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Anomalous bistable shift for a one-dimensional photonic crystal doped with a subwavelength layer and a nonlinear layer

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Abstract – It is found that a subwavelength layer of linear negative-index material (NIM) significantly modifies the characteristic of bistable shift for a one-dimensional photonic crystal containing a defect layer of NIM and a Kerr-type nonlinear-defect layer of positive-index material (PIM). Anomalous bistable shift occurs as the absolute value of magnetic permeability of the NIM layer increases. It is also found that the sequence of the thin film of NIM and the nonlinear layer has a major impact on this anomalous bistable shift. The validity of theoretical analysis is confirmed by numerical simulations for a Gaussian beam.

The Goos-Hänchen (GH) shift is known as a lateral shift from the path usually expected from geometrical optics when a light beam is totally reflected from the interface of two different media [1,2]. Recently, GH shifts in photonic crystals (PCs) have attracted much attention [3–7]. Felbacq *et al.* have shown that obvious GH shifts exist for a PC at frequencies both inside and outside a bandgap [3,4]. Giant negative GH shifts for a PC with a negative refractive index can be obtained by choosing an appropriate thickness of the homogeneous cladding layer [5]. When a light beam is incident on a one-dimensional (1D) PC containing a linear-defect layer, lateral shifts can be greatly enhanced near the defect mode [6]. With the introduction of a Kerr-type nonlinearity to a linear 1DPC, we find that there exists a hysteretic response between lateral shift and the incident intensity [7].

It has been reported that a subwavelength layer of linear negative-index material (NIM) leads to significant changes in the hysteresis width when a nonlinear slab is illuminated at an angle near total internal reflection [8]. It is expected that such a thin film of NIM will significantly modify the characteristics of bistable shifts. In this letter, we regard the bilayer consisting of a subwavelength layer of NIM and a Kerr-type nonlinear layer of conventional positive-index material (PIM) as a combined defect for a 1DPC and investigate the effect of the thin film on the hysteretic behavior of lateral shift.

Consider a wave beam of angular frequency ω incident from the vacuum upon a finite 1DPC at an angle θ_0. We use the symmetric multilayer stack $(AB)_mACD(AB)_mA$ as a 1DPC structure. A and B denote the alternate layers of linear PIM. C and D represent the subwavelength layer of NIM and the Kerr-type nonlinearity of PIM, respectively. m is the period number. The relative dielectric permittivity and magnetic permeability of A, B, C, D layers are assumed to be ϵ_A, μ_A, ϵ_B, μ_B, ϵ_C, μ_C, μ_D, respectively. The dielectric permittivity in the Kerr-type nonlinear material can be written in the form of $\epsilon = \epsilon_D + \chi_3|E(z)|^2$, where ϵ_D is the linear dielectric permittivity and χ_3 is the nonlinear coefficient. The thicknesses of layers A, B, D satisfy $\sqrt{\epsilon_A\mu_A}d_A = \sqrt{\epsilon_B\mu_B}d_B = \lambda_{pc}/4$ and $\sqrt{\epsilon_D\mu_D}d_D = \lambda_{pc}/2$. Such structure can create a bandgap with center frequency $2\pi c/\lambda_{pc}$ at normal incidence. The physical parameters are chosen to be: $\epsilon_A = 5.29$, $\epsilon_B = 1.71$, $\mu_A = \mu_B = \mu_D = 1$, $d_C = 0.15\,\mu$m, $\lambda_{pc} = 7.8422\,\mu$m, $\theta_0 = 30°$, $\chi_3 = 1.3 \times 10^{-11}\,m^2/V^2$ and $m = 3$.

