

Excitation of guided waves in layered structures with negative refraction

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Abstract: We study the electromagnetic beam reflection from layered structures that include the so-called *double-negative metamaterials*, also called *left-handed metamaterials*. We predict that such structures can demonstrate a giant lateral Goos-Hänchen shift of the scattered beam accompanied by a splitting of the reflected and transmitted beams due to the resonant excitation of surface waves at the interfaces between the conventional and double-negative materials as well as due to the excitation of leaky modes in the layered structures. The beam shift can be either positive or negative, depending on the type of the guided waves excited by the incoming beam. We also perform finite-difference time-domain simulations and confirm the major effects predicted analytically.

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References and links

1. F. Goos and H. Hänchen, "Ein neuer und fundamentaler versuch zur totalreflexion," *Ann. Physik* **1**, 333–346 (1947).
2. T. Tamir, "Leaky waves in planar optical waveguides," *Nouvelle Revue D'Optique* **6**, 273–284 (1975).
3. A. Otto, "Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection," *Zeitschrift fur Physik* **216**, 398–410 (1968).
4. A. Otto, "Spectroscopy of surface polaritons by attenuated total reflection," in *Optical properties of solids-new developments*, B. O. Seraphin, ed., (North-Holland, Netherlands, 1975), 677–729.
5. R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science* **292**, 77–79 (2001).
6. J. B. Pendry and D. R. Smith, "Reversing light with negative refraction," *Phys. Today*, **57**, 37–43 (June 2004).
7. R. Ruppin, "Surface polaritons of a left-handed medium," *Phys. Lett. A* **277**, 61–64 (2000).
8. I. V. Shadrivov, A. A. Sukhorukov, Yu. S. Kivshar, A. A. Zharov, A. D. Boardman, and P. Egan, "Nonlinear surface waves in left-handed materials," *Phys. Rev. E* **69**, 16617–9 (2004).
9. I. V. Shadrivov, A. A. Zharov, and Yu. S. Kivshar, "Giant Goos-Hänchen effect at the reflection from left-handed metamaterials," *Appl. Phys. Lett.* **83**, 2713–2715 (2003).
10. R. W. Ziolkowski, "Pulsed and CW Gaussian beam interactions with double negative metamaterial slabs," *Opt. Express* **11**, 662–681 (2003), <http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-7-662>.

11. R. W. Ziolkowski, "Pulsed Gaussian beam interactions with double negative metamaterial slabs: errata," *Opt. Express* **11**, 1596–1597 (2003), <http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-13-1596>.
 12. L. M. Brekhovskikh, *Waves in Layered Media* (Academic Press, New York, 1980).
 13. P. R. Berman, "Goos-Hänchen shift in negatively refractive media," *Phys. Rev. E* **66**, 67603–3 (2002).
 14. I. V. Shadrivov, A. A. Sukhorukov, and Yu. S. Kivshar, "Beam shaping by a periodic structure with negative refraction," *Appl. Phys. Lett.* **82**, 3820–3822 (2003).
 15. X. Chen and C. F. Li, "Lateral shift of the transmitted light beam through a left-handed slab," *Phys. Rev. E* **69**, 066617–6 (2004).
 16. H. M. Lai, C. W. Kwok, Y. W. Loo, and B. Y. Xu, "Energy-flux pattern in the Goos-Hänchen effect," *Phys. Rev. E* **62**, 7330–7339 (2000).
 17. I. V. Shadrivov, A. A. Sukhorukov, and Yu. S. Kivshar, "Guided modes in negative-refractive-index waveguides," *Phys. Rev. E* **67**, 057602–4 (2003).
 18. P. Yeh, *Optical Waves in Layered Media* (John Wiley & Sons, New York, 1988).
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1. Introduction

An optical beam totally reflected from an interface between two transparent dielectric media is known to experience a lateral displacement from the point of reflection predicted by geometric optics because each plane-wave component of the beam undergoes a different phase change. Such a lateral beam shift is usually called the Goos-Hänchen effect [1]; it occurs at angles close to the angle of the total internal reflection by the interface, and the beam shift is usually much less than the beam width.

