Design of highly efficient optical diodes based on the dynamics of nonlinear photonic crystal molecules

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We investigate the unidirectional transmission behavior of photonic crystal (PC) molecules consisting of defect pairs with Kerr nonlinearity and focus on how to enhance the transmission contrast and maximum transmission of the resulting optical diodes. Theoretical analyses in combination with the numerical simulations based on the finite-difference time-domain technique are employed to evaluate the designed optical diodes. It is found that by intentionally and properly misaligning the resonant frequencies of the constitutional PC atoms, the transmission contrast as well as the maximum transmission of the nonlinear PC molecules can be significantly improved. The figure of merit that characterizes the performance of optical diodes can be enhanced by a factor of 5 as compared with the optical diodes constructed by single asymmetrically confined PC atoms. In addition, the optimum performance of the optical diodes can be achieved only when the operating frequency is properly chosen. © 2006 Optical Society of America

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1. INTRODUCTION

Optical diodes are considered to be one of the key components for all-optical signal processing and telecommunications in the future. Similar to electronic diodes that have been widely used in computers for the processing of electric signals, optical diodes offer unidirectional transmission of optical signals with specified frequencies and power densities. Thus, how to construct compact and efficient optical diodes has become a great challenge to researchers. Because of their unique properties in controlling the flow of light, photonic crystals (PCs) have been demonstrated to be a promising platform on which various functional devices can be realized,[1] including waveguides,[2] waveguide bends and intersections,[3,4] beam splitters,[5] filters,[6,7] delay lines,[8,9] lasers,[10] switches,[11–14] etc. Thus, it is also anticipated that PCs can be employed to build optical diodes with small size and high efficiency.

In fact, the first PC-based optical diode was proposed by Scalora *et al.* in the 1990s by utilizing the dynamical shift of the band edges of nonlinear PCs.[15] Several years ago, Gallo *et al.* demonstrated an optical diode in a $LiNbO_3$ grating where the transition between the second-harmonic wave and the basic wave depends on the waveguiding direction.[16] Then Mingaleev and Kivshar proposed an optical diode based on a PC line-defect waveguide where four nonlinear PC defects are arranged in an asymmetric fashion.[17] Also, Feise *et al.* investigated the bistable diode in an asymmetric multilayer structure made of left-handed materials.[18] In 2005 an electrotunable optical diode built with photonic bandgap heterojunctions made of liquid crystal was realized in the laboratory.[19]

Recently, we proposed the use of single asymmetrically confined PC defects (or PC atoms) with Kerr nonlinearity for the construction of optical diodes.[20] Because of the asymmetric confinement, the threshold for the transmission jump depends on the launch direction of the input wave, and the PC atoms exhibit to some extent unidirectional transmission when the power density of the input wave is properly chosen. However, a detailed analysis based on the coupled-mode theory (CMT) reveals that there exists an upper limit of 9 for the transmission contrast of the resulting optical diodes.[20] Obviously, this value is not sufficient for practical applications. To improve the transmission contrast, we have tried to extend the basic idea to coupled PC defects with symmetric and asymmetric confinements (or PC molecules of various configurations). It was found that both the transmission contrast and the threshold transmission could be greatly enhanced by using nonlinear PC molecules.[21] So far, it has been recognized that the unidirectional transmission of PC structures originates from the asymmetric configuration and nonlinearity.[15–21] Thus, an asymmetric confinement is generally utilized to introduce unidirectional transmission in PC molecules composed of identical defects.[20,21] From another point of view, however, it is expected that PC molecules composed of nonidentical defects with symmetric confinement can also provide unidirectional transmission. In this case, it is required that the constitutional defects possess similar resonant frequen-

