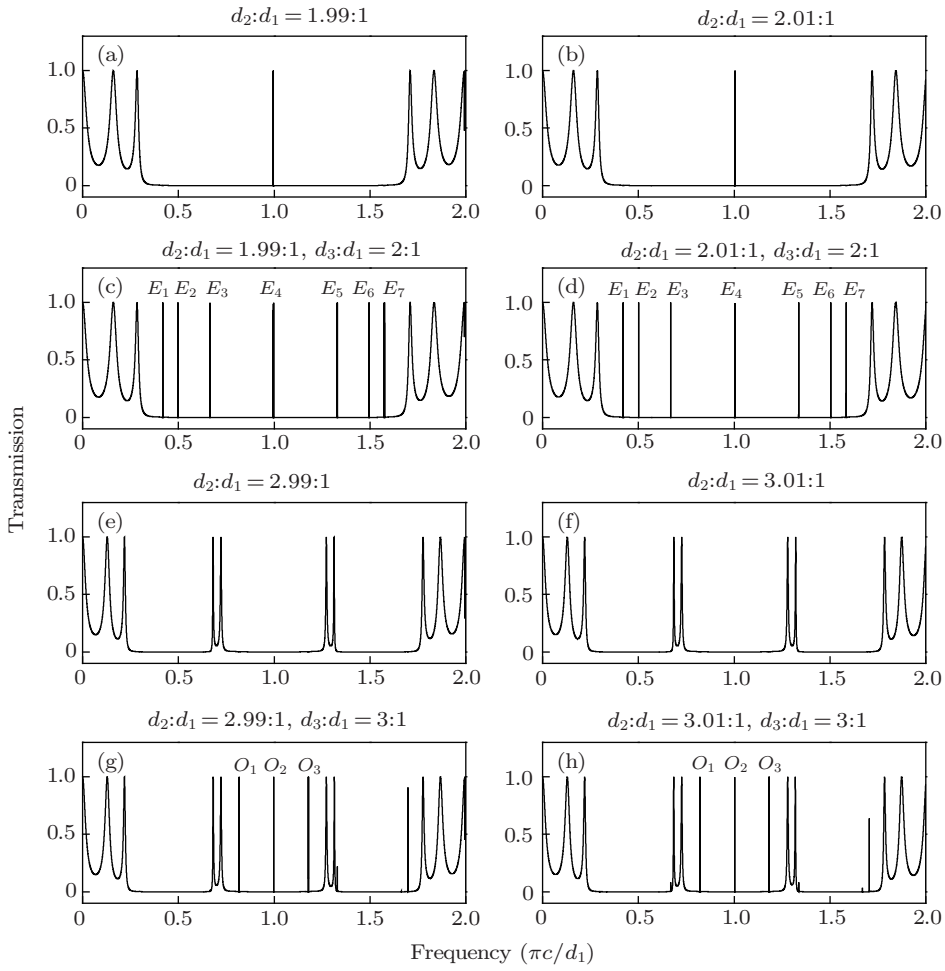


Fig. 5. Transmission spectra of the networks shown in Fig. 1, where panels (a), (b), (e), and (f) are the results of perfect systems and panels (c), (d), (g), and (h) are those of defective networks, E_i ($i = 1, 2, \ldots, 7$) denotes the i-th group of centric narrow passbands of defective networks with even matching ratio of the waveguide length. O_i ($i = 1, 2, 3$) denotes the i-th group of centric narrow passbands of defective networks with odd matching ratio of waveguide length. The matching ratios of waveguide length of the 8 subfigures are, respectively, as follows: (a) $d_2 : d_1 = 1.99 : 1$. (b) $d_2 : d_1 = 2.01 : 1$. (c) $d_2 : d_1 = 1.99 : 1$ and $d_3 : d_1 = 2 : 1$. (d) $d_2 : d_1 = 2.01 : 1$ and $d_3 : d_1 = 2 : 1$. (e) $d_2 : d_1 = 2.99 : 1$. (f) $d_2 : d_1 = 3.01 : 1$. (g) $d_2 : d_1 = 2.99 : 1$ and $d_3 : d_1 = 3 : 1$. (d) $d_2 : d_1 = 3.01 : 1$ and $d_3 : d_1 = 3 : 1$.