However, much larger beam shifts are known to occur in layered structures that support *surface or guided waves* which, when being excited, are able to transfer the incoming beam energy along the interface. Such guided waves are not excited in the case of a single interface separating two dielectric media because the phase matching condition between the incident beam and the surface waves cannot be fulfilled. However, guided waves can be excited in layered structures when the beam is incident at an angle larger than the angle of total internal reflection. In this case, the guided waves are also termed *leaky waves* [2]. Excitations of leaky waves by scattering of electromagnetic waves are usually realized in two well-known geometries, which are used in the solid-state spectroscopy, also known as the attenuated (or frustrated) total internal reflection experiments. These two excitation geometries are: (i) glass prism-air-dielectric structure, usually called the *Otto configuration* [3] and (ii) prism-dielectric film-air structure, usually called the *Kretschmann configuration* (see, e.g., Ref. [4] and references therein).

Recent experimental fabrication [5] and extensive theoretical studies [6] of the properties of novel microstructured materials with negative refraction, called *double-negative (DNG) metamaterials* or *left-handed metamaterials*, demonstrate that an interface between the conventional and DNG media can support *surface waves* (or *surface polaritons*) of both TE and TM polarizations [7, 8]. Existence of surface waves for all parameters of the interface suggests that they can enhance dramatically the value of the Goos-Hänchen effect for the beam reflection because such surface waves can transfer the energy of the incoming beam along the interface, as was first discussed in Ref. [9].

The purpose of this paper is twofold. First, we study analytically the manifestation of the giant Goos-Hänchen effect that can be observed in the beam reflection by two types of layered structures that include DNG media. In these geometries, we demonstrate resonant excitation of (i) surface waves at a surface of a DNG medium, and (ii) leaky waves in a structure with a DNG slab. We study the corresponding stationary guided modes in the layered structures, and then demonstrate, by solving the stationary scattering problem, resonant reflection and transmission due to the excitation of leaky waves in the two geometries. Second, we use direct numerical finite-difference time-domain (FDTD) simulations [10, 11] to study the temporal dynamics of the beam scattering and surface wave excitation, and confirm numerically the major predictions of our theory.

2. Lateral beam shift

First, we recall that, in the framework of the scalar theory of linear wave scattering [12], the lateral shift Δ_r of a beam reflected by a layered dielectric structure can be defined as

$$\Delta_r = \frac{d\Phi_r}{dk_x}, \quad (1)$$

where the index 'r' refers to the reflected beam and Φ_r is the phase of the reflection coefficient. The approximation Eq. (1) is obtained with the assumptions that the beam experiences total internal reflection and that the phase of the reflection coefficient Φ_r is a linear function of the wavevector component k_x across the spectral width of the beam.

This lateral beam shift and the Goos-Hänchen effect have been calculated for several problems of beam reflection from layered structures with DNG materials, in particular, for the beam reflection from a single interface [10, 11, 13], and a periodic structure of alternating right- and left-handed layers [14]. Also, the shift of the beam transmitted through a DNG slab has been studied theoretically in Ref. [15].

However, if the phase Φ_r is not a linear function of the wave number k_x across the spectral width of the beam (e.g., for narrow beams with wide spectrum), the approximate formula (1) for the shift of the beam as a whole is, strictly speaking, not valid. In such a case, one can first obtain the structure of both the reflected and transmitted beams as follows,

$$E_{r,t}(x) \frac{1}{2\pi} \int_{-\infty}^{\infty} \{R(k_x), T(k_x)\} \bar{E}_i(k_x) dk_x, \quad (2)$$

where \bar{E}_i is the Fourier spectrum of the incident beam, and then define the relative shift of the beams, $\Delta_{r,t}$, by using the normalized *first moment* of the electric field of the reflected and transmitted beams, $\Delta_{r,t} \Delta_{r,t}^{(1)}$, where

$$\Delta_{r,t}^{(n)} = \frac{\int_{-\infty}^{\infty} x^n |E_{r,t}(x)|^2 dx}{a^n \int_{-\infty}^{\infty} |E_{r,t}(x)|^2 dx}, \quad (3)$$

and a is the width of the incident beam.