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cies. Previously, one of the authors (S. Lan) introduced the concept of a defect pair that is defined as two defects with the same resonant frequency and different sizes.[22] In general, a defect pair is composed of donor and acceptor defects. Apparently, the PC molecules consisting of defect pairs have the advantage that the constitutional defects are nearly degenerate in the linear case while they become distinguished once nonlinearity is introduced. Since the asymmetric configuration in such PC molecules is provided by the difference in defect size, an asymmetric confinement is not necessary, ensuring a high transmission in the linear case. Therefore, the nonlinear PC molecules consisting of defect pairs are quite promising for the construction of highly efficient optical diodes. In this paper, we investigate systematically the design of optical diodes based on nonlinear PC molecules composed of defect pairs to find the criteria for optimizing the structure and the operating frequency of the PC molecules. The paper is organized as follows. In Section 2 we illustrate the basic structure of the nonlinear PC molecules to be used for the construction of optical diodes. Their transmission behaviors characterized by the nonlinear finite-difference time-domain (FDTD) simulations are presented in Section 3. In Section 4 we qualitatively analyze the dynamics of nonlinear PC molecules and address the different response behaviors in comparison with nonlinear PC atoms. Significant enhancement in the figure of merit of optical diodes achieved by intentionally and properly misaligning the resonant frequencies of the two defect modes is described in Section 5. The optimization of the structure and working frequency of nonlinear PC molecules is discussed in Section 6, and a summary of our study is given in Section 7.

2. STRUCTURE OF NONLINEAR PHOTONIC CRYSTAL MOLECULES CONSISTING OF DEFECT PAIRS

The basic structure of the nonlinear PC molecules to be studied here is schematically shown in Fig. 1(a). Twelve identical air holes are drilled in a slab waveguide made of a material with Kerr nonlinearity (e.g., GaAs or AlGaAs). This kind of structure can be easily obtained with the present fabrication technologies.[6,7,9] In practice, the roughness of the sidewalls of the drilled holes may lead to scattering loss for light propagating in the waveguide. However, it is expected that the scattering loss in our case is not pronounced because the electric field is strongly concentrated in the defect region. For the same reason, the fluctuation in the diameters of the air holes has little effect on the transmission of the PC defect. Here, the linear refractive index and the nonlinear coefficient for the Kerr material are assumed to be $n_0=3.37$ and $n_2=0.01\ \mu\text{m}^2/\text{W}$. The radius of the air holes is $0.12\ \mu$m and the width of the waveguide is $0.6\ \mu$m. The distance between the neighboring air holes is kept at $a=0.4\ \mu$m except that between the third and fourth air holes and that between the ninth and tenth air holes. Two defects are introduced by increasing the separation between the third and fourth air holes to $1.34a$ and that between the ninth and tenth air holes to $2.088a$. In the following, the two defects are denoted as defects A and B and their sizes are

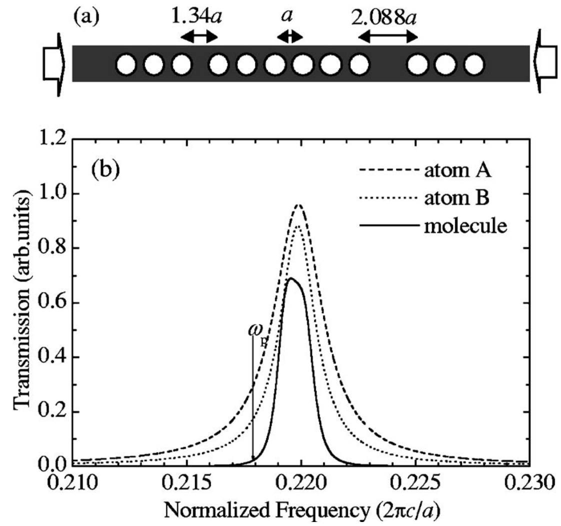

Fig. 1. (a) Basic structure of the nonlinear PC molecules studied in this paper. (b) Linear transmission spectrum of the nonlinear PC molecule in which $d_A=1.34a$ and $d_B=2.088a$ (solid curve). The spectra of the two constitutional atoms (atom A, dashed curve, and atom B, dotted curve) are also provided for reference. The frequency of the input wave (or the pump frequency) ω_p is indicated by an arrow.

represented by d_A and d_B for the sake of convenience. Thus, we have $d_A=1.34a$ and $d_B=2.088a$ in this case and this choice makes the two defects possess the same resonant frequency.