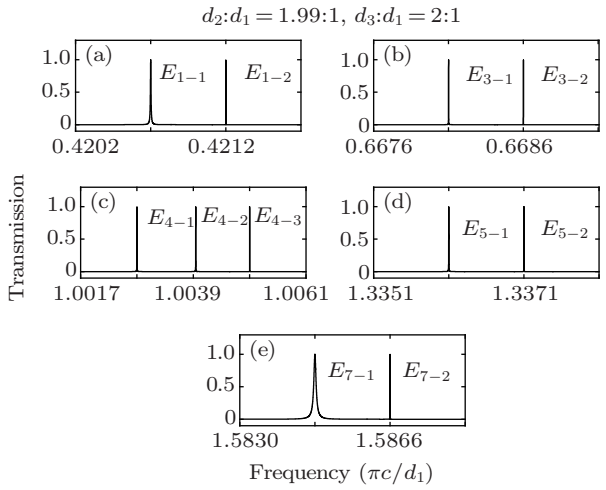


Fig. 6. Enlarged drawing of Fig. 5(c). Fine structures of (a) E_1, (b) E_3, (c) E_4, (d) E_5, and (e) E_7.

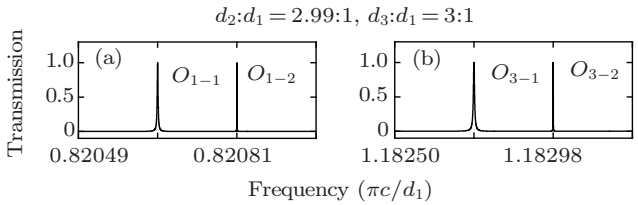


Fig. 7. Enlarged drawing of Fig. 5(g). Fine structure of (a) O_1 and (b) O_3.

For symmetric defective networks with broken even matching ratio of waveguide length $d_2 : d_1 = (2 \pm 0.01) : 1$, we have calculated 2 systems with the defect of $d_3 : d_1 = 2 : 1$, the numerical results are plotted in Figs. 5(c) and 5(d). For symmetric defective networks with broken odd matching ratio of waveguide length $d_2 : d_1 = (3 \pm 0.01) : 1$, we have also calculated 2 systems with the defect of $d_3 : d_1 = 3 : 1$, the numerical results are plotted in Figs. 5(g) and 5(h). From Fig. 5 and our numerical results we find the following three points of properties.

i) Many groups of transparent ENPPs are created in the middle of the transmission spectra. The group numbers for even and odd n are 7 (see Figs. 5(c) and 5(d)) and 3 (see Figs. 5(g) and 5(h)), respectively. The widths of ENPPs decrease with the decrement $|\Delta d|$. This property may be useful for the designing of narrow passband filters or switches.

ii) For even n, the numbers of each group ENPPs are 2, 1, 2, 3, 2, 1, and 2, respectively. For odd n, the numbers of each group ENPPs are 2, 1, 2, respectively. In order to distinguish the fine structure of each group ENPP, we enlarge Figs. 5(c) and 5(g) in Figs. 6 and 7, respectively. From Figs. 6 and 7 one can demonstrate the rule of the number of ENPPs clearly. Further, from Subsubsection 3.2.2 one can see that the numbers of each group ENPPs will be dependent on defect number and number of unit cells. For example, for a defective network with even n, 9 unit cells and 3 defects, the numbers of each group ENPPs are 4, 3, 4, 11, 4, 3, and 4, respectively, where $4 = 1 +$'defect number', $3 =$'defect number', and $11 =$'defect number'+'number of unit cells'-1. For a defective network with odd n, 9 unit cells and 3 defects, the numbers of each group ENPPs are 4, 3, and 4, respectively.

iii) The ENPPs will shift with the change of Δd and the rule is as the same as that in Subsubsection 3.1.1.

3.2. Influence of defect number and number of unit cells

In order to investigate the influence of defect number and number of unit cells on the number and width of ENPPs in the middle of the transmission spectra, we calculate a symmetric defective network with U unit cells and D centric consecutive defects. As an example, figure 8 shows a 2SCTWN with 9 unit cells ($U = 9$), 3 defects ($D = 3$), one entrance, and one exit.

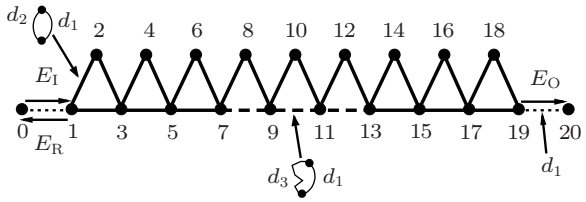


Fig. 8. The two-segment-connected triangular waveguide network with 9 unit cells, 3 defects, one entrance, and one exit, where each solid line denotes two segments of one-dimensional waveguides with the lengths of d_1 and d_2, respectively, each dash line represents a defect constructed from two segments of one-dimensional waveguides with the lengths of d_1 and d_3, respectively, and each dot line expresses one segment of one-dimensional waveguide with the length of d_1. $E_{\rm I}$, $E_{\rm R}$, and $E_{\rm O}$ are the input, reflective, and output electromagnetic waves, respectively.

