Giant Goos-Häenchen Shift of a Gaussian Beam Reflected from One-Dimensional Photonic Crystals Containing Left-Handed Lossy Metamaterials

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ABSTRACT— We perform a theoretical investigation on the Goos-Häenchen shift (the lateral shift) in one-dimensional photonic crystals (1DPCs) containing left-handed (LH) metamaterials. The effect was studied by use of a Gaussian beam. We show that the giant lateral displacement is due to the localization of the electromagnetic wave which can be both positive and negative depending on the incidence angle of Gaussian beam that can be excited the forward and backward surface states, respectively. Dependence of beam width on the incidence angle of beam and thickness of air layer for both backward and forward surface states are studied in this paper. We also find that the weak lossy in LH layers of 1DPCs may affect these shifts. These giant negative and positive lateral shifts are smaller than that of the lossless structure.

KEYWORDS: Goos-Häenchen shift, loss, metamaterial, photonic crystal, surface state.

I. INTRODUCTION

Since the original work of Yablonovitch [1] and John [2], photonic crystals composed of periodic dielectric media have attracted considerable attention [3], [4]. The Photonic crystal structures inhibit the propagation of electromagnetic waves in a certain range of frequencies, in analogy with electronic band gaps in semiconductors. These structures may contain layers of left-handed metamaterial, which we refer to as left-handed photonic crystal.

In 1968, Veselago [5] proposed the concept of left-handed metamaterials (LHMs) with both negative permittivity and negative permeability, and predicted some peculiar electromagnetic properties such as the reversal of Doppler shift for radiation [6], the reversal of Cherenkov radiation [7], the negative refraction [8] and reversal of Goos–Häenchen shift [9].

When a light beam illuminates the interface between two homogeneous media under total internal reflection, the barycenter of the reflected beam does not coincide with that of the incident one: that is the Goos–Häenchen effect [10]. The Goos-Häenchen shift has potential applications in various optical fields such as oscillating wave sensor [11], [12] optical temperature sensor [13] and optical waveguide switch [14]. The Goos-Häenchen shift has also used as a probe in evanescent slab waveguide sensors [15]. Furthermore with the development of near-field scanning optical microscopy and lithography [16], the Goos-Häenchen shift has attracted more attention for potential device applications in optical modulations. Recently, the Goos–Häenchen shifts have been extensively studied in various situations, for example, absorbing media [17], electro-optics crystal [18], and periodic structures [19]. The Goos–Häenchen shifts related with LHMs have been extensively studied for potential device applications. The Goos-Häenchen shift is usually much less than the beam width. However, larger beam shifts may occur in the layered systems supporting *surface waves*, which are able to transfer energy along the interface [9].

Surface modes are a special type of wave localized at the interface separating two different media. The existence of electromagnetic surface waves was suggested by Kossel and later considered in an approximate manner by Arnaud [20]. Recently, the band theory of periodic media was used in an exact analysis of the optical surface waves [21]. In periodic systems, the modes localized at the surfaces are known as Tamm states [22], first found as localized electronic states at the edge of a truncated periodic potential. Surface states have been studied in different fields of physics, including optics [21], where such waves are confined to the interface between periodic and homogeneous media [23], [24].

In this paper, we consider a one-dimensional photonic crystal containing LHM layers to show that excitation of forward surface wave results in a positive Goos–Häenchen shift and excitation of backward surface wave results in a negative Goos–Häenchen (GH) shift. This paper is organized as follows: In Section 2, we introduce the model of the system under consideration and formulate the GH shift and beam width variation of a Gaussian beam reflected from LH photonic crystal. In Section 3, we discuss dependence of GH shift and beam width on the incidence angle of beam and thickness of air layer. Also, in this section the effect of lossy metamaterial on GH shift are presented. Finally, paper is concluded in Section 4 with brief comments.

II. STRUCTURE AND FORMALISM

We consider that the propagation of a Gaussian beam through a one-dimensional photonic crystal consists of cells, each made of LH and right-handed (RH) uniform layers of widths d_2 and d_1 whose respective indices of refraction are n_2 and n_1, respectively. LH photonic crystal was capped by a layer of the LH metamaterial (with width d_c) and this layered structure was separated from dense medium by an air layer as shown in Fig. 1. To study the GH shift in this structure, we suppose that the dielectric layers are in the *x*-*y* plane and the z direction is normal to the interface of each layer.