3. UNIDIRECTIONAL TRANSMISSION BEHAVIOR OF NONLINEAR PHOTONIC CRYSTAL MOLECULES

In this paper, the nonlinear FDTD method is employed to characterize the unidirectional transmission behaviors of the nonlinear PC molecules.[23] For simplicity, we perform numerical simulations on pure two-dimensional (2D) structures that are confirmed to be good approximations for 2D PC slabs.[24] In the numerical simulations, the grid size used for both directions is $a/20$ and a perfectly matched layer boundary condition is employed. The linear transmission spectrum of the PC molecule obtained by the FDTD simulation is shown in Fig. 1(b) where the spectra of the two constitutional PC atoms forming a defect pair are also provided for reference. It is obvious that the two PC atoms have slightly different quality (Q) factors and peak transmissions. However, they are coupled together through the overlap of wave functions to form a PC molecule. As compared with the spectra of the PC atoms, the spectrum of the PC molecule exhibits steeper edges, a flatter top, and a lower peak transmission. If we examine the distributions of the electric field inside the two PC atoms, it is found that the field pattern is monopole in atom A while it is dipole in atom B. In order words, the electric field is concentrated at the center of atom A while there exists a node at the center of atom B. Since the shift of the defect mode depends strongly on the field distribution inside the PC atom, the responses or sensitivities to the external excitation are different for the two PC atoms. Consequently, it is expected that the PC molecule will exhibit to some extent a unidirectional transmission behavior. In Fig. 2 we present the dependence of the transmission through the PC molecule on the input power density for a pump frequency of $\omega_p = 0.21796(2\pi c/a)(\lambda_p = 1.8352\,\mu\text{m})$. Similar to the single asymmetrically confined PC atoms we studied previously,[20] it is observed that for both launch directions a sharp transition in the transmission occurs when the power density of the input wave reaches a certain level, which is generally referred to as the threshold for transmission transition or transmission jump. The threshold for the rightward input wave is $\sim 1.30\,\text{W}/\mu\text{m}$ while that for the leftward one is $\sim 2.10\,\text{W}/\mu\text{m}$. Therefore, the PC molecule will transmit light unidirectionally when the power density of the input wave is set in between 1.30 and $2.10\,\text{W}/\mu\text{m}$. In general, two quantities are employed to characterize the performance of an optical diode. They are the transmission contrast at the threshold and the threshold transmission. Obviously, the transmission contrast at the threshold is defined as the ratio of the high transmission to the low one. In Fig. 2, the transmission contrasts are derived to be $C_1 = 7.08$ and $C_2 = 1.17$ for the rightward and leftward input waves, respectively, at the thresholds. In addition, the threshold transmissions for both launch directions are found to be ~ 0.20. Apparently, the parameters like these are far from the requirements for practical applications. In principle, we can enhance the transmission contrast of the PC molecule by increasing the frequency detuning of the input wave with respect to its resonant frequency. However, the increase in the transmission contrast by this way is achieved by sacrificing the threshold transmission. Similarly, the threshold transmission can be improved by decreasing the frequency detuning of the input wave at the expense of the transmission contrast. Therefore, it is more reasonable to use the product of transmission contrast and threshold transmission as a figure of merit to evaluate the efficiency of an optical diode. No significant change in the figure of merit is found for the PC molecule when the frequency detuning of the input wave is varied. According to Fig. 2, the figure of merit is calculated to be ~ 1.5 for the rightward input wave at the threshold, which is much larger than that for the leftward input wave. Thus, how to significantly enhance the figure of merit of the resulting optical diodes by optimizing the structure of the PC molecules has become the focus of our study.

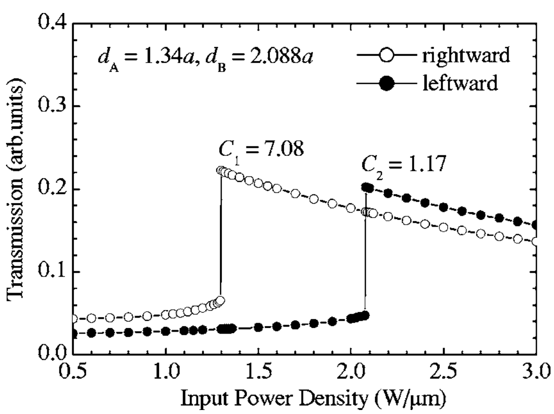

Fig. 2. Transmission behaviors (transmission as a function of the input power density) of the nonlinear PC molecule in which $d_A = 1.34a$ and $d_B = 2.088a$ at a pump frequency of $0.21796(2\pi c/a)$ for two launch directions. The transmission contrasts at the two thresholds (C_1 and C_2) are indicated.

