Modulation of bistable lateral shifts in a one-dimensional nonlinear photonic crystal consisting of indefinite metamaterials

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(Received 10 November 2009; revised manuscript received 24 January 2010; published 16 April 2010)

Nonlinear propagation characteristics are investigated theoretically in a one-dimensional photonic band-gap structure containing indefinite metamaterials. It is found that optical bistability can be achieved at very low threshold values of normalized input intensity in this composite structure when the indefinite metamaterial is a cut-off, anticut-off, and never cut-off medium. It is also found that there exists corresponding bistable lateral shift which is strongly dependent on the parameters of indefinite metamaterials.

DOI: 10.1103/PhysRevE.81.046603 PACS number(s): 41.20.−q, 42.25.Gy, 42.25.Bs, 78.20.Ci

I. INTRODUCTION

It's well known that the field of metamaterials includes a large range of engineered materials with predesigned properties. A theoretical study of such a medium was made in 1967 by Veselago [1] and the medium was labeled as a "left-handed medium," which is still in use up to now [2,3]. Yet the fabricated materials are intrinsically anisotropic on account of the orientations of the rings and rods in space [4,5]. One of the anisotropic metamaterials, i.e., indefinite metamaterial (IMM), in which not all the principal components of the electric permittivity and magnetic permeability tensors have the same sign, has received increasing attention over the past few years [6–9]. Recently, various applications of IMMs have been proposed and investigated in the frequency range of microwaves. For instance, the high-, low-, and band-pass spatial filters can be constructed by using the bilayers in the IMMs [7] and the planar waveguide made of IMMs has been reported to support an infinite number of guided modes [10].

In the recent years, nonlinear Goos-Hänchen (GH) lateral shift have inspired considerable interest, such as the bistable lateral shift for one-dimensional photonic crystals (1DPC) doped with nonlinear dielectric [11], and the giant bistable lateral shift due to surface plasmon excitation in Kretschmann configuration with Kerr nonlinear dielectric [12], as well as the tunable GH shift in the two-dimensional photonic crystals [13]. However, most work of nonlinear GH shifts has been carried out in isotropic materials. Therefore, it is worth discussing the bistable lateral shift through a 1DPC consisting of indefinite metamaterials. IMM is identified four classes based on their dispersion relations [6], which are called cut-off, anticut-off, never cut-off, and always cut-off medium. In the following paper, we will investigate the nonlinear characteristics of 1DPC consisting of different types of IMMs and a nonlinear defect.

This Brief Report is organized as follows: in Sec. II, the theoretical model of 1DPC containing IMMs and a nonlinear defect will be shown. In Sec. III, we will discuss the dependence of bistability properties on the four types of IMM. The conclusion is given in Sec. IV.

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II. THEORETICAL MODEL

We consider a one-dimensional multilayer stack $(AB)_m N(BA)_m$ in the background material $C(\varepsilon_C,\mu_C)$ as shown in Fig. 1, where m is the period number, $A(\varepsilon_A,\mu_A)$ is isotropic normal material and $B(\hat{\varepsilon}_B,\hat{\mu}_B)$ is indefinite metamaterial.

The anisotropic permittivity and permeability tensors of IMM are defined as follows [14]:

$$\hat{\varepsilon}_B=\begin{pmatrix}\varepsilon_{Bx} & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix},\quad \hat{\mu}_B=\begin{pmatrix}1 & 0 & 0\\ 0 & \mu_{By} & \mu_{zy}\\ 0 & \mu_{yz} & \mu_{Bz}\end{pmatrix}. \tag{1}$$

These terms can be achieved by using a network of thin wires and a periodic arrangement of split ring resonators [15,16]. They can be positive or negative by changing corresponding structure parameters and incident frequencies [17–20]. Note that the off-diagonal terms μ_{zy} and μ_{yz} would not alter the results in our paper. N is the Kerr-type nonlinear material and the effective permittivity is $\varepsilon=\varepsilon_L+\chi_3|E(z)|^2$, where χ_3, ε_L are the Kerr nonlinear coefficient and the linear part of effective permittivity, respectively, and the effective permeability is μ_N. The optical thicknesses of layers A and B satisfy $\sqrt{\varepsilon_A\mu_A}d_A=\sqrt{|\varepsilon_{Bx}||\mu_{By}|}d_B=\lambda_{pc}/4$ and $\sqrt{\varepsilon_L\mu_N}d_N=\lambda_{pc}/2$ for nonlinear layer N, where λ_{pc} is the midgap wavelength of PC at normal incidence.