We consider that the incident beam has a Gaussian profile as:

$$E_i(x) = \exp\left[-(x/a)^2 - ik_{x0}x\right], \tag{1}$$

where a is the width of beam, θ is the beam incidence angle and $k_{x0} = k_0 \sin\theta$ is the wave number component along the interface with $k_0 = \omega\sqrt{(\varepsilon_0\mu_0)}/c$. We can define the lateral shift Δ of a wide beam reflected by a periodic dielectric structure as:

$$\Delta = -d\varphi / dk_x \tag{2}$$

where φ is the phase of the reflected coefficient and k_x is the wave vector component along the interface. The relation (2) is obtained with the assumption that the beam experiences total internal reflection and the phase of reflection coefficient φ is a linear function of the wave vector component k_x across the spectral width of the beam. Meanwhile, in the case where the phase φ is not a linear function of the wave vector component, k_x, the formula (2) for the shift of the beam as a whole is not valid [25]. In such a case, one can first obtain the structure of the reflected beams as follows:

$$E_r(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R(k_x)\overline{E}_i(k_x)\, e^{ik_x x} dk_x \tag{3}$$

where $\overline{E}_i$ is Fourier spectrum of incidence beam and $R(k_x)$ is the reflection coefficient. For calculation of the Bloch modes, we use the well-known transfer matrix method [26], [27]. By using transfer matrix method the reflection coefficient for our geometry can be found as $R = -M_{12}/M_{11}$ where, M_{12} and M_{11} are the elements of the transfer matrix. The relative beam shift, Δ_1, can be defined as the normalized *first momentum* of the electric field of the reflected beam, where

$$\Delta_n = a^{-n}\int_{-\infty}^{\infty} x^n |E_r(x)|^2 dx \left(\int_{-\infty}^{\infty}|E_r(x)|^2 dx\right)^{-1} \quad (4)$$

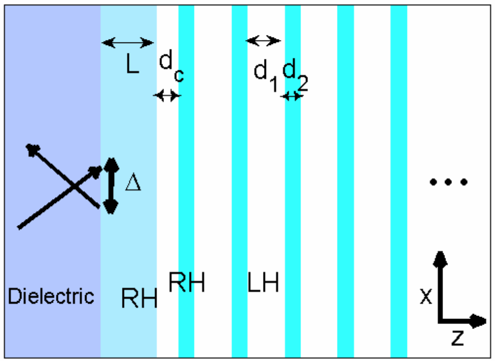

Fig. 1 Geometry of the problem. In our calculations, we take the following values: $d_1 = 2.5\,cm$, $d_2 = 1\,cm$, $d_c = 0.6 d_1$, $n_0 = 3.5$, $\mu_0 = 1$, $n_1 = -2$, $\mu_1 = -1$, $n_2 = 1.5$, $\mu_2 = 1$, $n_R = 1$, $\mu_R = 1$.

The second moment of the reflected beam, defined by above equation, characterizes a relative width of the reflected beam as $W = \sqrt{\Delta_2}$ [9].

III. RESULTS AND DISCUSSION

We chose the following parameters for the structure: $d_1 = 2.5cm$, $d_2 = 1cm$, $d_c = 0.6 d_1$, $n_D = 3.5$, $\mu_D = 1$, $n_1 = -2$, $\mu_1 = -1$, $n_2 = 1.5$, $\mu_2 = 1$, $n_0 = 1$, $\mu_0 = 1$. Here μ_D, μ_1, μ_2 and μ_0 are magnetic permeabilities of dense media, LHM, RHM and air layers, respectively. We also take Gaussian beam width as $a = 100\,cm$. First, for simplicity we consider photonic crystal containing the lossless metamaterials.

