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Abstract. An all-optical diode (AOD) with structure $(AB)^m(BA)^n(BBAA)^k$ is proposed based on asymmetric light localization, and its optical bistability are numerically investigated by the nonlinear transfer matrix method. Research results show that the behavior of the AOD strongly depends on the period number m , n , and k , the transmission direction of the AOD is related to the values of m and n , while k affects the transmission contrast of the AOD. It is a significant reference for the design of all-optical signal processing devices. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3558733]

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1 Introduction

An all-optical diode (AOD) is a spatially nonreciprocal device and plays an important role in all optical signal processing. In recent years, various structures of AOD have been designed with different materials, such as metamaterials,¹⁻³ and the efficiency of AOD is characterized by the transmission contrast $C = (T_{\text{Left}} - T_{\text{Right}})/(T_{\text{Left}} + T_{\text{Right}})$.⁴ To obtain a high transmission contrast in the structure of photonic multilayer, one way is to use the nonreciprocal reflection caused by nonlinear absorption of metal,^{5,6} another way is to use the spatial asymmetry of the structure (e.g., Thue–Morse structure) with Kerr nonlinear dielectric materials.^{7,8} However, the transmission of the AOD in the first way is relatively low because of the absorption of metal, and although high transmission can be reached in the spatial Thue–Morse structure with the second way, the structure is comparatively complicated when the generation number of the Thue–Morse structure becomes large, which limits its application in practical.

In this work, an AOD is designed with a simple photonic multilayers $(AB)^m(BA)^n(BBAA)^k$. In comparison to the mirror-symmetric structure $(AB)^m(BA)^m$, which cannot realize nonreciprocal transmission, the spatially asymmetric structure $(AB)^m(BA)^n(BBAA)^k$ (with $m = n$) possesses

not only the high transmission but also the nonreciprocal transmission due to asymmetric light localization. Furthermore, when different materials are assigned to represent A and B [i.e., the structures of the form $(AB)^m(BA)^n(BBAA)^k$ and $(BA)^m(AB)^n(AABB)^k$ whose linear properties have been studied in Ref. 9], the nonlinear performances of both forms are examined and a better assignment is suggested for designing the AOD.

2 Simulation and Discussion

The linear and nonlinear material parameters of the photonic multilayer structure $(AB)^m(BA)^n(BBAA)^k$ are selected as those in Ref. 7, where A and B denote polydiacetylene 9-BCMU organic material and TiO₂ material with linear refractive indices $n_A = 1.55$, $n_B = 2.3$, thickness $d_A = 92$ nm, $d_B = 62$ nm, nonlinear Kerr refractive indices $n_2(9\text{-BCMU}) \approx 2.5 \times 10^{-11}$ cm²/W, and $n_2(\text{TiO}_2) \approx 10^{-14}$ cm²/W, respectively. Thus, the resonant wavelength λ_{res} of the structure satisfies the relationship $n_A d_A = n_B d_B = \lambda_{\text{res}}/4$.

The nonlinear transmission of the structure is calculated by using the nonlinear transfer matrix method.¹⁰ As an example, the nonlinear transmission spectra of the structure $(AB)^6(BA)^6(BBAA)^6$ for left and right incidence are shown in Fig. 1(a). In region II (between two straight dashed-dotted lines) of Fig. 1(a), the transmission of the left incident light locates at the upper branches because its intensity is beyond bistability threshold, while the transmission of the right incident light stays at the lower branches for its intensity is below bistability threshold. Thus, an AOD whose direction is left is realized by using the nonreciprocal transmitted character in region II. Then to explore the mechanism of the AOD action, Fig. 1(b) shows the different field distributions for both directions. Thus, it is because the asymmetric light localization caused by combing with part $(BBAA)^6$ that the bistability thresholds for both directions of photonic multilayer $(AB)^6(BA)^6(BBAA)^6$ are differentiated.