4. DYNAMICS OF NONLINEAR PHOTONIC CRYSTAL MOLECULES

To find a way to improve the threshold transmission, we analyze the transmission jumps appearing in nonlinear PC atoms and molecules and find out what determines the threshold transmission. For a nonlinear PC atom, the physical origin for the transmission transition is the positive feedback effect.[25] When the defect mode is shifted to the pump frequency, both the transmission through the PC atom and the field intensity inside the PC atom increase rapidly, accelerating the shift of the defect mode. Since the defect mode oscillates harmonically if the response of the nonlinear material to the external excitation is instantaneous, we have suggested recently that the threshold transmission observed in numerical simulations or practical measurements is the time-averaged transmission within an oscillation period.[26] Therefore, the threshold transmission (or the maximum transmission) can never reach the peak transmission of the defect mode.

Because of the existence of linear coupling, the dynamics of nonlinear PC molecules is quite complicated, especially for those composed of different PC atoms. Basically, the spectral shape (or the transient spectrum) of a nonlinear PC atom remains unchanged when the defect mode is shifted in the presence of an external pump. In sharp contrast, the transient spectrum of a PC molecule varies instantaneously when the defect modes of the two constitutional PC atoms are shifted simultaneously under the excitation. This is the major difference in dynamical response between nonlinear PC atoms and molecules. The transient transmission at the pump frequency is determined by the transient spectrum of the PC molecule.

In the presence of external excitation, the resonant frequencies of the two PC atoms will be separated due to the different shifts of the two defect modes. At a fixed time, the PC molecule is formed by coupling two PC atoms with different resonant frequencies. According to the CMT, the transmission spectrum of a PC molecule composed of two PC atoms with different resonant frequencies ω_{01} and ω_{02} can be expressed as follows[27]:

$$T(\omega) = \left(\frac{4}{\tau_1\tau_2\tau_3\tau_4 \sin^2\varphi}\right)\left\{\left[\frac{1}{\tau_1'\tau_4'} + \frac{1}{\tau_2\tau_3\sin^2\varphi} - \prod_{i=1}^{2}(\omega - \omega_i)\right]^2 + \left(\frac{\omega-\omega_1}{\tau_4'} + \frac{\omega-\omega_2}{\tau_1'}\right)^2\right\}^{-1}, \quad (1)$$

where $1/\tau_1$, $1/\tau_2$, $1/\tau_3$, $1/\tau_4$ represent the decay rates of the two PC atoms along the two waveguiding directions; $\tau_1' = (1/\tau_a + 1/\tau_1)^{-1}$, $\tau_4' = (1/\tau_b + 1/\tau_4)^{-1}$, where $1/\tau_a$ and $1/\tau_b$ denote the decay rates of atoms A and B due to internal loss; and $\omega_1 = \omega_{01} + (\tau_2 \tan\varphi)^{-1}$ and $\omega_2 = \omega_{02} + (\tau_3 \tan\varphi)^{-1}$, where φ is the transmission phase difference between the two atoms. If we assume that there is no internal loss for both atoms and all the linear parameters for the two atoms are almost the same except the resonant frequency, then we have $1/\tau_1=1/\tau_2=1/\tau_3=1/\tau_4=1/\tau$ and $1/\tau_a=1/\tau_b=0$ and the transient spectrum of the PC molecule can be simplified as

$$T(\omega)=\left(\frac{4}{\tau^4\sin^2\varphi}\right)\left\{\left[\frac{1}{\tau^2}+\frac{1}{\tau^2\sin^2\varphi}-(\omega-\omega_1)(\omega-\omega_2)\right]^2+\left(\frac{\omega-\omega_1}{\tau}+\frac{\omega-\omega_2}{\tau}\right)^2\right\}^{-1}. \quad (2)$$

Thus, the transmissions at the two peaks of the transient spectrum of the PC molecule can be easily deduced to be

$$T_{\mathrm{peak}}=\left(1+\frac{\tau^2|\omega_{01}-\omega_{02}|^2}{4}\right)^{-1}. \quad (3)$$

According to Eq. (3), it is apparent that the maximum transmission of the PC molecule decreases with an increase in the separation between the two defect modes. Therefore, a high threshold transmission will be expected if the separation between the two defect modes remains to be small at the threshold. Intuitively, it is required that the shifts of the two defect modes be nearly the same. Apparently, the former condition is not fulfilled in the nonlinear PC molecules composed of identical atoms. In this case, the shift of the defect close to the launch site is always larger because of the stronger field intensity inside, especially in the case of a large frequency detuning for the input wave.