Suppose a wave beam of angular frequency ω incident from the background upon this 1DPC at an angle θ_0. Without loss of generality, we assume that the wave vector lies in the $y-z$ plane and the incident electric field is $\vec{E}=\hat{x}E_0\exp[i(\beta y+k_{Cz}z-\omega t)]$, where β and k_{Cz} are y and z components of the incident wave vector, where $\beta=k_C\sin\theta_0=k_0\sqrt{\varepsilon_C\mu_C}\sin\theta_0$, $k_0=\omega/c$ and $k_{Cz}=k_C\cos\theta_0$. Here we only consider the *TE* mode and the treatment for the *TM* mode is similar.

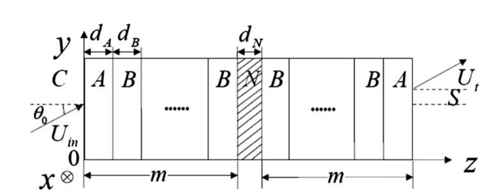

FIG. 1. Schematic of a 1DPC with a nonlinear defect.

Generally, the electric and magnetic fields at two sides of some layer can be related via transfer matrix [21]. For isotropic material A, the transfer matrix is shown as:

$$M_A = \begin{pmatrix} \cos(k_{Az}d_A) & -i\dfrac{k_0\mu_A}{k_{Az}}\sin(k_{Az}d_A) \\ -i\dfrac{k_{Az}}{k_0\mu_A}\sin(k_{Az}d_A) & \cos(k_{Az}d_A) \end{pmatrix}, \quad (2)$$

where $k_{Az}=\sqrt{\varepsilon_A\mu_A k_0^2-\beta^2}$.

For indefinite metamaterial B, the transfer matrix should be modified in the form:

$$M_B = \begin{pmatrix} \cos(k_{Bz}d_B) & -i\dfrac{k_0\mu_{By}}{k_{Bz}}\sin(k_{Bz}d_B) \\ -i\dfrac{k_{Bz}}{k_0\mu_{By}}\sin(k_{Bz}d_B) & \cos(k_{Bz}d_B) \end{pmatrix}, \quad (3)$$

where k_{Bz} satisfies the dispersion relation as follows:

$$k_{Bz}^2 = \frac{\mu_{By}}{\mu_{Bz}}\left(\frac{\omega^2}{c^2}\varepsilon_{Bx}\mu_{Bz}-\beta^2\right) \quad (4)$$

It is noted that the choice of the sign of the wave vector k_{Bz} must ensure the Poynting vector inside the indefinite medium to point away from the interface between the incident and indefinite medium; hence k_{Bz} and μ_{By} must have the same sign [22,23].

For Kerr-type nonlinear material N, the transfer matrix is presented as follows [24]:

$$M_N = \frac{k_0}{k_{z+}+k_{z-}}\begin{pmatrix} \dfrac{k_{z-}}{k_0}\exp(-ik_{z+}d_N)+\dfrac{k_{z+}}{k_0}\exp(ik_{z-}d_N) & \exp(-ik_{z+}d_N)-\exp(ik_{z-}d_N) \\ \dfrac{k_{z-}k_{z+}}{k_0^2}[\exp(-ik_{z+}d_N)-\exp(ik_{z-}d_N)] & \dfrac{k_{z+}}{k_0}\exp(-ik_{z+}d_N)+\dfrac{k_{z-}}{k_0}\exp(ik_{z-}d_N) \end{pmatrix}, \quad (5)$$

where k_{z+} and k_{z-} are z components of wave vector for the forward and backward propagating waves, which are given by

$$k_{z\pm} = \sqrt{\frac{\omega^2}{c^2}\varepsilon_L\mu_N-\beta^2}(1+U_\pm+2U_\mp)^{1/2}, \quad (6)$$

with $U_\pm=\chi_3 k_0^2|A_\pm|^2/(k_0^2\varepsilon_L\mu_N-\beta^2)$. Here A_+ and A_- are the amplitudes of the forward and backward waves. The wave vectors k_{z+} and k_{z-} in the Kerr-type nonlinear layer can be obtained from the following coupled nonlinear equation:

$$\begin{pmatrix} U_+ \\ U_- \end{pmatrix} = \left|\begin{pmatrix} 1 & 1 \\ \dfrac{k_{z+}}{(k_0\mu_N)} & \dfrac{-k_{z-}}{(k_0\mu_N)} \end{pmatrix}^{-1}(M_BM_A)^m\begin{pmatrix} 1 \\ p_f \end{pmatrix}\right|^2 U_t, \quad (7)$$

where U_t is the transmitted intensity and $p_f=\sqrt{\varepsilon_C\mu_C k_0^2-\beta^2}/(k_0\mu_C)$. The explicit form of M_N can be obtained by using fixed point iteration [25]. In our numerical simulations, we take $U_\pm=0$ as the initial values and 1000 iterations to find the stable solutions. Once $U_\pm$ are determined, the transfer matrix M_N in the Kerr-type nonlinear layer can be calculated by Eqs. (5) and (6). Then the transfer matrix M for the composite medium can be written as

$$M=(M_AM_B)^m M_N (M_BM_A)^m, \quad (8)$$

where m is the period number. Therefore the transmission coefficient can be given by

$$t = \frac{2p}{[M_{11}+M_{12}p]p+[M_{21}+M_{22}p]}, \quad (9)$$

where $p=\sqrt{\varepsilon_C\mu_C}\cos\theta_0$ and M_{ij} are the elements of 2×2 matrix M. The power transmittance T is identified as $T=t\cdot t^*=U_t/U_{in}$, where U_{in} is the incident intensity. According to the stationary phase method [26], the lateral shift of the beam through the 1DPC is obtained as follows:

$$s = -\left.\frac{d\phi_t}{d\beta}\right|_{\theta=\theta_0} = -\frac{1}{\sqrt{\varepsilon_C\mu_C}k_0\cos\theta}\left.\frac{d\phi_t}{d\theta}\right|_{\theta=\theta_0}, \quad (10)$$

where ϕ_t is the phase shift of transmitted beam and $\phi_t=\arctan[\mathrm{Im}(t)/\mathrm{Re}(t)]$.

III. COMPUTATION RESULTS AND DISCUSSION

It's known that the dispersion relation of the IMMs shown in Eq. (4) can be either elliptic or hyperbolic according to different combinations of the parameters [6]. Different types of IMMs will lead to different properties of one-dimensional nonlinear photonic crystals. For simplicity, we define $\alpha=\varepsilon_{Bx}\mu_{By}$ and $\gamma=\mu_{By}/\mu_{Bz}$. Next, we make our discussions based on four classes of indefinite metamaterials.

A. Case 1: Cut-off medium ($\alpha>0$ and $\gamma>0$)

As we know, when a defect without nonlinearity is introduced in the photonic band-gap structures, the corresponding linear defect mode will appear in the forbidden band [27]. An

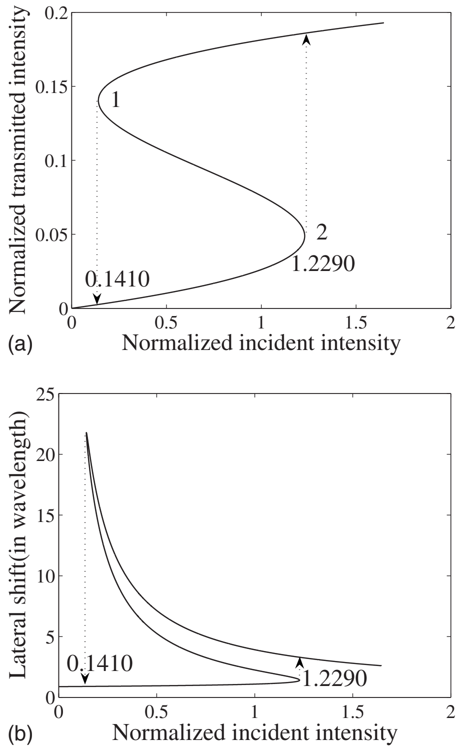

FIG. 2. The variations in (a) the normalized transmitted intensity and (b) the lateral shift with the normalized incident intensity.