Suppose wave vectors lie in the yz-plane and the electric field E in the x-direction. For TE waves, the electric field and y-component of the magnetic field at the two sides of the j-th Kerr-type nonlinear layer of width d_j can be related by a characteristic matrix [7,9]:

see eq. (1) *on the next page*

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$$M_j(k_y) = \frac{k_0}{k_{j+}+k_{j-}} \begin{bmatrix} \frac{k_{j-}}{k_0}\exp(-ik_{j+}d_j) + \frac{k_{j+}}{k_0}\exp(ik_{j-}d_j) & \exp(-ik_{j+}d_j) - \exp(ik_{j-}d_j) \\ \frac{k_{j-}k_{j+}}{k_0^2}[\exp(-ik_{j+}d_j) - \exp(ik_{j-}d_j)] & \frac{k_{j+}}{k_0}\exp(-ik_{j+}d_j) + \frac{k_{j-}}{k_0}\exp(ik_{j-}d_j) \end{bmatrix}, \quad (1)$$

where k_{j+} and k_{j-} are the propagation constants of forward- and backward-propagating waves and are given by $k_{j\pm} = [(k_0^2\epsilon_j - k_y^2)(1 + U_{j\pm} + 2U_{j\mp})]^{1/2}$, $k_0 = \omega/c$, k_y is the y-component of incident wave vector and $U_{j\pm} = k_0^2\chi_3|A_{j\pm}|^2/(k_0^2\epsilon_j - k_y^2)$. Here A_{j+} and A_{j-} are the amplitudes of forward and backward waves, ϵ_j is the linear dielectric permittivity. For a given transmitted intensity U_t, one can solve a set of coupled nonlinear equations by using fixed point iteration to determine $k_{j\pm}$ [10]. For linear layers of double-negative material or PIM, we use the following transfer matrix to relate the electric and magnetic component at z and $z + \Delta z$ [11]:

$$\begin{bmatrix} \cos(k_z\Delta z) & -i\frac{k_0\mu}{\sqrt{k_0^2\varepsilon\mu - k_y^2}}\sin(k_z\Delta z) \\ -i\frac{\sqrt{k_0^2\varepsilon\mu - k_y^2}}{k_0\mu}\sin(k_z\Delta z) & \cos(k_z\Delta z) \end{bmatrix}, \quad (2)$$

where $k_z = \delta\sqrt{k_0^2\epsilon\mu - k_y^2}$. We take $\delta = 1$ for a PIM and $\delta = -1$ for a NIM. Then the transmission coefficient is given by:

$$t(k_y) = \frac{2p_f(k_y)}{[M_{11} + M_{12}p_f(k_y)]p_f(k_y) + [M_{21} + M_{22}p_f(k_y)]}, \quad (3)$$

where $p_f(k_y) = (k_0^2 - k_y^2)^{1/2}/k_0$, $M_{ij}(k_y)$ are the elements of the 2×2 matrix $M(k_y) = \Pi_{j=1}^{j=2m+4} M_j(k_y)$ and $M(k_y)$ represents the characteristic matrix for the composite medium. From eq. (3), the phase shift $\phi(k_y)$ of the transmitted beam with respect to the incident beam can be obtained.

For an incident beam that is sufficiently wide, the lateral shift Δ of the transmitted beam through the multiple layered structure can be calculated analytically as [6,12]

$$\Delta = -d\phi(k_y)/dk_y|_{\theta=\theta_0}. \quad (4)$$

For a given U_t, one can calculate the incident intensity U_i through the formula $T = tt^*$.

Figure 1(a) shows the relationship of Δ and U_i for a 1DPC in three cases: i) a single nonlinear defect layer 1 characterized by $\epsilon_D = 2.46$, $\mu_D = 1$; ii) a defect layer of PIM with $\epsilon_c = 2.46$, $\mu_c = 1$ combined with layer 1; iii) a defect layer of NIM with $\epsilon_c = -2.46$, $\mu_c = -1$ combined with layer 1. The typical hysteresis curves indicate that such composite structures can produce bistable GH shifts for the transmitted waves. Wang and Zhu's study revealed that lateral shift can be greatly enhanced near the resonance for the highly localized electromagnetic wave [6]. It is well known that strong nonlinear effect in the Kerr-type defect layer can cause the defect mode to move towards the incident wave frequency [13,14] and resonance occurs when the defect mode almost equals to the incident wave frequency [14]. So, the phenomenon that the lateral shift in fig. 1(a) may be enormous is comprehensible.