As a matter of fact, the transverse structure of the reflected and transmitted beams can have a complicated form; and, in general, it can be asymmetric so that the shift defined by Eq. (3) may differ essentially from the value following from Eq. (1).

The case $\Delta \ll 1$ corresponds to a beam shift much smaller than the beam width. On the other hand, the case $\Delta \geq 1$ is much more interesting; and it corresponds to the so-called giant Goos-Hänchen effect. The second moment of the reflected and transmitted beams, $\Delta_{r,t}^{(2)}$, defined by Eq. (3), characterizes a relative width of the reflected and transmitted beams,

$$W_{r,t} = \sqrt{\Delta_{r,t}^{(2)}}.$$

In what follows, we assume, without restrictions of generality, that the interface between the first and the second media is located at $z = 0$, and that the incident beam is Gaussian and has the beam width a , i.e., at the interface the electric field of the beam has the form $E_i(x, z = 0) = \exp(-x^2/4a^2 - ik_{x0}x)$. The angle of incidence of the beam, ϕ , is defined with respect to the normal to the interface so that the wave number component along the interface in the medium from which the beam is incident is $k_{x0} = k_1 \sin \phi$, and the corresponding wave number in the medium into which the transmitted beam propagates is $k_1 = \omega \sqrt{(\epsilon_1 \mu_1)}/c$.

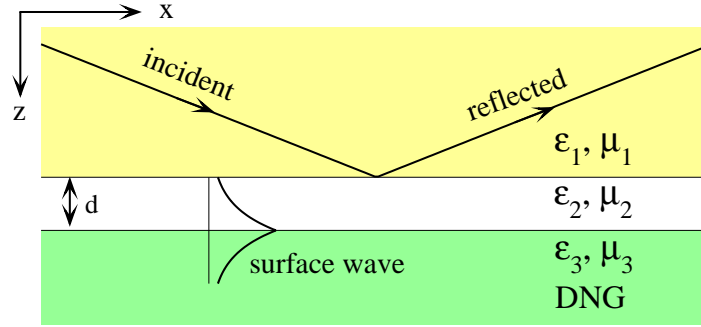


Fig. 1. Schematic geometry of the excitation of surface waves in a three-layer structure that includes a DNG medium.

3. Excitation of surface waves

We consider a two-dimensional, three-layered structure schematically depicted in Fig. 1, where the input beam is incident from an optically dense medium (the first medium) with $\epsilon_1\mu_1 > \epsilon_2\mu_2$ at an incident angle larger than the angle of total internal reflection. Medium 2 represents a gap layer of width d that separates medium 1 and medium 3. We assume that the third medium consists of a DNG metamaterial which possesses negative real parts of both the dielectric permittivity ϵ_3 and magnetic permeability μ_3 . The interface between the media 1 and 2 generates reflected and transmitted beams. The interface between media 2 and 3 can support surface waves which are excited resonantly when the tangential component of the wavevector of the incident beam coincides with the propagation constant of the corresponding surface polariton. In such a case, the surface wave can transfer the energy along the interface leading to an effective enhancement of the lateral shift of the reflected and transmitted beams.

