Significant Enhancement of Unidirectional Transmission in Asymmetrically Confined Photonic Crystal Defect Pairs *

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By carrying out the two ideas of asymmetrical confinement and asymmetrical response into the photonic crystal (PC) structures that contain two or more nonlinear defects, we find that significantly unidirectional transmission can be achieved while the transmission for the positive launch direction maintains at large values. Our analyses are supported by the simulation results based on the finite-difference time-domain technique.

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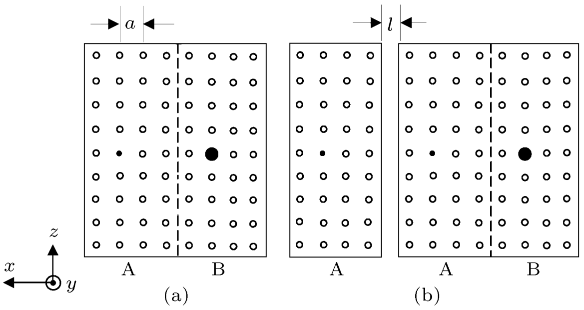
In the past two decades, photonic crystals (PCs) received remarkable attention for their potential applications in the all-optical information processing.[1−3] For example, the bistability of the nonlinear PC defects has been utilized to design optical switches, transistors, logical gates, and memories.[4−9] Also, PC defects are expected to build the optical diodes, a device that transmits optical signals unidirectionally. The first PC-based optical diode was proposed by Scalora *et al.* in 1994.[10] Since then, several operating schemes have been suggested theoretically and experimentally, providing very useful information for designing PC-based optical diodes.[11−13] To find the physical mechanism governing the unidirectional transmission, we recently employed a slab waveguide that contains a single Kerr nonlinear PC defect being asymmetrically confined and investigated its transmission characters in the framework of the coupled mode theory.[14] It was shown that the transmission contrast ratio has an upper limit of 9, which is not large enough for practical applications. To increase the contrast ratio, we further proposed a structure consisting of two coupled PC defects.[15] Although the maximum transmission contrast can be much enhanced, the length of the internal waveguide in that structure is not easy to modulate. Meanwhile, another alternative structure called the PC defect pair,[16] which consists of two PC defects having equal resonant frequency and different field distribution, has been proven to possess unidirectional transmission.[17,18] Due to different nonlinear responses of the involved PC defects to the external excitation, i.e., the asymmetrical dynamic responses, the transmission contrast can be very obvious, but the transmission for the positive launch is not so high.

To take advantage of the above-mentioned ideas of the asymmetric confinement and the asymmetric response, in this Letter we suggest an improved PC defect pair whose PC defects are confined asymmetrically. By detailed simulations based on the finite-difference time-domain technique (FDTD), we show that the transmission contrast ratio can be significantly enhanced, while the transmission for the positive launch remains at large values.



(a) (b)

Fig. 1. Schematic PC structures containing (a) two PC defects and (b) three PC defects that are made of Kerr material. All the defects possess almost the same resonant frequency and are confined asymmetrically.

The schematic structures studied here are shown in Figs. 1(a) and 1(b). They are the simple square PC structures of dielectric rods containing two or three defects. Each dashed box represents a unit containing one PC defect that is confined asymmetrically, with one normal rod at its left side and two normal rods at its right side. Increasing the number of the normal rod will lead to a large quality factor of the defect mode. As a result, it eases the demand of the input power, but the positive transmission may become smaller. The normal dielectric rods have a linear refractive index of $n_0(=3.4)$, and a radius of $0.2a$, where $a(=1.0\,\mu\mathrm{m})$ is the lattice constant of the PCs. The two types of defects, denoted as A and B, are introduced by changing the normal radius to $R_a(=0.117a)$ and $R_b\,(=0.371a\,)$, respectively. By choosing such

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radii, defects A and B possess almost equal resonant frequency and form a PC defect pair.[16] The distribution of the electric field inside defect A is monopole while it is dipole in defect B, as R_a is smaller than the normal radius while R_b is among the radius corresponding to the dipole distribution.[19] Namely, the electric field is concentrated in the centre of defect A whereas the electric field is zero (a node) in the middle of defect B. Here the defect rods are made of Kerr material that meets the relation of $n(x,z) = n_0 + n_2E^2(x,z)$, where $n_2(= 1.5 \times 10^{-5}\,\mu\text{m}^2/\text{W})$ is the nonlinear coefficient of the material and $E^2(x,z)$ is the local electric field intensity, defect mode A is more sensitive to the external excitation than defect mode B.