The surface states can be obtained from the dispersion relation [28]. In Fig. 2, we presented the dispersion diagram of the surface modes for $d_c = 0.6 d_1$ in the first spectral gap. The slope of the dispersion curve determines the corresponding group velocity of the mode. As shown in Fig. 2, we observe the mode degeneracy, i.e. for the same frequency ω (or wave number $k = \omega / c = 1.037\,cm^{-1}$) there exist two modes with different value of normalized wave number component along the interface β in the first gap. For the photonic structure considered in Fig. 1, the surface waves at the interface can be either backward propagating corresponding to point (a) of Fig. 2 with $\beta = 1.36$ or forward propagating corresponding to point (b) of Fig. 2 with $\beta = 1.05$.

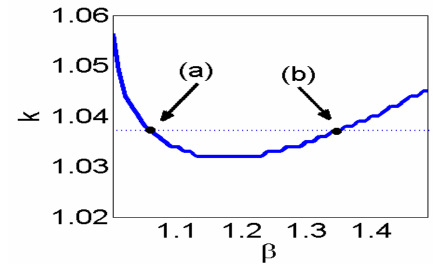

Fig. 2 Dispersion properties of the surface states in the first spectral gap for $d_c = 0.6 d_1$. Points (a) and (b) correspond to backward and forward surface states respectively.

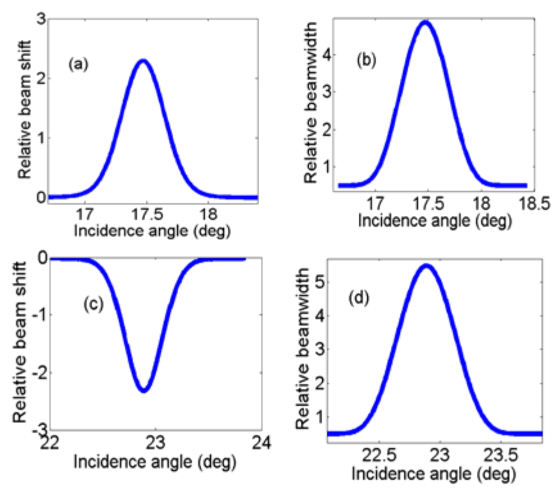

Fig. 3 Relative beam shift and beam width versus the incidence angle corresponding to forward (a), (b) and backward (c), (d) surface states. Here $L = 3.6\,cm$ for (a), (b) and $L = 2.12\,cm$ for (c), (d).

In Figs. 3(a) and 3(b) (Figs. 3(c) and 3(d)), the dependence of relative beam shift, Δ_1, and relative beam width, W, on the incidence angle corresponding to a forward (backward) surface state are plotted, respectively. It is obvious that relative beam shift of wave in Fig. 3(a) is positive, while it is negative as shown in Fig. 3(c). Indeed, in this structure, we have forward wave for incidence angle of $\theta = 17.45^\circ$, as shown in Fig. 3(a). To obtain backward wave, we can use a Gaussian beam with incidence angle of $\theta = 22.86^\circ$, as shown in Fig. 3(c). The resonant points of the beam shift and beam width appeared in Fig. 3 correspond to the phase matching condition for k_x.

Figure 4 shows the relative beam shift and beam width versus the thickness of air layer for the case of forward (Figs. 4(a) and 4(b)) and backward (Figs. 4(c) and 4(b)) surface states. In Figs. 4(a) and 4(b), we take the incidence angle of Gaussian beam $\theta = 17.45^\circ$ for forward wave corresponding to the peak points in Figs. 3(a) and 3(b). Similarly, we take in Figs. 4(c) and 4(d) $\theta = 22.86^\circ$ for backward wave corresponding to the peak points in Figs. 3(c) and 3(d).

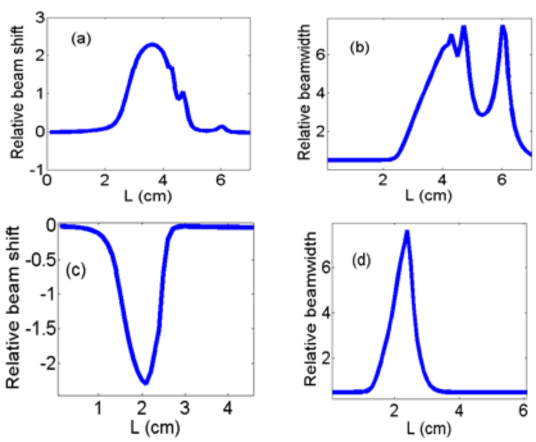

Fig. 4 Relative beam shift and beam width versus the thickness of air layer for $\theta = 17.45^\circ$ (a), (b) and $\theta = 22.86^\circ$ (c), (d) corresponding to the peak points in Figs 3(a), 3(b), 3(c) and 3(d), respectively.