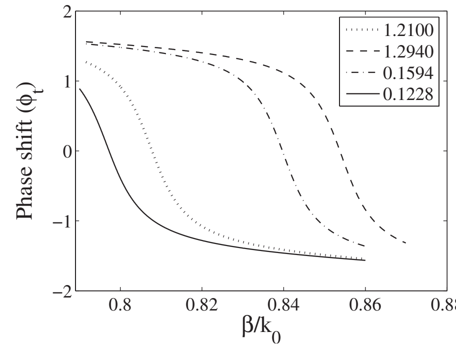

FIG. 3. The phase shift ϕ_t as a function of β for different I_{in}, where the physical parameters are all the same with Fig. 2. β is rescaled by β/k_0. The normalized incident intensities 1.2100 and 1.2940 (0.1594 and 0.1228) are near the point 2 (1).

incident wave which is tuned at the linear defect mode frequency can pass through this structure with almost no reflection. But the incident light frequency is tuned in the forbidden band (not at the linear defect mode frequency), the electric field will decrease exponentially in the structure. With a Kerr-type nonlinear material doped in 1DPC, the corresponding defect mode frequency will now change with the local light intensity, that is, the incident intensity. Owing to the introduction of the nonlinearity, the strong nonlinear effect causes the defect mode to move toward the incident wave frequency [28]. Therefore, optical bistability will occur when the defect mode frequency almost equals to the incident light frequency.

First, we discuss the case of $\varepsilon_{Bx}>0$, $\mu_{By}>0$, and $\mu_{Bz}>0$. For simplification, we describe the material properties of the indefinite metamaterials by specifying the principal axes tensor permeability components $\hat{\mu}_B=(1,\mu_{By},\mu_{Bz})$ and the z component of its permittivity tensor ε_{Bx}. The parameters are taken as follows: $\varepsilon_C=6.0025$, $\varepsilon_A=4.41$, $\varepsilon_L=3.61$, $\mu_C=\mu_A=\mu_N=1.00$, $\varepsilon_{Bx}=0.9$, $\hat{\mu}_B=(1,0.7,1.5)$, $\lambda_{pc}=2$ mm, $\chi_3=0.01$, $m=3$, $\theta_0=20°$, and $\omega/2\pi=1.759\times10^{11}$ Hz. It is noted that the physical parameters should be correctly chosen in order to obtain defect mode and corresponding bistable lateral shift at the same time. Figure 2(a) shows a typical S-shape bistability curve, where points 1 and 2 represent the switch-down and switch-up threshold values, respectively. And we also plot the variation in the corresponding lateral shift S with the incident intensity I_{in} in Fig. 2(b), from which a hysteretic response between S and I_{in} can be found.

In order to illustrate the hysteretic response between S and I_{in}, we have investigated the phase shift ϕ_t with respect to β for different I_{in} as shown in Fig. 3. It is shown that when the incident intensity increases between 1.2100 and 1.2940 near point 2, there is a abrupt change in the phase shift ϕ_t. This implies that the lateral shift changes quickly with the incident intensity increasing up to point 2. On the contrary, when the incident intensity decreases between 0.1594 and 0.1228 near point 1, there also exits a abrupt change in ϕ_t which cause the lateral shift to jump to a smaller value. In a word, since the bistable shift is closely related to the phase shift, which is explained by the reshaping effect, that is, the constructive and destructive interference between each plane wave components, due to the different phase shifts of each transmitted plane wave components transmitted the 1DPC structure, there will exist the hysteretic behavior of S with the variation in I_{in}.

In the following, we discuss the influence of indefinite metamaterials on nonlinear bistability. Figures 4(a) and 4(b) show the bistability of the transmission properties and lateral shifts for different ε_{Bx} and $\hat{\mu}_B$ of the IMMs, where the insets show the corresponding incident frequency. It is seen that the thresholds of bistability decrease as $|\alpha|$ and $|\gamma|$ increase, while the peaks of bistable shift increase. It is known that the linear defect mode frequency depends on the structure, which causes the influences on the threshold of optical bistability [28]. The threshold of bistability is much lower when a Kerr-type nonlinearity is doped in a 1DPC and the threshold value is dependent on how far away the incident wave frequency deviates from the linear defect mode. In our case, the linear defect mode shifts to low frequency with the increasing of $|\alpha|$ and $|\gamma|$, hence the frequency offsets become smaller and the thresholds decrease.