3.2.1. Networks with integer MRWLs

In this subsection we investigate the 2SCTWNs with $d_2 : d_1 = n : 1$, $d_3 : d_1 = (n + \Delta d) : 1$, and $-0.1 \leq \Delta d \leq 0.1$. The properties are obtained as follows.

(I) When n is even, 7 groups of transparent ENPPs are created in the middle of the transmission spectrum. The numbers of ENPPs for each group are $D+1$, D, $D+1$, D, $D+1$, D, and $D+1$, respectively (see Fig. 9).

(II) When n is odd, 3 groups of transparent ENPPs are created in the middle of the transmission spectrum. The numbers of ENPPs for each group are $D+1$, D, and $D+1$, respectively (see Fig. 10).

(III) The centric ENPP is the narrowest one and the widths of all ENPPs decrease with the increment of U.

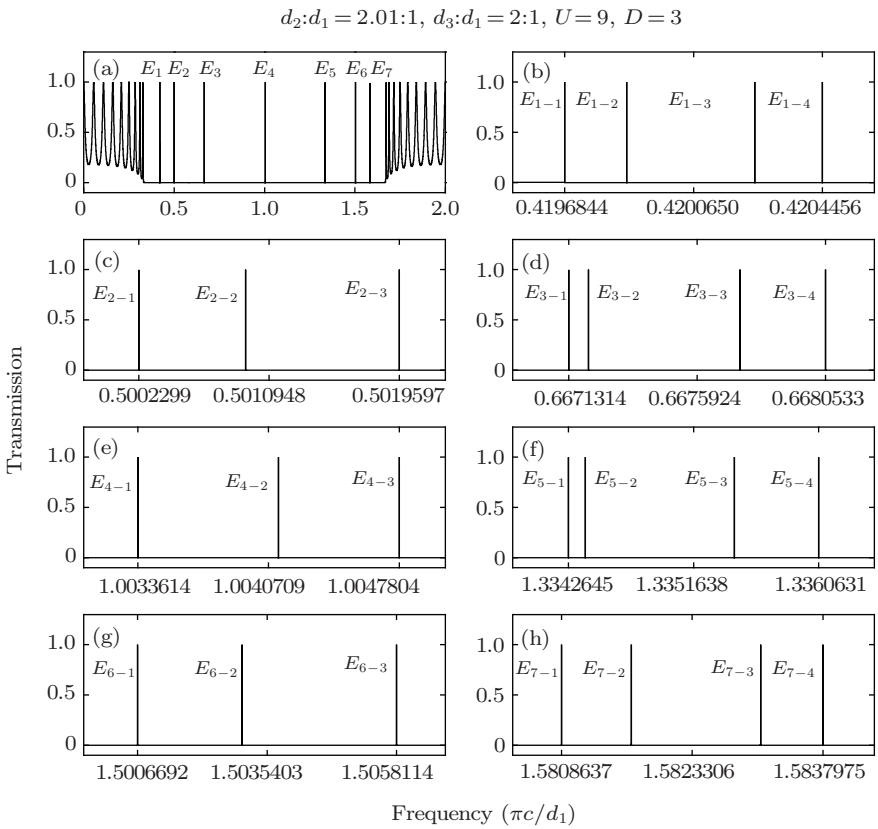


Fig. 9. Transmission spectra of the defective network shown in Fig. 8 with $d_2 : d_1 = 2 : 1$, $d_3 : d_1 = 1.99 : 1$, 9 unit cells and 3 defects. Panel (a) is the total spectra. Panels (b)–(h) are the fine structures of E_1–E_7, respectively.