Based on the FDTD technique, we first investigate the unidirectional transmission of the structure of Fig. 1(a) that contains a PC defect pair. Then, we examine the structure of Fig. 1(b) where a PC defect pair couples with another defect A. We optimize the transmission contrast ratio by modulating the parameter l, the distance between the margins of the two A defects as indicated in Fig. 1(b).

In the FDTD simulations, the grid sizes in the x and z directions are set as $a/24$, and the boundary width of the perfectly matched layer is a. We choose to simulate TM mode of the PC structure whose electric field is parallel to the rods. The isolated defect modes of A and B under very low input power are shown in Fig. 2(a). The resonant frequencies are almost the same, with $\omega_A = 0.3007(2\pi c/a)$ and $\omega_B = 0.3000(2\pi c/a)$, where c is the velocity of light in vacuum. However, their quality factors are very different, with $Q_A(= 195.6)$ much larger than $Q_B(= 76.9)$. For comparison, we also present in Fig. 2(a) the transmission spectrum of their coupled structure, i.e., the PC defect pair shown in Fig. 1(a). Due to the coupling effect of the frequency splitting, the mode of the defect pair possesses two transmission peaks. One is $\omega_1 = 0.2999(2\pi c/a)$ and the other is $\omega_2 = 0.3018(2\pi c/a)$.