The resonances observed in Fig. 4 suggest that for some thickness of air layer, for example $L = 3.6cm$ and $L = 2.12cm$, the quality factor of the surface mode will increase, thus the relative beam shift and beam width of the reflected Gaussian beam will increase accordingly. However, for large or small thickness of air layer, the relative beam shift and beam width are small because no surface wave is excited. Figs. 5(a) and 5(b) show the profiles of the reflected (solid) and incident (dotted) beams as the field amplitude versus coordinate x. Here Figs. 5(a) and 5(b) correspond to forward and backward surface states with the incidence beam angles of $\theta = 17.45^\circ$ and $\theta = 22.86^\circ$, respectively.

Meanwhile, to gain a deeper understanding on the properties of reflected beam we study the effect of changing the spatial widths of the incident beam on the shape of the reflected beam and value of the GH shift. Our study shows that the relative beam shift and beam width will moderately decrease with the increasing width of the incident beam.

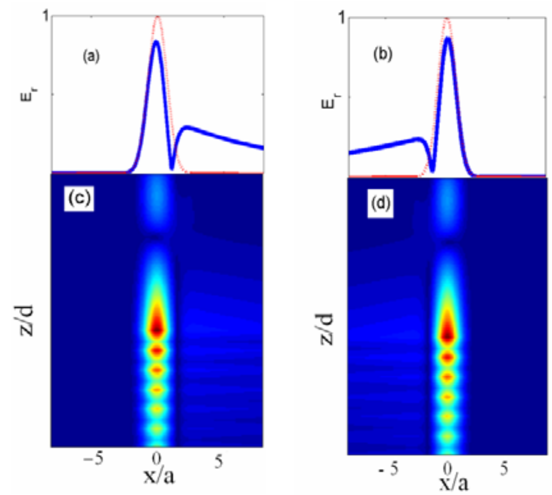

Fig. 5 Profiles of the reflected (solid) and incident (dotted) beams shown as the field amplitude versus coordinate x for incidence angle of beam (a) $\theta = 17.45^\circ$ in the case forward surface state (b) $\theta = 22.86^\circ$ in the case backward surface state. Field distribution of the surface states are shown in (c) and (b) corresponding to (a) and (b). Here $d = d_1 + d_2$.

It is obvious that the reflected beam has a distinctive double peak structure. The first peak corresponds to a mirror reflection and the second peak is shifted relative to the point of incidence which appears due to the excitation of surface waves. At the resonance, the relative beam shift becomes larger than the beam width. The components of the beam spectrum outside this region (shown in Figs. 3(a) and 3(c)) are reflected in the usual mirror like fashion, while the spectral components of the beam near the resonance transform into an excited surface wave. These spectral components are responsible for the appearance of the second peak in the shifted reflected beam.

To better understanding the GH shift, we perform numerical simulation to show the backward and forward surface state already presented in Fig. 5. The field distribution of surface states corresponding to Figs 5 (a) and 5(b) are shown in Figs 5(c) and 5(d), respectively. To do this, we considered the relation (3) for the reflected beam and calculated the dependence of field amplitude on the coordinate z using transfer matrix method. We conclude that the surface wave, excited at the interface, has a distinctive vortex-like structure. This surface wave transfers energy in the negative or positive direction depending on the backward or forward surface state. Thus the energy is reflected from the interface as a shifted beam.