5. ENHANCEMENT OF THE FIGURE OF MERIT OF OPTICAL DIODES

From Fig. 2, we can see that the threshold for the rightward input wave is lower than that for the leftward one. It implies that defect mode A is easier to be shifted than defect mode B. Now let us see what will happen if we intentionally misalign the two defect modes. In Fig. 3 we present the linear transmission spectra of three PC molecules in which the size of defect B has been gradually reduced to be $2.080a$, $2.075a$, and $2.070a$. For each PC molecule, the spectra of atoms A and B are also provided for reference. Because of the reduction in size, defect mode B appears at a higher frequency in the absence of external excitation. In addition, the overall transmission is reduced with an increase in the separation between the two defect modes. When the input wave is launched from the left side, the separation between the two defect modes will become larger because defect mode A is shifted toward low frequency. Thus, it is expected that the threshold transmission will be reduced with an increase in the misalignment. If the input wave comes from the right side, however, the situation becomes quite interesting. In this case, defect mode B is shifted first toward low frequency. As a result, the separation between the two defect modes is narrowed and the overall transmission is enhanced. With an increase in the power density, defect mode B will eventually coincide with defect mode A. A further increase in the power density leads to an increase in the separation. However, defect mode A may catch up with defect mode B if the power density is further raised because it is more sensitive to the external excitation. Consequently, the separation between the two defect modes remains small at all excitation densities. Therefore, a high threshold transmission is expected if the initial misalignment is properly chosen.

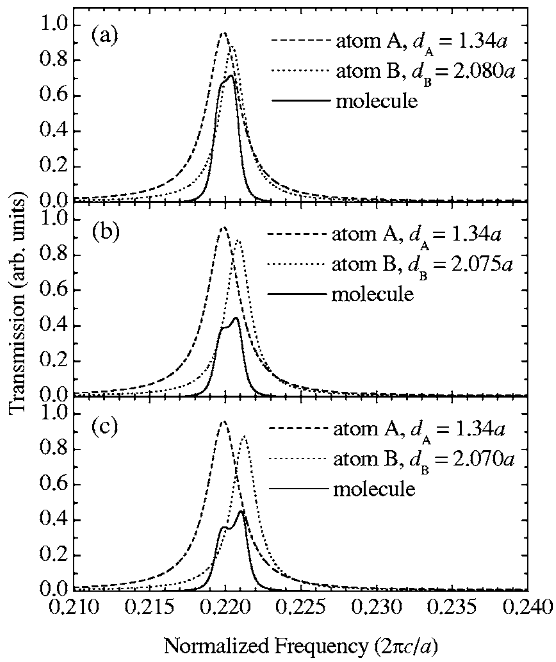

Fig. 3. Linear transmission spectra of the nonlinear PC molecules (solid curves) in which (a) $d_A=1.34a$ and $d_B=2.080a$, (b) $d_A=1.34a$ and $d_B=2.075a$, (c) $d_A=1.34a$ and $d_B=2.070a$. In each graph, the spectra of the two constitutional atoms (atom A, dashed curves; atom B, dotted curves) are also provided for reference.

Keeping this in mind, we have examined the transmission behaviors of the three PC molecules in which the two defect modes are intentionally misaligned. The simulation results for a pump frequency of $\omega_p=0.21796(2\pi c/a)$ $\times(\lambda_p=1.8352\ \mu\mathrm{m})$ are shown in Fig. 4. For the rightward input wave, the threshold remains nearly unchanged, while a gradual reduction in the transmission contrast is observed. As for the leftward input wave, it is found that the threshold increases with a decrease in the size of defect B. Meanwhile, it is observed that the transmission contrast is gradually improved while the threshold transmission is slightly increased. For the PC molecule in which $d_B=2.070a$, it is noticed that the transmission contrast is markedly enhanced to ~26.4 while the threshold transmission is greatly increased to ~0.48. In this case, the figure of merit is calculated to be 12.67, indicating an order-of-magnitude enhancement as compared with the PC molecule without any misalignment. Furthermore, this value is not only five times larger than that obtained in single asymmetrically confined PC atoms but is also slightly higher than that achieved in the coupled PC defects with a different configuration.[20,21] This result verifies our analysis based on the dynamics of nonlinear PC molecules and provides us the design criteria for the optical diodes based on nonlinear PC molecules.