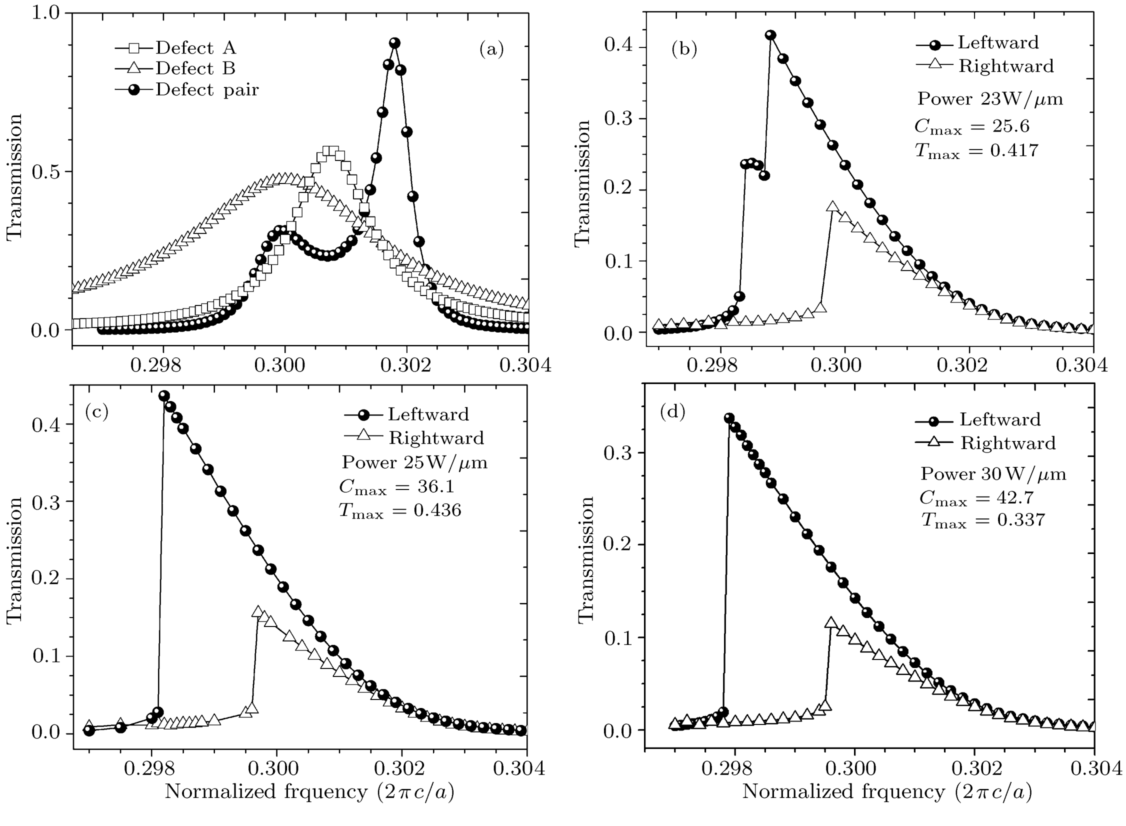

Fig. 2. (a) Linear spectra of defect A, defect B, and their coupled structure. (b), (c), and (d) Nonlinear transmission spectra of the coupled structure, with the launch power chose as 23 W/μm, 25 W/μm, and 30 W/μm, respectively.

To examine the nonlinear transmission behaviour, continuous waves with different input powers are launched from the left and right sides of the mentioned structure in turn. In general, evidently unidirectional transmission can only be achieved for a special range of input powers. Figures 2(b), 2(c), and 2(d) show the results that correspond to the input power of 23 W/μm, 25 W/μm, and 30 W/μm, respectively. It is obvious that the transmission characteristics are similar to the cases of the single defect structure.[14,15] However, the maximum contrast ratio $C_{\max}$, defined as the ratio of the maximum transmission for the positive launch to the corresponding transmission for the negative launch, reaches from 25 to 42 as shown inside the figures. They are much larger than those in the single defect cases.[14,15] What is more, the positive maximum transmission $T_{\max}$, which ranges from 0.34 to 0.44 as indicated inside the figures, remains at large values. Also, $T_{\max}$ and $C_{\max}$ are all larger than those presented by the symmetrically confined defect pairs.[17] We can explain the enhanced unidirectional transmission as follows. First, the transmission jump appears when the cw frequency is slightly smaller than the defect mode frequency. Due to $Q_{\rm B} < Q_{\rm A}$, the frequency-detuned cw couples into the structure from defect B more easily than from defect A. Thus, the frequencies corresponding to the transmission jump in the leftward launch cases [roughly at $0.2980(2\pi c/a)$] are more away from the defect mode than those in the rightward launch cases [roughly at $0.2995(2\pi c/a)$]. Second, due to the node in its field distribution as mentioned, defect B is less sensitive to the external excitation than defect A. Based on the considerations, the arrangement of defects A and B in the structure can promote the instantaneous transmission jumps of the two defect modes, creating a very high transmission. In Fig. 2(b), the spectrum for the leftward launch exhibits two transmission jumps as the input power of 23 W/μm is not large enough to achieve the instantaneous jumps. Further increases of the input power to 25 W/μm and 30 W/μm make the instantaneous transmission jumps of the two defect modes at $0.2980(2\pi c/a)$ and $0.2978(2\pi c/a)$. As a result, we can find from Figs. 2(c) and 2(d) that the maximum transmission reaches about 0.45 and 0.34, respectively. For the rightward launch where defect A is close to the input cw, the power at the frequency of $0.2980(2\pi c/a)$ or $0.2978(2\pi c/a)$ is difficult to couple into the structure, nonlinear Kerr effect is weak and the defect modes shift hardly, so the transmission for the rightward launch is very small.