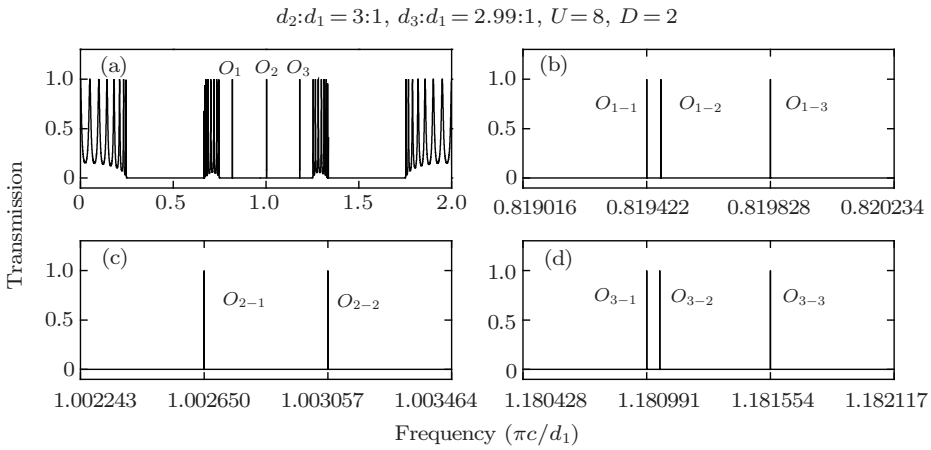


Fig. 10. Transmission spectra of the defective network shown in Fig. 8 with $d_2 : d_1 = 3 : 1$, $d_3 : d_1 = 2.99 : 1$, 8 unit cells and 2 defects. Panel (a) is the total spectra. Panels (b)–(d) are the fine structures of O_1–O_3, respectively.

3.2.2. Networks with non-integer MRWLs

Comparing with Subsubsection 3.2.1, the properties of ENPPs for the symmetric defective networks with $d_3 : d_1 = n : 1$ and $d_2 : d_1 = (n + \Delta d) : 1$, where $-0.1 \leq \Delta d \leq 0.1$ are very similar to each other. The properties are obtained as follows.

I) When n is even, 7 groups of transparent ENPPs are created in the middle of the transmission spectrum. The numbers of ENPPs for each group are $D+1$, D, $D+1$, $D+U-1$, $D+1$, D, and $D+1$, respectively (see Fig. 11).

II) When n is odd, 3 groups of transparent ENPPs are created in the middle of the transmission spectrum. The numbers of ENPPs for each group are $D+1$, D, and $D+1$, respectively (see Fig. 12).

III) The centric ENPP is the narrowest one and the widths of all ENPPs decrease with the increment of U.

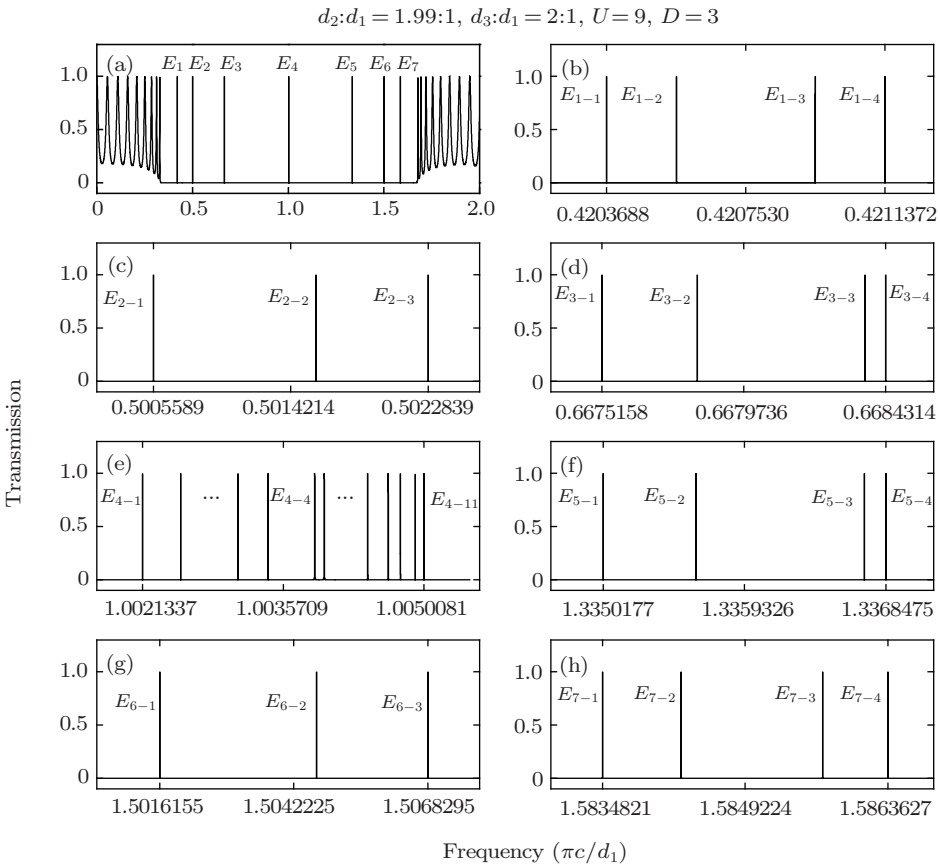


Fig. 11. Transmission spectra of the defective network shown in Fig. 8 with $d_2 : d_1 = 1.99 : 1$, $d_3 : d_1 = 2 : 1$, 9 unit cells and 3 defects. Panel (a) is the total spectra. Panels (b)–(h) are the fine structures of E_1–E_7, respectively.