Figure 5 give the bistable curves of the transmission properties and the lateral shifts in the case of $\varepsilon_{Bx}<0$, $\mu_{By}<0$, and $\mu_{Bz}<0$. There exists negative bistable lateral shift in this condition. It is found that the lateral shift is greatly enhanced when the incident intensity decreases from a value higher than the switch-up threshold and reaches the negative maximum value at another threshold. In Refs. [29–31], indefinite metamaterials can exhibit negative refraction in some condition. Therefore, unusual electric magnetic phenomena occur in the photonic structure containing this type of indefinite metamaterial such as the electric-field distribution in the structure. When a wave beam propagates through a 1DPC,

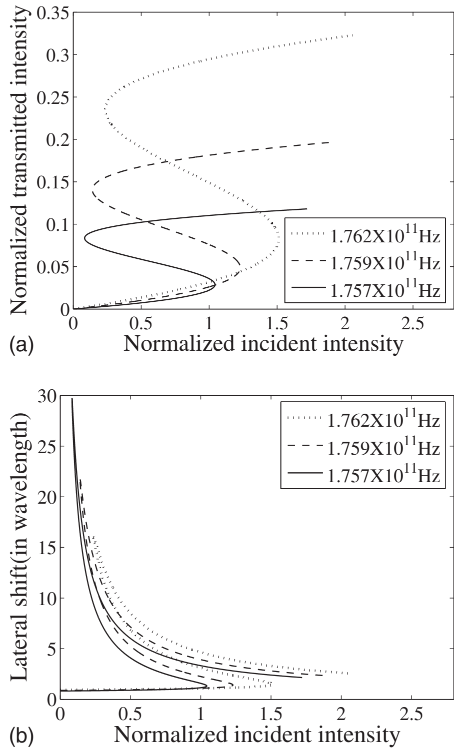

FIG. 4. The dependence of (a) the normalized transmitted intensity and (b) the lateral shift on the normalized incident intensity for various ε_{Bx} and $\hat{\mu}_B$ at the incident angle $\theta_0=20°$. Dotted line, $\varepsilon_{Bx}=0.95$, $\hat{\mu}_B=(1,0.65,1.4)$, $|\alpha|=0.6175$, and $|\gamma|=0.4643$; dashed line, $\varepsilon_{Bx}=0.9$, $\hat{\mu}_B=(1,0.7,1.5)$, $|\alpha|=0.63$, and $|\gamma|=0.4667$; solid line, $\varepsilon_{Bx}=0.85$, $\hat{\mu}_B=(1,0.75,1.6)$, $|\alpha|=0.6375$, and $|\gamma|=0.4688$. Other parameters are same with Fig. 2.

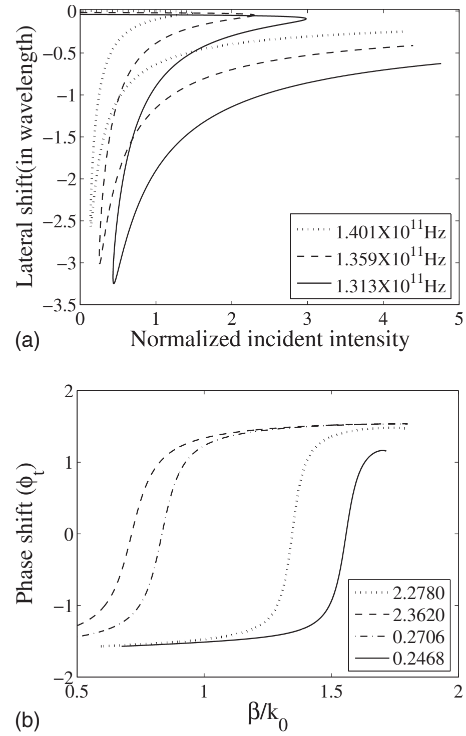

FIG. 5. (a) The dependence of the lateral shift on the normalized incident intensity for various ε_{Bx} and $\hat{\mu}_B$ at $\theta_0=20°$. Dotted line, $\varepsilon_{Bx}=-1.4$, $\hat{\mu}_B=(1,-1.55,-1.1)$, $|\alpha|=2.17$, and $|\gamma|=1.4091$; dashed line, $\varepsilon_{Bx}=-1.5$, $\hat{\mu}_B=(1,-1.5,-1)$, $|\alpha|=2.25$, and $|\gamma|=1.5$; solid line, $\varepsilon_{Bx}=-1.6$, $\hat{\mu}_B=(1,-1.45,-0.9)$, $|\alpha|=2.32$, and $|\gamma|=1.6111$. (b) The phase shift ϕ_t as a function of β with various I_{in} for $\varepsilon_{Bx}=-1.5$, $\hat{\mu}_B=(1,-1.5,-1)$, where the corresponding switch-up and switch-down thresholds are 2.2970 and 0.2579, respectively.