To investigate the influence of the material assignment to the action of the AOD, the properties of the photonic multilayers $(BA)^m(AB)^n(AABB)^k$ and $(AB)^m(BA)^n(BBAA)^k$ are examined. As shown in Fig. 2(a) with an example $m = n = k = 6$, though both structures can realize perfect transmission, the bandwidth of the resonant mode of the former structure is narrower than that of the latter structure. Then with our calculation, the upper branches of optical bistability of the former structure falls faster than that of the latter structure. As demonstrated by comparing Figs. 2(b) and 1(a), with a

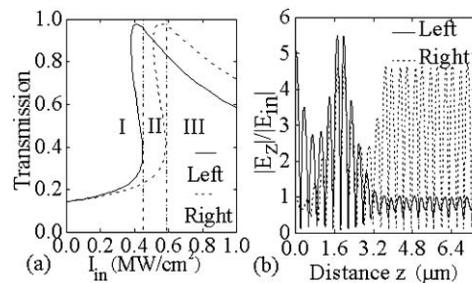


Fig. 1 (a) Nonreciprocal transmission behavior depending on the input intensity I_{in} at incident wavelength $\lambda = 576$ nm under normal incidence for left and right directions. An AOD is realized with $T_{\text{left}} = 0.958$, $T_{\text{right}} = 0.230$, $I_{in} = 0.448$ MW/cm². (b) The electric field intensity distributions for both incident directions at wavelength $\lambda = 576$ nm.

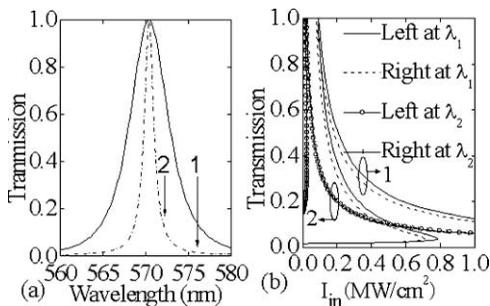


Fig. 2 (a) Linear transmission of structures $(AB)^6(BA)^6(BBAA)^6$ (solid line) and $(BA)^6(AB)^6(AABB)^6$ (dashed line) and (b) nonlinear transmission of structure $(BA)^6(AB)^6(AABB)^6$ for two incident directions at wavelength $\lambda_1 = 576$ nm and $\lambda_2 = 572$ nm corresponding the arrows 1 and 2 in (a), respectively.

rapid falling of the upper branches, the transmission and transmission contrast of $(BA)^6(AB)^6(AABB)^6$ is lower than that of $(AB)^6(BA)^6(BBAA)^6$ at wavelength $\lambda = 576$ nm. Moreover, as can be seen from Fig. 2(b), for the structure $(BA)^6(AB)^6(AABB)^6$, the shorter the incident light wavelength is, the lower the difference is between the forward and backward bistability thresholds. Hence, the assignment with the form $(AB)^m(BA)^n(BBAA)^k$ is better to design the AOD with high transmission and high-transmission contrast.

In the following, the influences of the period numbers m , n , and k to the behavior of the forward/backward bistability of the structure $(AB)^m(BA)^n(BBAA)^k$ are discussed. Figure 3

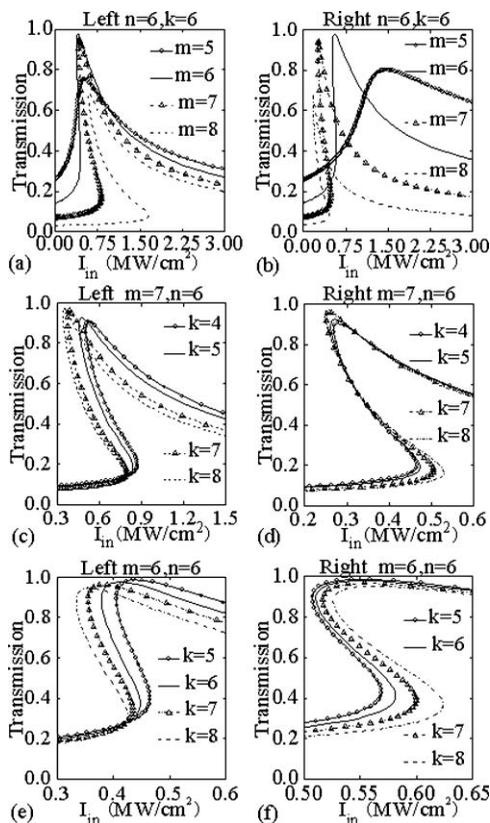


Fig. 3 Influences of the period numbers m , n , and k to the behavior of bistability for two directions at wavelength $\lambda = 576$ nm. (a,c,e) The light incidents from left and (b,d,f) from the right.