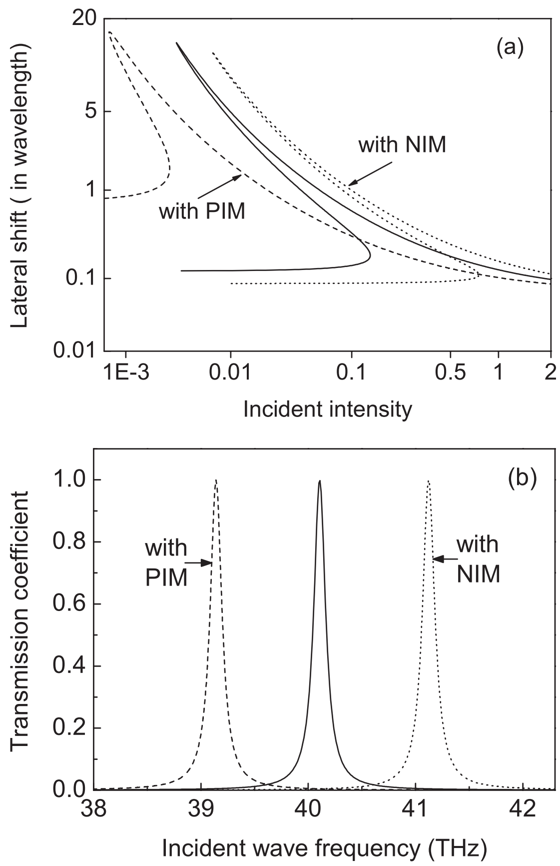

Fig. 1: (a) Δ *vs.* U_i for a 1DPC in the case of i) a single nonlinear defect layer 1 (solid curve); ii) a PIM layer combined with layer 1 (dashed curve); iii) a NIM layer combined with layer 1 (dotted curve). (b) Linear-transmission coefficient *vs.* incident frequency corresponding to the three configurations in (a). $\omega/2\pi = 38.8\,\mathrm{THz}$.

Observe fig. 1(a) carefully, we find that the bistability threshold increases and the peak of lateral shift decreases in the case of NIM. And opposite effect occurs in the case of PIM. What causes this to happen? The frequency dependence of linear transmission coefficient for the three figures corresponding to fig. 1(a) is displayed in fig. 1(b). From this picture, we can observe that the linear-defect mode shifts to high frequency in the case of the NIM layer and shifts to low frequency in the case of the PIM layer. This is because of the fact that the thin film of the subwavelength layer introduces an additional phase shift that affects the resonant condition. In the case of a

NIM layer, the negative phase shift of negative refraction causes the linear-defect mode of the whole structure to shift to high frequency, which weakens the electric-field intensity distribution in the nonlinear layer (in the linear case). So the bistable threshold increases accordingly. We have demonstrated that the peak of the bistable shift is dependent on the frequency offset between the incident frequency and the linear defect mode frequency [7]. The introduction of the NIM layer causes the linear-defect mode to move far away from the incident frequency. Thus, the phenomenon that the peak of lateral shift decreases in the case of the NIM layer can be understood easily.

In the following, we discuss the influence of the NIM film parameters on the hysteretic behavior of Δ and compare the results to those for the PIM case with the same absolute parameters.

We first vary the magnetic permeability μ_c under the condition that the dielectric permittivity ϵ_c is kept fixed. Figure 2(a) depicts that Δ *vs.* U_i for $\epsilon_c = -0.5$. From this picture we can observe clearly that the shape of the hysteresis is significantly modified with the variation of μ_c. As $|\mu_c|$ increases, the bistability threshold increases and the peak of lateral shift decreases. This is because of the fact that the increment of $|\mu_c|$ causes the linear-defect mode to move far away from the incident wave frequency. On the other hand, as $|\mu_c|$ increases, the upper part of the hysteresis moves downwards while the bottom part moves upwards, and the interval between the two parts decreases. When μ_c reaches -4, the upper part and the bottom part of the hysteresis basically overlaps. Then, with further increment of $|\mu_c|$, the primary bottom part of the hysteresis exceeds the primary upper part and the interval between the two parts becomes larger and larger with increasing $|\mu_c|$.