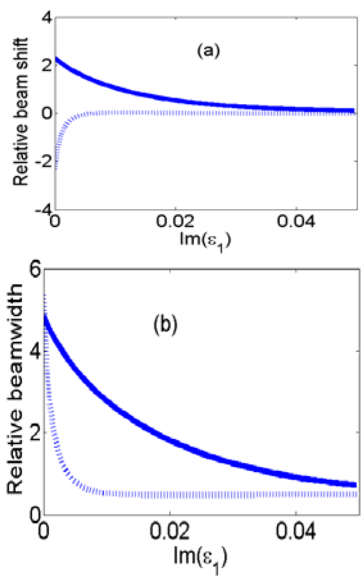

Fig. 6 Relative beam shift (a) and beam width (b) versus the imaginary part of the dielectric permittivity corresponding to forward wave (solid) and backward wave (dotted).

It is known that losses are always present in left-handed materials. Stockman has proved that negative refraction can be reached only if substantial losses are presented [29]. For studying effect of losses, which may be present in LHM layers of our structure, we add the imaginary parts to the dielectric permittivity and magnetic permeability of LHM layers. We suppose ε_1 and μ_1 are complex quantities and can be expressed as the real and imaginary parts of them. For simplicity of analysis, we take $\mathrm{Im}(\mu_1) = -2\times10^{-5}$ and vary the imaginary part of ε_1.

We plot relative beam shift and beam width versus the imaginary part of the dielectric permittivity for forward wave (Figs. 6(a) and 6(b), (solid)) and for backward wave (Fig. 6(a) and 6(b), (dotted)). As shown in Fig. 6, the major effect produced by the losses is observed for shifted beam component because the losses in LHM affect mostly the surface wave and, therefore, for large value of loss the surface state can't be excited then relative beam shift or GH shift is negligible. Also, the beam width of wave will be decrease.

IV. Conclusion

Briefly, we investigated the excitation of the electromagnetic surface wave in a slab of a right-handed layer separating a one-dimensional periodic photonic crystal and a homogenous dielectric medium. We showed that such structure could exhibit a giant lateral shift due to the resonant excitation of surface waves at the interface between the right-handed layer and photonic crystal containing left-handed layers. These beam shifts could be either positive or negative depending on the type of the surface waves excited by incoming beam. Indeed, excitation of forward surface wave results in a positive Goos–Häenchen shift and excitation of backward surface wave results in a negative Goos–Häenchen (GH) shift.

We also performed a series of numerical simulations to model the field distribution of the beam scattering for both types of backward and forward surface states. We observed that weak loss can affect GH shift; so that the GH shift is large in lossless structure rather than in lossy structure.

References

[1] E. Yablonovitch, "Inhibited spontaneous emission in solid-state physics and electronics," Phys. Rev. Lett. Vol. 58, pp. 2059-2062, 1987.

[2] S. John, "Strong localization of photons in certain disordered dielectric super lattices," Phys. Rev. Lett. Vol. 58, pp. 2486-2489, 1987.

[3] J. Lumeau, L.B. Glebov, and V. Smirnov, "Tunable narrowband filter based on a combination of Fabry-Perot etalon and volume Bragg grating," Opt. Lett. Vol. 31, pp. 2417-2419, 2006.

[4] S.W. Shao, X.S. Chen, W. Lu, M. Li, H.Q. Wang, "Fractal independently tunable multichannel filters," Appl. Phys. Lett. Vol. 90, pp. 211113 (1-3), 2007.

[5] V .G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," Sov. Phys. Usp. Vol. 10, pp. 509-5014, 1968.

[6] N. Seddon and T. Beapark, "Observation of the inverse Doppler effect," Science, Vol. 302, pp. 1537-1540, 2003.

[7] C. Luo, M. Ibanescu, S. G. Johnson, and J. D. Joannopoulos, "Cerenkov radiation in photonic crystals," Science, Vol. 299, pp. 368-371, 2003.

[8] J. B. Pendery, "Negative refraction," Contemp. Phys. Vol. 45, pp. 191-202, 2004.

[9] I. V. Shadrivov, A. A. Zharov, and Y. S. Kivshar, "Giant Goos-Häenchen effect at the reflection from left-handed metamaterials," Appl. Phys. Lett. Vol. 83, pp. 2713-(1-3), 2003.

[10] F. Goos and H. Häenchen, "Ein neuer und fundamentaler versuch zur total reflexion," Ann. Phys. (Leipzig), Vol. 6, pp. 333-346, 1947.

