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Super-strong photonic localization in symmetric two-segment-connected triangular defect waveguide networks

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ABSTRACT

In this paper we study photonic localizations of symmetric two-segment-connected triangular defect waveguide networks (STSCTDWNs). It is found that very strong photonic localizations can be generated at the nodes connected with defect waveguide(s) of STSCTDWNs in which intensities are 12 orders of magnitude larger than previous reported results. The formulae of the largest intensity of photonic localization (LIPL) are obtained. It may possess potential applications for the designing of all-optical devices based on strong photonic localization in lower frequency regime, e.g., RF or microwave.

1. Introduction

Photonic crystals (PCs) are capable of exhibiting photonic band gaps (PBGs) and photonic localizations [1,2] when electromagnetic (EM) waves propagate through them. This provides probabilities for people to control and confine the propagation of EM waves. By now people have paid much attention to PCs and have found applications in many fields [3–8].

However, to fabricate a PC is not very easy, even so far people have not made a breakthrough in the fabrication of three-dimensional PCs in visible wavelength range [9]. Additionally, introducing certain type and number of defects in the certain position of a PC is much more difficult than fabricating a perfect PC. Fortunately, the optical waveguide networks composed of one-dimensional (1D) waveguide segments can overcome the aforementioned difficulty. Firstly, the difficulty of the fabrication does not increase with the increment of the dimension of waveguide networks. Secondly, introducing arbitrary type and number of defects in arbitrary position of a waveguide network is very flexible and convenient. As a result, optical waveguide networks have been widely studied [10–22].

It is known that a defect mode can be formed by introducing a site defect into a PC and can be used for designing high power lasers [7], wavelength demultiplexing devices [23], high power superluminescent light emitting diodes (SLEDs) [24,25], microcavities [26], all-optical switches [27], and so on. Generally, the stronger the photonic localization of a defect PC is, the better the function of an optical device will be. So, how to design new defect PBG structures being able to generate stronger photonic localizations is one of the attracted problems in the field of PBG materials. It will be useful for the designing of new micro–nano optical devices based on defect PBG structures.

In recent years, our group has researched a series of properties of optical waveguide networks [16–22]. Very recently, we [21] studied the optical transmissions of symmetric two-segment-connected triangular defect waveguide networks (STSCTDWNs) and found that several groups of extreme narrow transparent photonic passbands (ENTPPs) could be produced in the middle of the transmission spectra. In this paper we further study photonic localizations of STSCTDWNs and find that for the EM waves with the frequencies of ENTPPs, strong photonic localizations are generated in the nodes connected with defect waveguides and the largest intensity of photonic localizations (LIPLs, I_{max}) can be larger than 10^{20}, which is 12 orders of magnitude larger than previous reported results [11,15,16,28]. On the other hand, we obtain the formulae of LIPL dependent on the breaking degree of defects and the number of unit cells. Our results show that adjusting the parameters of a STSCTDWN, one can acquire arbitrary LIPL theoretically. It may possess potential applications for the designing of all-optical devices based on strong photonic localization in lower frequency regime, e.g., RF or microwave.

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We organize this paper as follows. In Section 2, we introduce our designed model (STSCTDWNs), network equation, and generalized eigenfunction method. The numerical results and discussions of the strong localizations in STSCTDWNs are presented in Section 3. Finally, a brief summary is given in Section 4.

2. Model and methods

2.1. Model

In this paper we study the STSCTDWNs, where the defects are located continuously and symmetrically at the center of the systems. This requires that a STSCTDWN with odd unit cells can only possess odd centric defects and its symmetric center will be a defect unit cell, while a STSCTDWN with even unit cells can only possess even centric defects and its symmetric center will be a node. As the examples of the cases with odd and even defects, we plot the STSCTDWNs with one and two defects in Fig. 1. Fig. 1 (a) shows the STSCTDWN with three unit cells ($U=3$), one centric defect ($D=1$), one entrance and one exit. Fig. 1(b) shows the STSCTDWN with four unit cells ($U=4$), two centric defects ($D=2$), one entrance and one exit. In Fig. 1, each solid (dashed) line denotes two segments of 1D waveguides with the lengths of d_1 and d_2 (d_1 and d_3) and the matching ratio of waveguide length (MRWL) is $d_2 : d_1 = n : 1$ ($d_3 : d_1 = (n+\Delta d) : 1$). Here n is a positive integer, Δd is the breaking degree of defects and is ordered as $0 < |\Delta d| \le 0.1$. We define the connecting way of the solid (dashed) line as a perfect (defect) pattern. Additionally, each dotted line expresses one segment of 1D waveguide with the length of d_1.