The enlargement of the hysteresis for $\mu_c = -6$ is depicted in fig. 2(c). It is very interesting to find that the hysteresis curve crosses itself. The physical meaning of the interesting curve can be described. When U_i increases from zero, Δ first increases slowly, and when U_i reaches the high threshold value U_1, Δ suddenly switches to a lower value. Then, Δ decreases slowly with increasing of U_i. When U_i decreases from a value higher than U_1, Δ will not jump back to the higher value, but continues to increase slowly until U_i reaches the low threshold value U_2, at which Δ jumps to a lower value. Then Δ decreases slowly with decreasing of U_i. In comparison with the case of PIM, the hysteresis crosses itself. This is an anomalous phenomenon.

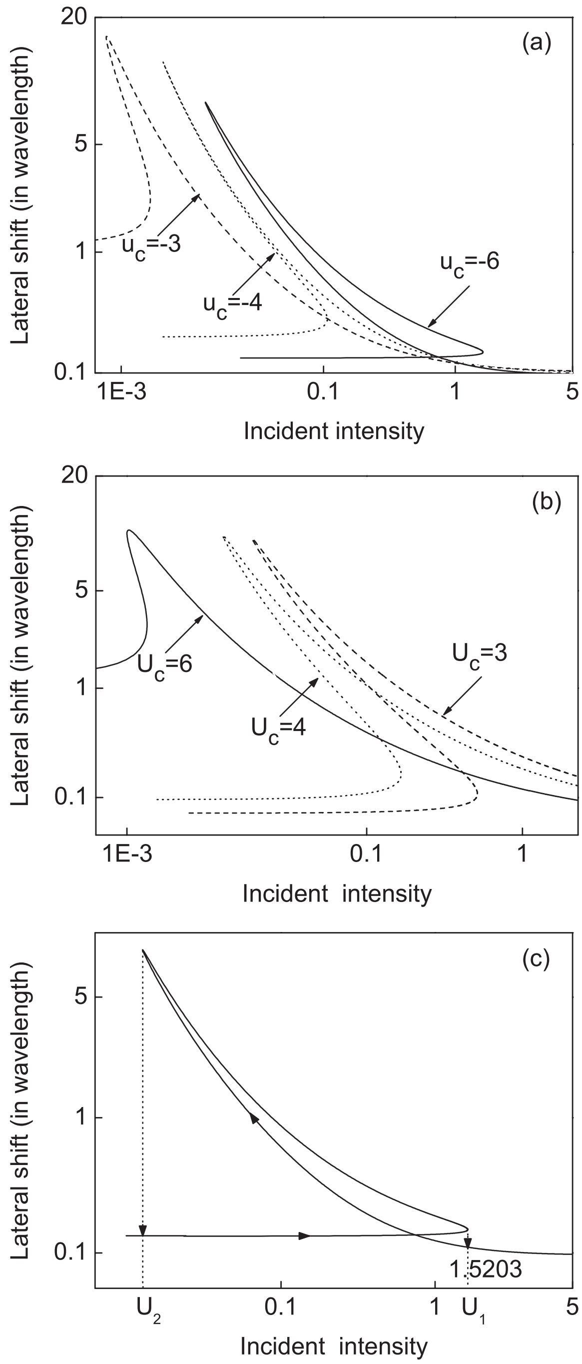

Fig. 2: (a, b) Δ *vs.* U_i for different μ_c in (a) the NIM case, (b) the PIM case; (c) the enlargement of anomalous bistable shift for $\mu_c = -6$; for (a, c) $\omega/2\pi = 42.8\,\text{THz}$ and (b) $\omega/2\pi = 35.3\,\text{THz}$.

With the introduction of the thin film with $\epsilon_c = -0.5$ and $\mu = -6$, unusual electric magnetic phenomena occur in the photonic structure, such as the electric-field distribution in the structure as is shown in fig. 3(a–d). When a wave beam propagates through a photonic crystal, multiple transmissions occur due to multiple reflections between layers. The whole transmitted beam is the coherent superposition of its successively transmitted constituents. When $\mu_c = -6$, the variation of U_i changes the equivalent refractive index of the nonlinearity, which affects each transmitted constituents. As a result, this causes the anomalous variation of the phase shift of the whole transmitted beam. To understand it more clearly, we have investigated ϕ with respect to k_y for different U_i. From figs. 4(a) and (b), we can observe that around some fixed k_y (*e.g.* $k_y/k = 0.5$) ϕ experiences a distinct sharp variation for different U_i. Normally, when U_i increases from