[11] X. B. Yin and L. Hesselink, "Goos-Häenchen shift surface plasmon resonance sensor," Appl. Phys. Lett. Vol. 89, pp. 261108 (1-3), 2006.

[12] Y. Wang, H. Li, Z. Cao, T. Yu, Q. Shen, and Y. He, "Oscillating wave sensor based on the Goos-Häenchen effect," Appl. Phys. Lett. Vol. 92, pp. 061117 (1-3), 2008.

[13] C. W. Chen, W. C. Lin, L. S. Liao, Z. H. Lin, H. P. Chiang, P. T. Leung, E. Sijercic, and W. S. Tse, "Optical temperature sensing based on the Goos-Häenchen effect," Appl. Opt. Vol. 46, pp. 5347-5351, 2007.

[14] T. Sakata, H. Togo, and F. Shimokawa, "Reflection-type 2×2 optical waveguide switch using the Goos–Häenchen shift effect," Appl. Phys. Lett. Vol. 76, pp. 2841-2843, 2000.

[15] S. A. Taya, E. J. El-Farram, and T. M. El-Agez, "Goos–Häenchen shift as a probe in evanescent slab waveguide sensors," Int. J. Electron. Commun. (AEÜ), Vol. 66, pp. 204-210, 2012.

[16] A. Madrazo, and M. Nieto-Veperinas, "Detection of subwavelength Goos-Häenchen shifts from near-field intensities: a numerical simulation," Opt. Lett. Vol. 20, pp. 2445-2447, 1995.

[17] L. G. Wang, H. Chen, and S. Y. Zhu, "Large negative Goos-Häenchen shift from a weakly absorbing dielectric slab," Opt. Lett. Vol. 30, pp. 2936-2938, 2005.

[18] X. Chen, M. Shen, Z. F. Zhang, and C. F. Li, "Tunable lateral shift and polarization beam splitting of the transmitted light beam through electro-optic crystals," Appl. Phys. Vol. 104, pp. 123101 (1-6), 2008.

[19] L. G. Wang, and S. Y. Zhu, "Giant lateral shift of a light beam at the defect mode in one-dimensional photonic crystals," Opt. Lett. Vol. 31, pp. 101-103, 2006.

[20] J. A. Arnaud and A. A. M. Saleh, "Guidance of Surface Waves by Multilayer Coatings," Appl. Opt. Vol. 13, pp. 2343-2345, 1974.

[21] P. Yeh, A. Yariv, and A. Y. Cho, "Optical surface waves in periodic layerd media," Appl. Phys. Lett. Vol. 32, pp. 104 (1-2), 1978.

[22] I. E. Tamm, "Uber Eine Mogliche Art der Elektronenbindung an Kristalloberflachen," Phys. Z. Sowjet. Vol. 1, pp. 733-746, 1932.

[23] S. K. Morrison and Y. S. Kivshar, "Tamm states and nonlinear surface modes in photonic crystals," Opt. Commun. Vol. 266, pp. 323-326, 2006.

[24] A. Namdar, I. V. Shadrivov, and Y. S. Kivshar, "Backward Tamm states in left-handed metamaterials," Appl. Phys. Lett. Vol. 89, pp. 114104 (1-4), 2006.

[25] M. Miri, A. Naqavi, A. Khavasi, K. Mehrany, S. Khorasani, and B. Rashidian, "Geometrical approach in physical understanding of the Goos-Häenchen shift in one- and twodimensional periodic structures," Opt. Lett. Vol. 33, pp. 2940-2942, 2008.

[26] G.V. Morozov, D.W.L. Sprung, and J. Martorell, "Semiclassical coupled-wave theory and its application to TE waves in one-dimensional photonic crystals," Phys. Rev. E, Vol. 69, pp. 016612 (1-11), 2004.

[27] A. Yariv and P. Yeh, *Optical Waves in Crystals*, Wiley, New York, 1984.

[28] A. Namdar, "Tamm states in one-dimensional photonic crystals containing left-handed materials," Opt. Commun. Vol. 278, pp. 194-98, 2007.

[29] A. N. Lagarkov and V. N. Kisel, "Losses in metamaterials: Restrictions and benefits," Physica B, Vol. 405, pp. 2925-2929, 2010.

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