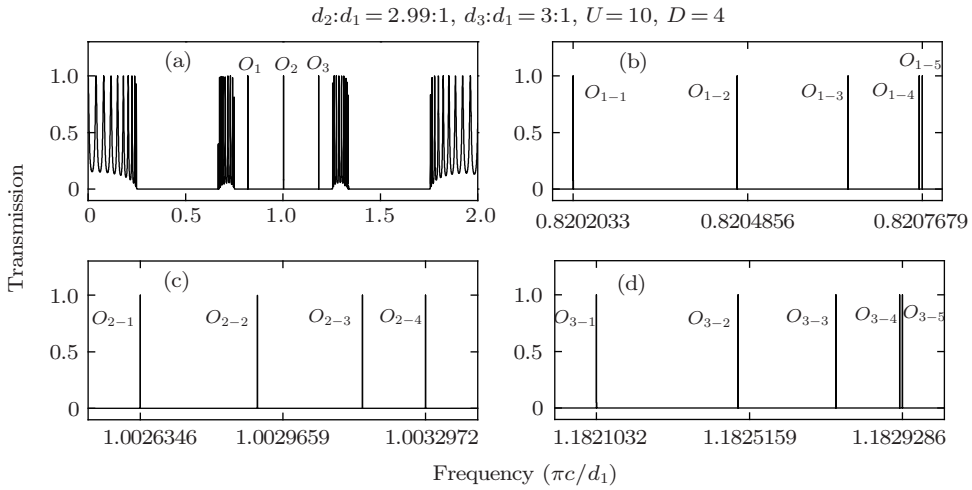


Fig. 12. Transmission spectra of the defective network shown in Fig. 8 with $d_2 : d_1 = 1.99 : 1$, $d_3 : d_1 = 2 : 1$, 9 unit cells and 3 defects. Panel (a) is the total spectra. Panels (b)–(d) are the fine structures of O_1–O_3, respectively.

4. Conclusion

In this paper, by means of a network equation and generalized eigenfunction method we investigated the transmission properties of perfect and symmetric defective 2SCTWNs.

For the symmetric networks with integer and non-integer MRWLs, we studied the influences of MRWL, number of defects, and number of unit cells on the number, width, and position of ENPPs in the middle of the transmission spectra and obtained the following rules.

a) After introducing defects in 2SCTWNs with the MRWL of $d_2 : d_1 = n : 1$ or $d_2 : d_1 = (n + \Delta d) : 1$ ($-0.1 \leq \Delta d \leq 0.1$), 7 (3) groups of transparent ENPPs will be created in the middle transmission spectra when n is even (odd).

b) For the defective 2SCTWNs with

$$d_2 : d_1 = n : 1,\ d_3 : d_1 = (n+\Delta d) : 1\ (-0.1 \le \Delta d \le 0.1),$$

U unit cells and D centric consecutive defects, the numbers of ENPPs for each group are $D+1$, D, $D+1$, D, $D+1$, D, and $D+1$, respectively, when n is even. When n is odd, the numbers of ENPPs for each group are $D+1$, D, and $D+1$, respectively.

c) For the defective 2SCTWNs with

$$d_3 : d_1 = n : 1,\ d_2 : d_1 = (n+\Delta d) : 1\ (-0.1 \le \Delta d \le 0.1),$$

U unit cells and D centric consecutive defects, the numbers of ENPPs for each group are $D+1$, D, $D+1$, $D+U-1$, $D+1$, D, and $D+1$, respectively, when n is even. When n is odd, the numbers of ENPPs for each group are $D+1$, D, and $D+1$, respectively.

d) ENPPs shift with the change of Δd. When Δd is negative/positive, ENPPs all shift to the right/left slightly and the shifting degree increases with the increment of $|\Delta d|$.

e) The widths of ENPPs decrease with the decrement of $|\Delta d|$.

In conclusion, we have obtained a series of quantitative rules of the number of ENPPs and some qualitative properties of the width and position of ENPPs. It may be useful for the designing of high-sensitive optical switches, wavelength division multiplexers, extreme-narrowband filters, and other correlative waveguide network devices.

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