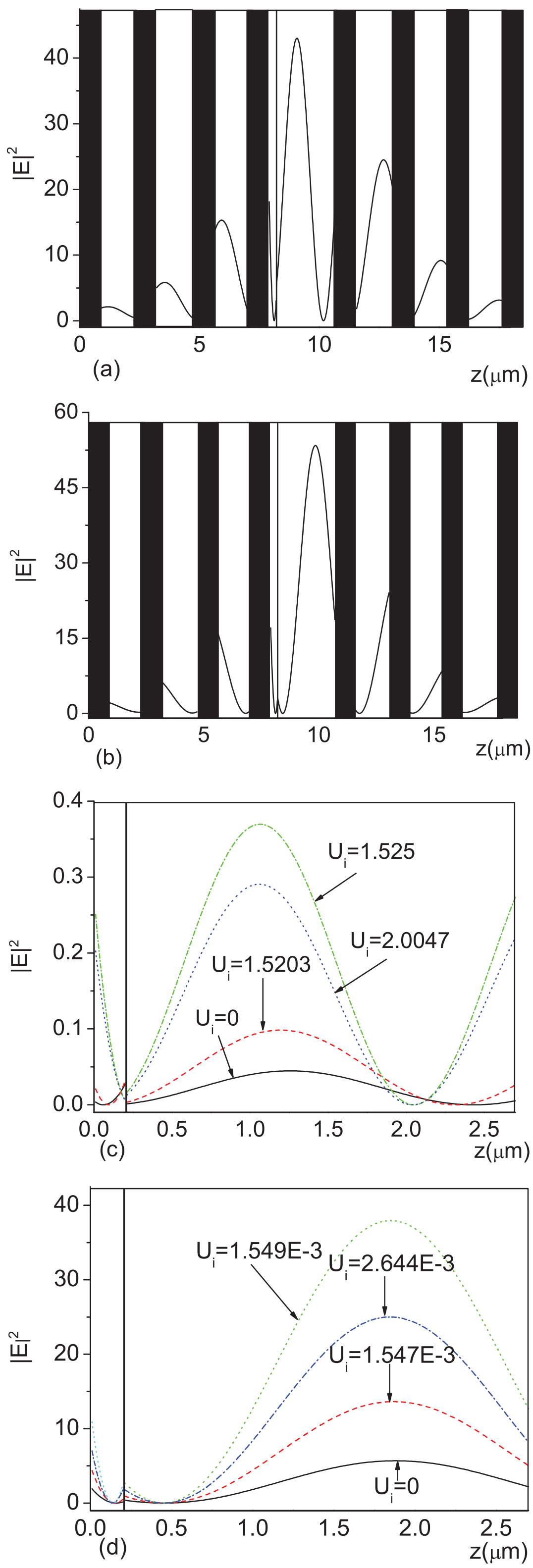

Fig. 3: (a, b) Electric-field distribution in photonic structure in the case of (a) the NIM layer, (b) the PIM layer when ω is the center frequency of the linear defect mode; (c, d) the effect of the incident intensity on the electric field distribution in the photonic structure for the case of (c) the NIM layer when $\omega = 42.8\,\text{THz}$ and for the case of (d) the PIM layer when $\omega = 35.3\,\text{THz}$.