In the geometry shown in Fig. 1, the reflection coefficient $R = R(k_x)$ for the TE-polarized monochromatic $[\sim \exp(i\omega t)]$ plane wave is defined as

$$R = \frac{(\alpha_1 + 1)(\alpha_2 + 1) - (\alpha_1 - 1)(\alpha_2 - 1)e^{2ik_z d}}{(\alpha_1 - 1)(\alpha_2 + 1) - (\alpha_1 + 1)(\alpha_2 - 1)e^{2ik_z d}}, \quad (4)$$

where $\alpha_1 = k_{z1}\mu_2/k_{z2}\mu_1$, $\alpha_2 = k_{z3}\mu_2/k_{z2}\mu_3$, $k_{zi} = (\omega^2\epsilon_i\mu_i/c^2 - k_x^2)^{1/2}$, for $i = 1, 2, 3$, and c is the speed of light in vacuum. For definiteness, we consider only the case of TE polarized waves, but our studies indicate that the results are qualitatively similar for the TM polarized waves.

Using Eq. (4), we can show that the phase of the reflection coefficient has an abrupt change when k_x coincides with the wavevector of a surface wave supported by the interface between medium 2 and 3. Thus, larger values of the lateral beam shift are expected at angles of incidence for which the beam spectrum contains the wavevector components having the same component k_x as the propagation constant of the surface waves. As was shown recently, both *forward* and *backward* surface polaritons can exist at the DNG interface [8], depending on the effective parameters $X = |\epsilon_3|/\epsilon_2$ and $Y = |\mu_3|/\mu_2$. Excitation of the forward surface waves results in an energy transfer in the direction of incidence. A negative shift of the reflected beam will be observed for an excitation of the backward surface waves; this case corresponds to the conditions $XY > 1$ and $Y < 1$.

We chose the following parameters for the media in our three-layered structure: $\epsilon_1 = 12.8$, $\mu_1 = \epsilon_2 = \mu_2 = 1$, $\epsilon_3 = -3$, $\mu_3 = -0.5$. The propagation constant of the surface waves, h , is found from the relation [8]

$$h^2 = \epsilon_2\mu_2 \frac{\omega^2 Y(Y - X)}{c^2 (Y^2 - 1)},$$

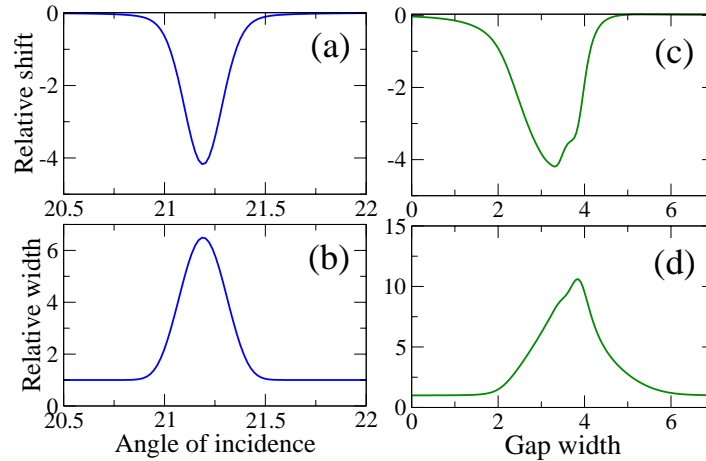


Fig. 2. (a,b) Relative beam shift, Δ_r , and beam width, W_r , vs. incidence angle (in degrees). (c,d) Relative shift and width of the reflected beam vs. normalized gap width $2\pi d/\lambda$ at $a/\lambda = 100/2\pi$. In (c,d) the angle of incidence corresponds to the point of maximum shift in (a).

and for this case the surface waves at the interface are backward propagating. Figures 2(a,b) show the dependence of the relative beam shift Δ_r and the beam width W_r on the angle of incidence when $a/\lambda_0 = 100/2\pi$ and $d/\lambda_0 = 3/2\pi$, where λ_0 is the free-space wavelength. A distinctive resonant dependence of the beam shift is observed, and the maximum of this shift corresponds to the phase matching condition $k_{x0} = h$.