multiple transmissions occur due to multiple reflections between layers. The whole transmitted beam is the coherent superposition of its successively transmitted constituents. Owing to this combinations of the $\hat{\varepsilon}_B$ and $\hat{\mu}_B$ components, the variation in incident intensity changes the equivalent refractive index of the nonlinearity, which affects each transmitted constituents. Thus, this causes the anomalous variation in the phase shift of the whole transmitted beam [32–35]. To understand it more clearly, we have investigated ϕ_t as a function of β with various I_{in} for $\varepsilon_{Bx}=-1.5$, $\hat{\mu}_B=(1,-1.5,-1)$ as shown in Fig. 5(b). We can observe that around some fixed β (e.g., $\beta/k_0=0.838$) the phase shift ϕ_t also experiences abrupt changes near the switch-up and switch-down thresholds, which results the bistable lateral shift. Note that the positive slope of ϕ_t leads to the negative lateral shift. As a result, this phenomenon that the bistable lateral shift is negative can be explained.

B. Case 2: Anticutoff medium ($\alpha<0$ and $\gamma<0$)

When $\mu_{By}>0$, Fig. 6(a) shows that when the incident intensity I_{in} is smaller than the switch-up threshold, the lateral shift is negative originally. But the lateral shift suddenly jumps to a positive value when I_{in} arrives to the switch-up threshold. On the other hand, with the decreasing in I_{in} from a higher value, the lateral shift increases in the beginning. However, the lateral shift drops to a negative value suddenly when I_{in} decreases in the switch-down threshold. This hysteretic behavior of S with the variation in I_{in} is not all the same with *case 1*. Meanwhile, we have also investigated the phase shift ϕ_t for different I_{in} as shown in Fig. 6(b). It can be found that the slopes of ϕ_t have abrupt changes near the thresholds, which indicate that the bistable lateral shift can be switched from negative to positive at the switch-up threshold and from positive to negative at the switch-down threshold. So the above phenomenon of the lateral shift S with I_{in} can be explained. For $\mu_{By}<0$, we can also get similar bistable shifts with $\mu_{By}>0$, but the shifts are one order of magnitude larger than $\mu_{By}>0$.

C. Case 3: Never cut-off medium ($\alpha>0$ and $\gamma<0$)

It can be found from Eq. (4) that the transverse wave vector k_{Bz} is always real. Any incident waves impinging the 1DPC containing never cut-off medium will be changed into propagating waves no matter whether the incident waves are propagating or evanescent. In the same way, we will discuss $\mu_{By}>0$ first. It is shown from Fig. 7(a) that there is the hysteretic behavior of S with the variation in I_{in} which exists in the case of anticut-off medium. The phase shift ϕ_t in Fig. 7(b) can account for the hysteretic behavior of S. For μ_{By}