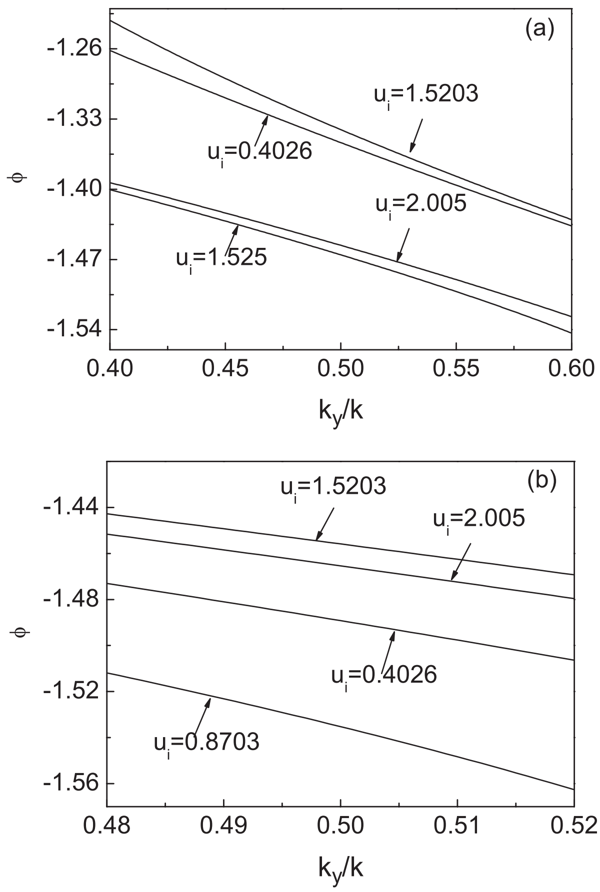

Fig. 4: Phase shift as a function of k_y with various U_{in} for $\mu_c = -6$ (a) when U_{in} increases from zero and (b) when U_{in} decreases from a high value. k_y is rescaled by k_y/k. For (a) $\omega = 42.8\,\text{THz}$ and (b) $\omega/2\pi = 35.3\,\text{THz}$.

zero, the variation of ϕ becomes sharp slowly, and when U_i reaches the high threshold, ϕ will suddenly jump to a state with a larger slope and then the slope becomes smaller and smaller with increasing of U_i [7]. While in the case of a NIM layer with larger $|\mu_c|$, when U_i reaches the high threshold, ϕ will not switch to a state with a larger slope, but to a state with a smaller slope. When U_i decreases from a value higher than U_1, the slope becomes larger and larger constantly until U_i reaches another threshold U_2. We have also investigated the effect of varying both μ_c and ϵ_c under the condition that the refractive index is fixed at $n = -1.5$. The results are similar to the case of varying μ_c only. This reveals that the anomalous bistable shift phenomenon is mainly caused by the large absolute value of the negative magnetic permeability for TE waves.

Finally, we study the effect of the sequence of the thin film and the nonlinear layer on the bistable shift. Figures 5(a) and (b) display the hysteresis curves for structure 1 $(AB)_3ADC(AB)_3A$ *vs.* structure 2 $(AB)_3ACD(AB)_3A$ when $|\epsilon_c| = 0.5$, $|\mu_c| = 3$ and $|\mu_c| = 6$. Dashed curves correspond to structure 1 and solid curves correspond to structure 2. Figure 5(a) represents the case for NIM and fig. 5(b) for PIM. In fig. 5(a), both