In the beam profiles shown in Fig. 3, we observe that the reflected beam has a *distinctive double-peak structure*. The first peak corresponds to a mirror reflection, while the second peak is shifted relative to the point of incidence. The latter can be explained by the excitation of surface waves. At the resonance, this lateral beam shift becomes larger than the width of the beam itself. The double-peak structure appears only for relatively narrow beams for which the beam spectrum is wider than the spectral width of the surface wave mode, the latter being found as the width of the resonance shown in Fig. 2(a). The components of the beam spectrum outside this region are reflected in the usual mirror-like fashion. The spectral components of the beam near the resonance transform into an excited surface wave, and they are responsible for the appearance of the second peak in the shifted reflected beam. For wider beams, such that their spectrum completely falls into the spectral region of the surface wave mode, only the shifted peak appears. With an increase of the beam width, however, the relative beam shift decreases due to the fact that the absolute shift of the beam grows slower than the beam width.

Figures 2(c,d) show the relative beam shift and width versus the normalized thickness of the gap medium. The resonances presented in Figs. 2(c,d) can be explained with the help of a simple physics argument. Indeed, when the gap separating medium 1 and 3 is absent (i.e., at $d = 0$) or very small, no surface waves are excited; and the beam shift is negligible. Increasing the width of the gap medium, we increase the quality factor of the surface mode, and thus increase the shift of the reflected beam. Similarly, for large values of d surface waves are not excited, and the shift of the reflected beam becomes small again.

To gain a deeper understanding of the physical mechanism for the large values of the Goos-Hänchen shift in the case when the layered structure includes the DNG medium, we calculate the energy flow distribution and compare it with the results for a conventional (double positive or right-handed) medium [16]. From the analysis of the structure of the energy flow, we

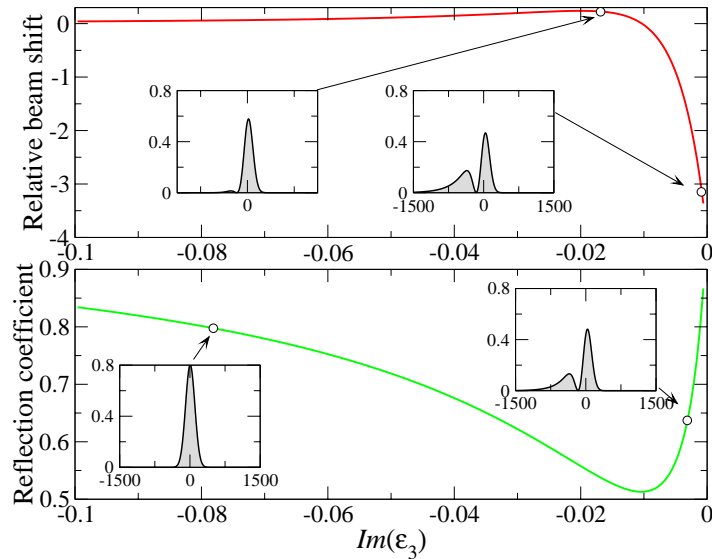


Fig. 3. (a) Relative beam shift and (b) reflection coefficient vs. the imaginary part of the dielectric permittivity, for $a/\lambda = 100/2\pi$ and $d/\lambda = 3/2\pi$. Insets show the profiles of the reflected beam.

conclude that the surface wave excited at the interface has a finite extension and a *distinctive vortex-like structure* as predicted earlier in Ref. [9] and other studies. This surface wave transfers the energy in the negative direction and, consequently, the energy is reflected from the interface as a shifted beam.

To make our predictions more realistic, we include the effect of losses into our analysis, which are always present in DNG metamaterials. We describe losses by introducing imaginary parts into the dielectric permittivity ϵ_3 and magnetic permeability μ_3 . In particular, we take $\mathcal{I}m(\mu_3) = -2 \cdot 10^{-5}$ and vary the imaginary part of ϵ_3 . We notice that the losses in the DNG medium affect primarily the surface waves. Therefore, the major effect produced by the losses is observed for the strongly shifted beam component.