6. OPTIMIZATION OF THE STRUCTURE AND PERFORMANCE OF OPTICAL DIODES

If we further reduce the size of defect B to $2.04a$, then the initial separation between the two defect modes becomes

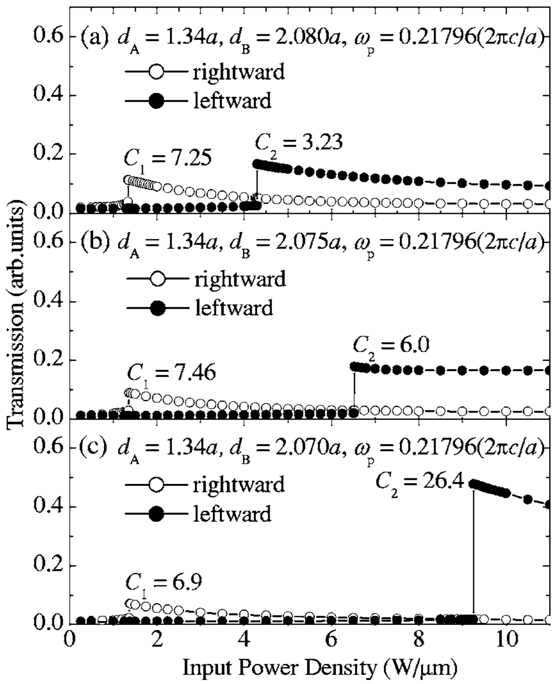

Fig. 4. Transmission behaviors (transmission as a function of the input power density) of the PC molecules in which (a) $d_A = 1.34a$ and $d_B = 2.080a$, (b) $d_A = 1.34a$ and $d_B = 2.075a$, (c) $d_A = 1.34a$ and $d_B = 2.070a$ at a pump frequency of $0.21796(2\pi c/a)$ for two launch directions. In each graph, the transmission contrasts at the two thresholds (C_1 and C_2) are indicated.

very large, leading to a low overall transmission, as shown in Fig. 5(a). The transmission behavior for the corresponding PC molecule is presented in Fig. 5(b). It can be seen that the threshold for the leftward input wave is greatly increased while that for the rightward one remains nearly unchanged. In addition, it is found that the threshold transmission for the rightward input wave is markedly reduced to ~0.03 while that for the leftward one is only slightly reduced to ~0.13. Although the transmission contrast at the second threshold is further increased to ~58, it is achieved mainly because of the large difference between the two thresholds and the significant reduction in the threshold transmission for the rightward input wave. Thus, the figure of merit for the leftward input wave at the threshold is decreased to ~7.0. Therefore, it implies that there exists an optimum misalignment for the two defect modes at which a large transmission contrast and a high threshold transmission can be realized.

So far, we have verified that the optimum performance of the PC molecule as an optical diode can be achieved when the size of defect B is chosen to be $2.070a$. On the basis of the analysis of the dynamics for nonlinear PC molecules, it is not difficult to understand that the performance of the resulting optical diode also depends on the operating frequency. In Fig. 6, we have examined the transmission behaviors of the optimum PC molecule when the frequency of the input wave is changed. When a large frequency detuning is employed [$\omega_p = 0.21717(2\pi c/a)$, $\lambda_p = 1.8419\ \mu$m], the thresholds for both launch directions are quite large because larger shifts for both defect modes are needed for the occurrence of transmission transition. As compared with the pump frequency of $0.21796(2\pi c/a)$, however, the transmission contrast at the first threshold is only slightly larger while that at the second threshold is much smaller. It is also noticed that the threshold transmissions at the two thresholds are rather small. The situations for smaller frequency detunings are shown in Figs. 6(c) and 6(d) where the frequencies of the input wave are chosen to be $0.21830(c/a)(\lambda_p = 1.8323\ \mu$m) and $0.21850(c/a)(\lambda_p = 1.8307\ \mu$m), respectively. With decreasing the frequency detuning, the thresholds for both launch directions become smaller while a slight reduction in the transmission contrast is observed. However, it is found that the reduction of the transmission contrast is partly compensated by the enhancement of the threshold transmission. Consequently, the figure of merit is gradually reduced from 12.76 to 10.68. However, a further decrease of frequency detuning will lead to a dramatic reduction in the figure of merit. To find out the optimum operating frequency for the designed optical diode, we have simulated the operations of the optical diode at different working frequencies and present the simulation results in Fig. 7. In Fig. 7(a) the threshold transmission and transmission contrast of the optical diode are plotted as a function of the frequency of the input wave. It can be seen that the transmission contrast has a maximum at $0.21766(2\pi c/a)(\lambda_p = 1.8377\ \mu$m) and it decreases rapidly for frequencies larger or smaller