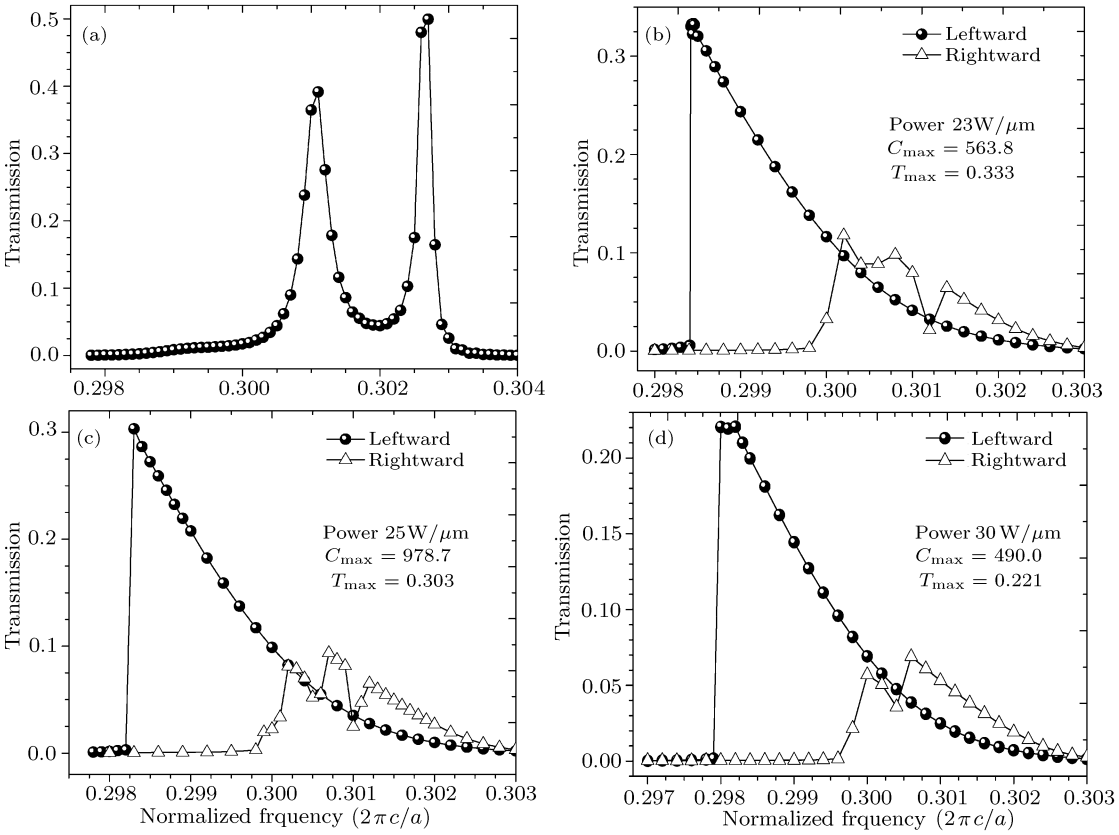

Fig. 3. (a) Linear spectrum of the structure shown in Fig. 1(b). Here (b), (c), and (d) shows the nonlinear transmission spectra of the structure shown in Fig. 1(b), in which the cw input powers are 23 W/μm, 25 W/μm, and 30 W/μm.

As the unidirectional transmission can be further enhanced through more defect coupling, it is natural for us to investigate a three-defect coupled structure, which contains the investigated defect pair and the other defect A, as shown in Fig. 1(b). Obviously, the shape of the linear transmission spectrum of the structure can be changed by modulating the distance l. In general, there are three transmission peaks in the spectrum due to the coupling effect. However, when we choose $l = -0.043a$, i.e. the distance of the two closed dielectric rods is $0.957a$, there are only two transmission peaks with very steep edges, as presented in Fig. 3(a). By doing so, we expect to greatly decrease the transmission for the rightward launch. These two peaks locate at $\omega_1' = 0.3011(2\pi c/a)$ and $\omega_2' = 0.3027(2\pi c/a)$, which are all larger than those in the investigated asymmetric defect pair.

The nonlinear transmissions corresponding to the leftward and rightward launches are provided in Figs. 3(b), 3(c), and 3(d), with three input powers of 23 W/μm, 25 W/μm, and 30 W/μm. We can see that the transmission contrast ratio increases significantly, with $C_{\max}$ reaches 563.8, 978.7, and 490.0, respectively. In comparison of Fig. 3 with Fig. 2, we find that the transmissions for the rightward launch are much smaller than those in the PC defect pair. It is the extremely low transmission for the rightward launch that provides the structure with high transmission contrast ratio. These $C_{\max}$ values show an order of magnitude of the maximum transmission contrast as compared with the reported results.[15,17–18] For the rightward launch cases, even the obvious transmission jump does not appear. Thus, it is proven further that the combining of asymmetrical confinement and the asymmetrical response can effectively enhance the transmission contrast, which is very important for the design of the PC-based optical diodes.

In summary, we have suggested an improved structure that combines the ideas of asymmetrical confinement and the asymmetrical response. Simulations reveal that the maximum transmission as well as the transmission contrast ratio is remarkably enhanced compared with the structures investigated before. Such structures are competitive candidates for the design of all-optical diodes.

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