When the beam is narrow, i.e. its spectral width is large, only a part of the beam energy is transferred to the surface wave, while the other part is reflected. This case is shown in Figs. 3(a,b). In this case an increase in the loss, i.e. an increase of the absolute value of $\mathcal{I}m(\epsilon_3)$, results in the suppression of the second peak in the reflected beam which, as noted above, appears due to the surface wave excitation [9].

Finally, we performed direct numerical FDTD simulations to study the temporal dynamics of the surface wave excitation. The FDTD simulator used in these calculations is described in [10, 11]. The DNG medium is modeled with a lossy Drude model for both the permittivity and permeability. The cell size was set at $\lambda_0/100$ to minimize any effects of the numerical dispersion associated with the FDTD method. We launch the beam with a waist λ_0 at the incident angle 21.17° to observe the backward wave excitation, i.e., this incident angle corresponds to the resonant surface wave excitation. The medium parameters are the same as those used in Fig. 2(a,b). The intensity of the electric field at the final step of the numerical simulations is shown in Fig. 4(a). In the top part of this figure we observe the interference of the incident and reflected beams. Though it is not easy to discern the double-peak structure of the reflected beam, one can clearly see the surface wave excited at the boundary between the air and DNG media. The fact that the maximum of the surface wave is shifted in the direction opposite to the

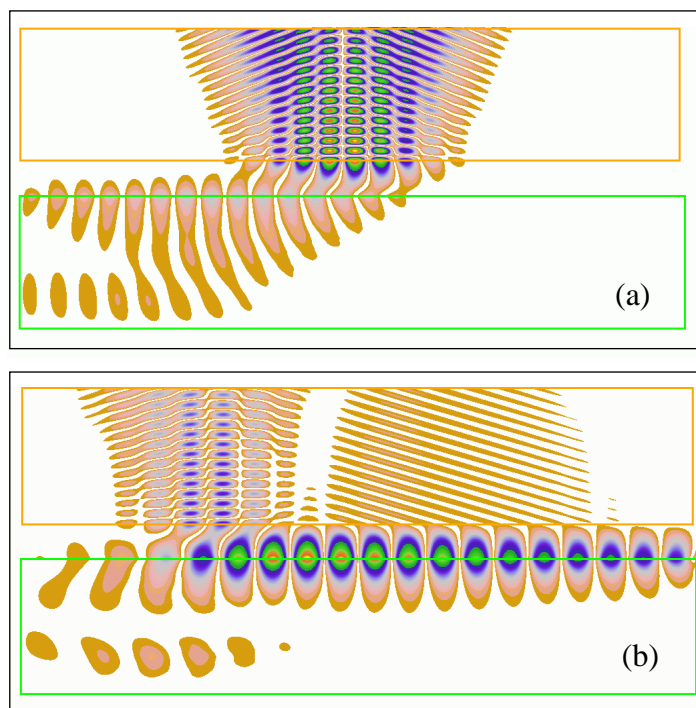


Fig. 4. Distribution of the electric field after the excitation of (a) backward surface wave (665K), and (b) forward surface wave (815K).

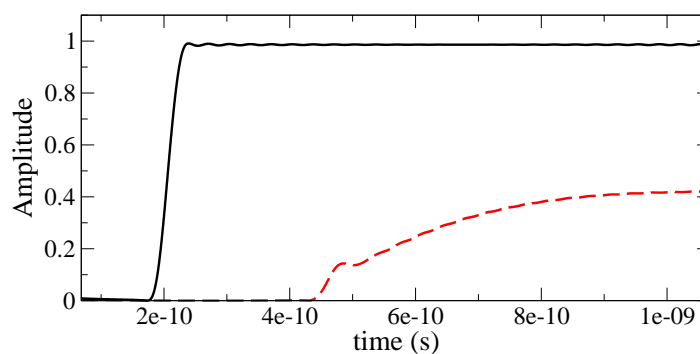


Fig. 5. Temporal variation of the amplitudes of the incident (solid) and surface (dashed) waves.

direction of the incident wave indicates that the excited surface wave is backward. The temporal variations of the amplitudes of the incident and surface waves are shown in Fig. 5.