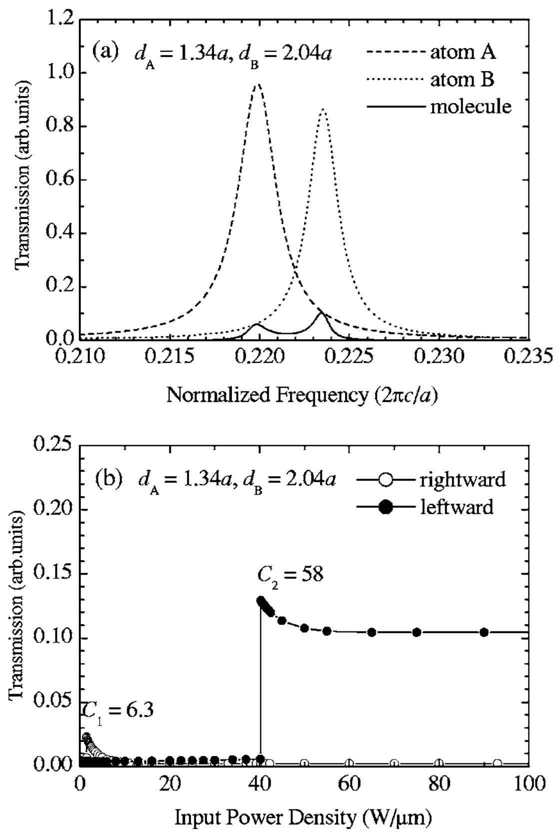

Fig. 5. (a) Linear transmission spectrum of the nonlinear PC molecule in which $d_A = 1.34a$ and $d_B = 2.040a$ (solid curve). The spectra of the two constitutional atoms (atom A, dashed curve; atom B, dotted curve) are also provided for reference. (b) Transmission behaviors (transmission as a function of the input power density) of the PC molecule at a pump frequency of $0.21796(2\pi c/a)$ for two launch directions. The transmission contrasts at the two thresholds (C_1 and C_2) are indicated.

than this value. As for the threshold transmission, it increases sharply at $\sim 0.21766(2\pi c/a)$ and gradually after this value. Therefore, the dependence of the figure of merit for the optical diode on the operating frequency exhibits a maximum of ~ 13 at $0.21776(2\pi c/a)$, as shown in Fig. 7(b). This frequency is considered to be the optimum working frequency for the designed optical diode. Apparently, there exists a wide frequency range [from $0.21760(2\pi c/a)$ to $0.21860(2\pi c/a)$] in which the figure of merit for the optical diode is above 10. Hence, the performance of the optical diode remains nearly unchanged provided that the operating frequency does not deviate too much from the optimum value.

It is necessary to indicate that the optimum structure described above is obtained when one of the defects has been chosen to be $1.34a$. The optimum operating frequency is also derived for the PC molecule in which $d_A = 1.34a$ and $d_B = 2.070a$. Optical diodes with higher efficiency may be achieved by deliberately selecting the constitutional defects. However, our research results reveal that a slight misalignment of the resonant frequencies of the constitutional defects can lead to a significant improvement in the performance of the resulting optical diodes. This criterion is quite useful for the design of the optical diodes based on nonlinear PC molecules.