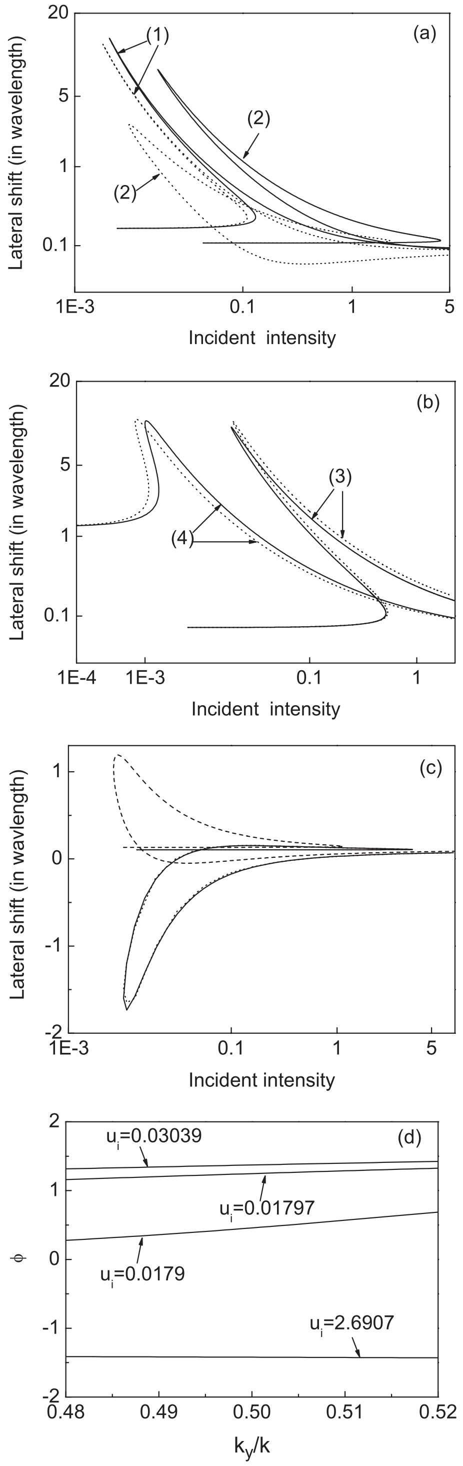

Fig. 5: (a, b) Comparison of Δ *vs.* U_i for structures $(AB)_3ACD(AB)_3A$ (solid curve) and $(AB)_3ADC(AB)_3A$ (dashed curve); (a) $\mu_c = -3$ (curve 1), -6 (curve 2); (b) $\mu_c = 3$ (curve 3), 6 (curve 4). (c) Δ *vs.* U_i for structure $(AB)_3ADC(AB)_3A$ when $\mu_c = -7$ (dashed curve) and $\mu_c = -8$ (solid curve, theoretical result; dotted curve, simulation result using a Gaussian beam with waist width $w_0 = 20\lambda$), $\omega/2\pi = 41.8$ THz). (d) Phase shift as a function of k_y with various U_{in} when U_{in} decreases from a high value. For (a)(d) $\omega/2\pi = 41.8$, (b) $\omega/2\pi = 35.3$ THz and (c) $\omega/2\pi = 42.9$ THz.

the peaks of the hysteresis curves and the thresholds for structure 1 are lower than structure 2. With the increase of $|\mu_c|$, this difference becomes more pronounced. And when μ_c reaches -8, the direction of the hysteresis curve for structure 1 suddenly switches from upwards to downwards and the majority of lateral shifts become negative. While for the case of PIM, the effect of the sequence of the subwavelength layer and the nonlinear layer on bistable shift is relatively slight. The different sequences of the subwavelength layer and the nonlinear layer result in different electric-field distribution in the nonlinear layer, which affects the equivalent refractive index of the nonlinear layer. On the other hand, unusual electromagnetic phenomena occur in the layer of NIM. Therefore, different effects occur for the case of the NIM layer and the PIM layer, respectively.

For the structure $(AB)_3ADC(AB)_3A$, the lateral shift may become negative when $\mu_c = -8$. Now, what the phase shift of the whole transmitted beam is like? In this situation, the relationship between ϕ and k_y for different U_i is displayed in fig. 5(d). Observe fig. 5(d) carefully, we can find that when the incident intensity decreases from a value higher than the high threshold to the low threshold, the slope (around $k_y/k = 0.5$) becomes larger gradually and the sign becomes positive from negative. Accordingly, the lateral shift becomes negative from positive and the absolute value becomes larger and larger. The further increment of $|\mu_c|$ together with the slight change of the equivalent refractive index for the nonlinearity contribute to each transmitted constituent.

To demonstrate the validity of the above analysis, numerical simulations for a Gaussian beam have been performed [7,12]. Calculation results (see fig. 5c) show that our theoretical analyses are in good agreement with the numerical simulations. The discrepancy between the numerical and theoretical results is due to the distortion of the transmitted Gaussian beams. Such distortion gradually disappears as the beam width becomes larger.

In summary, we have investigated bistable shifts of the transmitted beams for a 1DPC containing a subwavelength linear-defect layer of NIM and a Kerr-type defect layer of PIM. We find that a thin film of NIM significantly modifies the characteristic of the hysteretic behavior of the lateral shift, and an anomalous bistable shift occurs as $|\mu_c|$ increases. This anomalous phenomenon results from the interference of each transmitted constituent. The effect of the sequence of the layer of NIM and the nonlinear layer on the anomalous bistable shift becomes more pronounced with increasing $|\mu_c|$. The validity of the theoretical analysis is demonstrated by numerical simulations for a Gaussian beam.

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