In order to observe the process of the excitation of the forward surface wave, we take the medium parameters with a different set of values (see, e.g., Ref. [8]): $\epsilon_1 = 12.8$, $\mu_1 = \epsilon_2 = \mu_2 = 1$, $\epsilon_3 = -0.5$, $\mu_3 = -2$, and $d = \lambda$. Using the theoretical approach discussed above, we find that for an incident beam having a waist λ_0 , the resonant excitation of the forward surface waves should be observed with the incident angle 16.32° . The distribution of the electric field intensity calculated by the FDTD simulator is shown in Fig. 4(b). Here, we can identify clearly the *double-beam structure* of the reflected beam discussed above. The temporal dynamics of

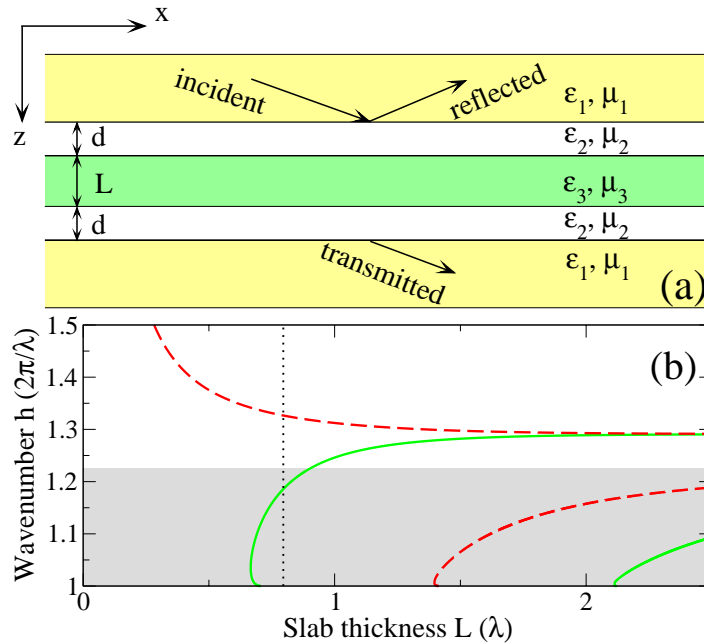


Fig. 6. (a) Geometry of the layered structure. (b) Dependence of the normalized wave number h of the guided modes in the center slab whose thickness is L , for odd (dashed) and even (solid) modes. The vertical dashed line in the lower figure corresponds to the thickness $L5\lambda/2\pi$ used in our calculations.

the forward wave excitation are similar to the case of the backward wave. The amplitude of the forward wave is much higher than the amplitude of the incident wave, in contrast to the case of the excitation of the backward wave shown in Fig. 5.

4. Excitation of slab modes

Now we consider the five-layer structure geometry shown in Fig. 6(a). The first and fifth slabs have the material parameters ϵ_1 and μ_1 . There are two gap slabs with material parameters ϵ_2 and μ_2 . The middle slab has the material parameters ϵ_3 and μ_3 . Without the slabs one and five (i.e. when $d \rightarrow \infty$) the structure reduces to an isolated slab. When this slab is a DNG medium, it is known to support guided modes. The presence of the optically dense medium makes these guided slab modes *leaky* [2], because these waves can now tunnel outside the guided region. The dense media on both sides of the center slab make it possible for such leaky waves to radiate in both directions.

For our studies, we use the same parameters as we did for the three-layered structure discussed in the previous section. The properties of the guided modes supported by a DNG slab have been analyzed earlier in Ref. [17]. Depending on the thickness of the DNG medium, the slab can support either one or several guided modes. Figure 6(b) shows the dependence of the wave number of the TE-polarized modes as a function of the slab thickness.