In fact, we have not only studied the STSCTDWNs, where the defects are located continuously and symmetrically at the center of the systems, but have also investigated other three kinds of related two-segment-connected triangular defect waveguide networks, where the defects are located continuously/discontinuously and symmetrically/asymmetrically in the systems. We find that when the defects are discontinuously and/or asymmetrically distributed in two-segment-connected triangular defect waveguide networks, although the LIPLs are all located at the nodes connected with defect waveguide(s), which are similar to those of STSCTDWNs, the LIPLs generated by these systems will be much smaller than those produced by STSCTDWNs. In this paper, we only focus on the networks that can produce super-strong photonic localizations, so the results for asymmetric two-segment-connected triangular defect waveguide networks have not been presented here.

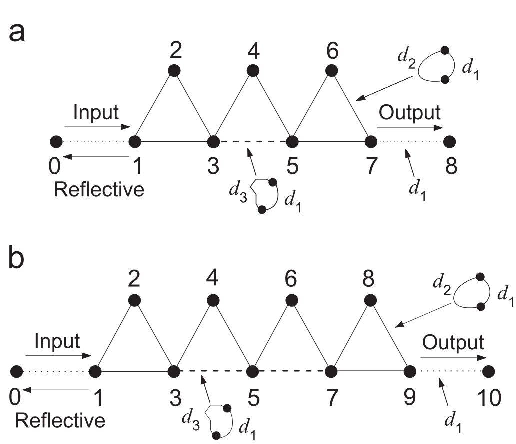

Fig. 1. STSCTDWNs with one entrance and one exit. Here each solid (dashed) line denotes two segments of 1D waveguides with the lengths of d_1 and d_2 (d_1 and d_3). Each dotted line expresses one segment of 1D waveguide with the length of d_1. "Input", "Reflective", and "Output" represent the input, reflective, and output EM waves, respectively. STSCTDWN with (a) three unit cells and one defect. (b) STSCTDWN with four unit cells and two defects.

2.2. Network equation

The networks studied in this paper are formed by 1D waveguide segments, consequently, only monomode propagation of EM waves needs to be considered and 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:

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

where $k = \omega/c$ and c is the speed of the EM wave in the vacuum. Moreover, the wave function is continuous at each node:

$$\begin{cases} \psi_{ij}|_{x=0} = \psi_i \\ \psi_{ij}|_{x=l_{ij}} = \psi_j, \end{cases} \tag{2}$$

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. At any node i, the energy flux conservation gives

$$\sum_j \frac{1}{\mu\omega} \psi_{ij} \frac{\partial \psi_{ij}}{\partial x} A_{ij} \bigg|_{x=0} = 0, \tag{3}$$

where the summation is over all segments linked directly to node i. Based on Eqs. (1)–(3) one can deduce the following network equation [14,16,29]:

$$-\psi_i \sum_j \cot kl_{ij} + \sum_j \psi_j \csc kl_{ij} = 0, \tag{4}$$

where cot and csc are the cotangent and cosecant functions, respectively. Using the aforementioned network equation and generalized eigenfunction method [30], one can calculate the wave function and photonic localization at each node. In this paper we define the intensity of photonic localization at node i as

$$I_i = |\psi_i|^2. \tag{5}$$

2.3. Generalized eigenfunction method

Actually, by use of Eq. (1) one can obtain the normalized wave functions of the entrance and exit in Fig. 1(a) as follows:

$$\begin{cases} \psi_0 = 1 + r \\ \psi_1 = e^{\imath kd_1} + re^{-\imath kd_1} \\ \psi_7 = t \\ \psi_8 = te^{\imath kd_1}, \end{cases} \tag{6}$$

where r and t are the reflection and transmission coefficients, respectively. On the other hand, by means of Eq. (4) one can obtain the relationship among the wave functions of all the nodes in the STSCTDWN with N nodes, which is a united equation set with N equations. For example, in Fig. 1(a), the number of the network nodes is $N=7$, but the number of the total system nodes is $N'=9$. Then the united equation set for these 7 nodes can be expressed as follows:

$$\begin{cases} -\psi_1(2\Lambda + \cot kd_1) + (\psi_2 + \psi_3)\Theta + \psi_0 \csc kd_1 = 0 \\ -2\psi_2\Lambda + (\psi_1 + \psi_3)\Theta = 0 \\ -\psi_3(3\Lambda + \Xi) + (\psi_1 + \psi_2 + \psi_4)\Theta + \psi_5\Omega = 0 \\ -2\psi_4\Lambda + (\psi_3 + \psi_5)\Theta = 0 \\ -\psi_5(3\Lambda + \Xi) + (\psi_4 + \psi_6 + \psi_7)\Theta + \psi_3\Omega = 0 \\ -2\psi_6\Lambda + (\psi_5 + \psi_7)\Theta = 0 \\ -\psi_7(2\Lambda + \cot kd_1) + (\psi_5 + \psi_6)\Theta + \psi_8 \csc kd_1 = 0, \end{cases} \tag{7}$$