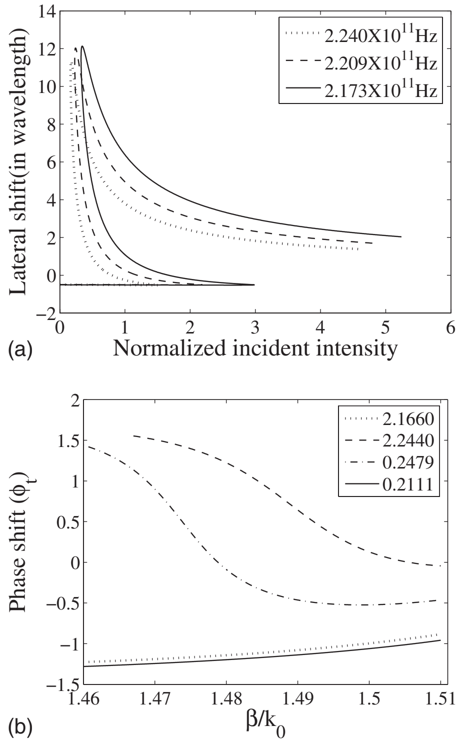

FIG. 6. (a) The dependence of the lateral shift on the normalized incident intensity for various ε_{Bx} and $\hat{\mu}_B$ at $\theta_0=37°$. Dotted line, $\varepsilon_{Bx}=-1.45$, $\hat{\mu}_B=(1,1.45,-1.05)$, $|\alpha|=2.1025$, and $|\gamma|=1.3810$; dashed line, $\varepsilon_{Bx}=-1.5$, $\hat{\mu}_B=(1,1.5,-1)$, $|\alpha|=2.25$, and $|\gamma|=1.5$; solid line, $\varepsilon_{Bx}=-1.55$, $\hat{\mu}_B=(1,1.55,-0.95)$, $|\alpha|=2.4025$, and $|\gamma|=1.6316$. (b) The phase shift ϕ_t as a function of β with various I_{in} for $\varepsilon_{Bx}=-1.5$, $\hat{\mu}_B=(1,1.5,-1)$, where the corresponding switch-up and switch-down thresholds are 2.181 and 0.2295, respectively.

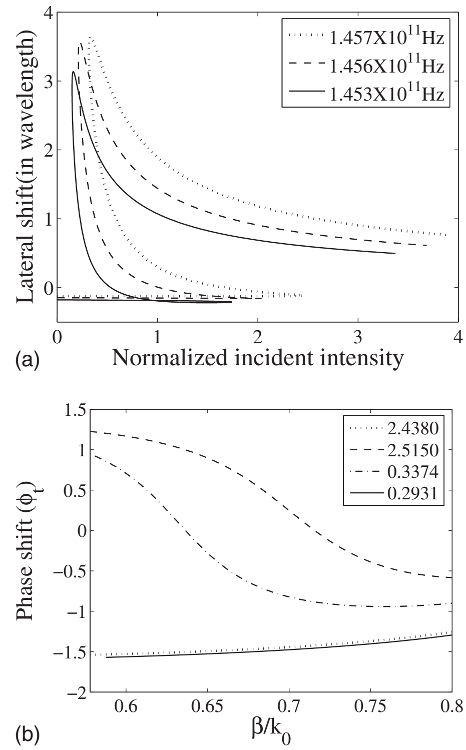

FIG. 7. (a) The dependence of the lateral shift on the normalized incident intensity for various ε_{Bx} and $\hat{\mu}_B$ at $\theta_0=15°$. Dotted line, $\varepsilon_{Bx}=0.95$, $\hat{\mu}_B=(1,1.59,-1.5)$, $|\alpha|=1.5105$, and $|\gamma|=1.06$; dashed line, $\varepsilon_{Bx}=0.9$, $\hat{\mu}_B=(1,1.7,-1.4)$, $|\alpha|=1.53$, and $|\gamma|=1.2143$; solid line, $\varepsilon_{Bx}=0.85$, $\hat{\mu}_B=(1,1.81,-1.3)$, $|\alpha|=1.5385$, and $|\gamma|=1.3923$. (b) The phase shift ϕ_t as a function of β with various I_{in} for $\varepsilon_{Bx}=0.95$, $\hat{\mu}_B=(1,1.59,-1.5)$, where the corresponding switch-up and switch-down thresholds are 2.453 and 0.3153, respectively.

<0, the behavior of bistable lateral shifts is similar with $\mu_{By}>0$.

D. Case 4: Always cut-off medium ($\alpha<0$ and $\gamma>0$)

It is obvious that there is no real solution to Eq. (4) and the transverse wave vector k_{Bz} is always imaginary. Because of this, any propagating or evanescent waves cannot propagate into the always cutoff medium and all incident beams are totally reflected. Hence there will be no transmitted beam shift at any condition.

IV. CONCLUSION

In summary, we have investigated the nonlinear bistable properties of a light beam transmitting through a nonlinear 1DPC containing four kinds of IMMs. It is shown that there exists a typical S-shaped curve of the normalized input-output intensity which indicates the bistability when the indefinite metamaterial is a cut-off, anticut-off, and never cut-off medium. There also exists the hysteresis response between the incident light intensity and the lateral shift of the transmitted beams which can be explained by the phase shift for different incident intensities. Moreover, the hysteresis response is strongly dependent on the parameters of IMMs, which may produce some potential applications in optical switches and optical spatial modulation.

ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China (Grants No. 60677030, No. 60808002, and No. 108040707), the Science and Technology Commission of Shanghai Municipality, China (Grant No. 08JC14097), and the Shanghai Leading Academic Discipline Program, China (Grant No. S30105).

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