shows the nonlinear transmission spectra at wavelength $\lambda = 576$ nm under normal incidence. Several interesting conclusions are obtained. First, as shown in Figs. 3(a) and 3(b), the bistability threshold enhances for left incidence but reduces for right incidence as m increases. Therefore, the direction of the AOD strongly depends on period number m . For example, the nonreciprocal transmission of AOD is left when $m = 6$, whereas it is right when $m > 6$. In fact, the direction of the AOD also strongly depends on period number n , whereas the action of n nearly equals that of m (for simplicity, the case of n is not shown here). Second, as seen from Figs. 3(c) and 3(d), a trade-off is found between the nonreciprocity and the maximum transmission. As k increases, the maximum transmission increases while the nonreciprocity decreases. For example, for $m = 7$ and $n = 6$, when $k = 6$, $T_{max} = 0.897$, the direction of the AOD is right, but when $k = 8$, $T_{max} = 0.947$, the nonreciprocal transmission disappears. Third, when $m = n$, as k increases, besides the reduction of the bistability threshold of the AOD, another trade-off is found between the transmission and the transmission contrast. As shown in Figs. 3(e) and 3(f), the transmission contrast increases while the transmission decreases. For example, for $m = 6$, when $k = 6$, $T_{left} = 0.958$, $T_{right} = 0.230$, and $C = 0.61$; but when $k = 8$, $T_{left} = 0.893$, $T_{right} = 0.185$, and $C = 0.65$. The dependence of the optical bistability on the period numbers is useful to adjust the functions of AOD.

Furthermore, it is known that the nonreciprocal transmission behavior of the structure $(AB)^m(BA)^n(BBAA)^k$ also

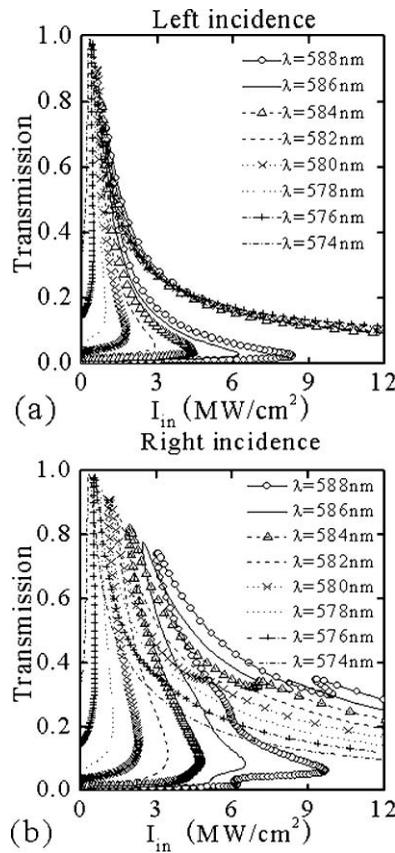


Fig. 4 Influences of the incident wavelength to the behavior of bistability for two directions. (a) The light incidents from left and (b) from the right.

depends on the wavelength of incident light due to the dynamic shift mechanism of the defect mode in nonlinear medium. Figures 4(a) and 4(b) show the effects of the incident wavelength to the behavior of forward/backward bistability, respectively. It is obtained that the bistability thresholds for both directions enhance as the wavelength of light increases.

3 Conclusions

In summary, a nonlinear AOD with the structure $(AB)^m(BA)^n(BBAA)^k$ is realized based on asymmetric light localization. Transmission of 98.5% is reached at the input intensity 0.448 MW/cm^2 with the photonic multilayer structure, which is nearly the same as that of the Thue–Morse structure, but the thickness of our structure ($7.392 \mu\text{m}$) is much thinner than that of the Thue–Morse structure ($12.096 \mu\text{m}$). Moreover, the performance of the AOD can be tuned by varying the period numbers in our structure. Therefore, the photonic multilayer structure provides significant reference for the design of all-optical signal processing devices.

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