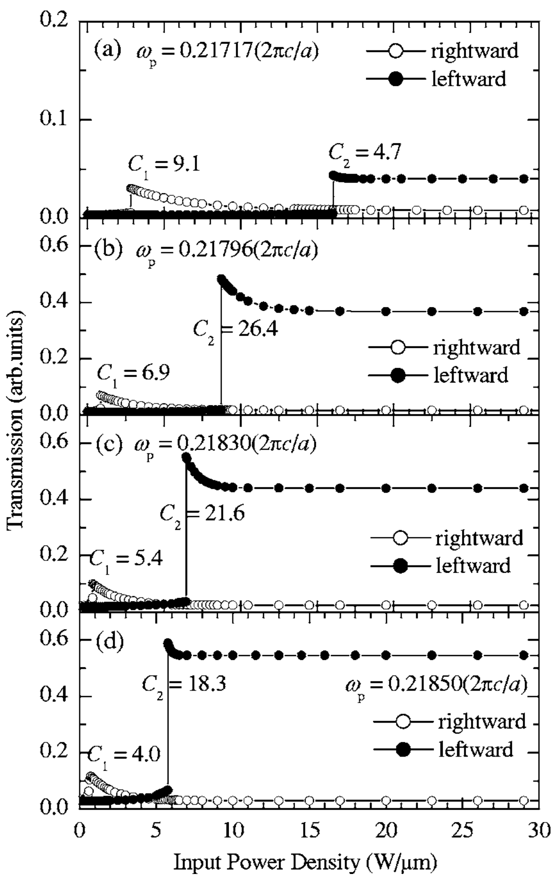

Fig. 6. Transmission behaviors (transmission as a function of input power density) of the optimum nonlinear PC molecule ($d_A = 1.34a$ and $d_B = 2.070a$) at different pump frequencies for two launch directions. (a) $\omega_p = 0.21717(2\pi c/a)$, (b) $\omega_p = 0.21796(2\pi c/a)$, (c) $\omega_p = 0.21830(2\pi c/a)$, (d) $\omega_p = 0.21850(2\pi c/a)$.

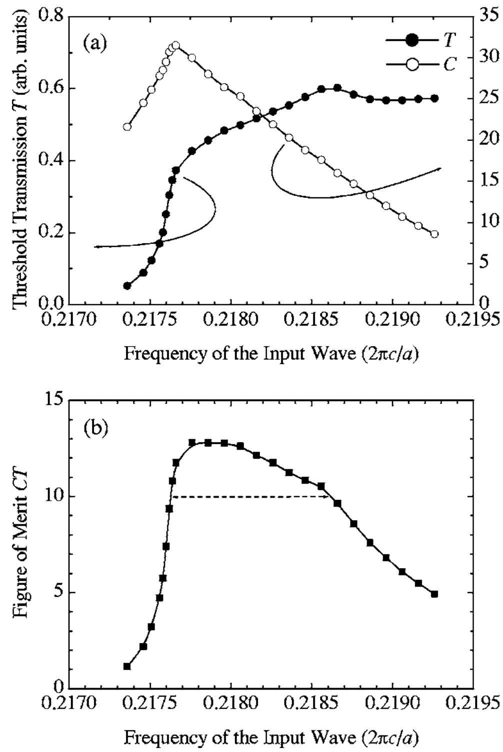

Fig. 7. (a) Threshold transmission and transmission contrast of the optimum nonlinear PC molecule ($d_A = 1.34a$ and $d_B = 2.070a$) as a function of the frequency of the input wave. (b) Dependence of the figure of merit of the resulting optical diode on the frequency of the input wave. The dashed line with arrows indicates the frequency range in which the figure of merit of the resulting optical diode is above 10.

7. CONCLUSION

In summary, we have investigated the design of optical diodes based on PC molecules consisting of defect pairs with Kerr nonlinearity. It is found that a significant enhancement of the transmission contrast and threshold transmission of the nonlinear PC molecules can be achieved by intentionally and properly misaligning the resonant frequencies of the constitutional PC atoms. The figure of merit that characterizes the performance of optical diodes has been increased by an order of magnitude and by a factor of 5 as compared with the PC molecule without misalignment and with single asymmetrically confined PC atoms, respectively. In addition, it is revealed that the operation of the resulting optical diodes also depends on the frequency of the input wave. The optical diodes proposed in this paper can be easily realized with the current fabrication technologies.[6,7,9]

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