Reflection and transmission coefficients for the scattering of monochromatic plane waves by the layered structure can be calculated with the help of the transfer-matrix method (see, e.g. Ref. [18]). We take the slab thickness $L = 5\lambda/2\pi$, so that both symmetric and antisymmetric modes can exist in this layered structure. Additionally, we select angles of incidence in such a way that k_x will be the same as the propagation constant of one of the guided modes discussed

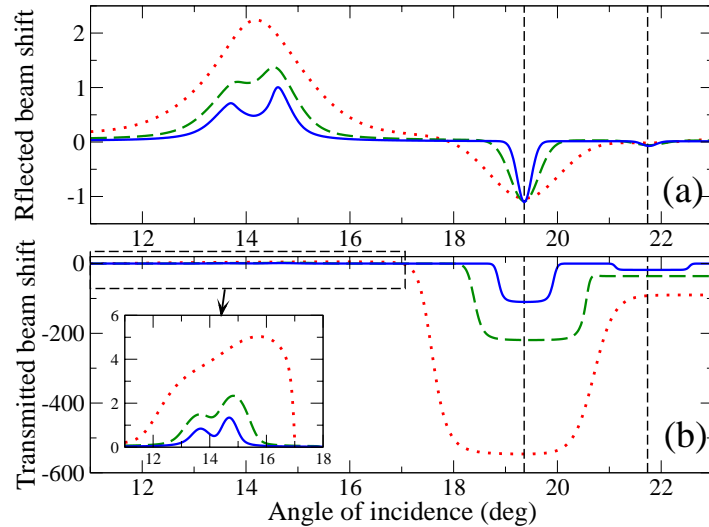


Fig. 7. Dependence of the relative shifts of the (a) reflected and (b) transmitted beams versus the angle of incidence, for $L = 5\lambda_0/2\pi$ and $d = \lambda_0$, and several values of the waist of the incident beam a : $a\lambda_0$ (dotted), $a = 5\lambda_0$ (dashed), and $a10\lambda_0$ (solid). The vertical lines indicate the position of the slab eigenmodes. The insert shows an enlargement of the domain marked by the dashed box in the main figure.

above, to achieve large values of the lateral shift of the reflected beam.

Figure 7 shows the shift of the reflected and transmitted beams, calculated with the help of Eq. (3), as a function of the angle of incidence. There is a distinctive resonant behavior for this shift. For a wide beam, the resonance maxima correspond to the phase matching condition $k_{x0} = h$; and, measuring the position of such resonances, we can determine the thickness of the DNG slab with a precision exceeding a wavelength. However, the two-peak structure of the resonances disappears for narrower beams because such beams have a wide angular spectrum and, hence, both modes are excited simultaneously. Moreover, the relative shift of the transmitted beam can be much larger than that of the reflected beam. This happens because the transmitted wave is composed only of a beam emitted by the excited leaky wave whereas the reflected beam consists of two parts: this leaky wave part and the mirror-like beam reflected from the structure. In contrast, the positive resonances in the low wave number gap regions correspond to the resonant reflections from that gap. The resulting fields can also be treated as excitations of leaky waves that are guided by the air gaps.

Figure 8 shows the shift of the reflected and transmitted beams versus the normalized thickness d of the gap slabs. The resonant-like behavior of these dependencies can be explained in the same way as was done for the case of the surface waves. If the gap is absent, no leaky waves are excited and, therefore, the shift of the reflected beam is much smaller than the incident beam width. If we increase the width of the gap separating the medium one and three, we increase effectively the quality factor for the excitation of guided modes, thus increasing the propagation distance of such waves and, hence, the lateral shift of the reflected beam. For large widths of the gap, the reflected beam spectrum is much wider than the spectrum of the leaky waves and, as a result, only a small part of the beam energy can be transferred to the guided waves, making the resulting beam shift small.

Figures 8(c,d) show the dependence of the beam shift on the width of the incident beam. A change of the width of the incident beam modifies its spectral extent; thus it changes the ratio

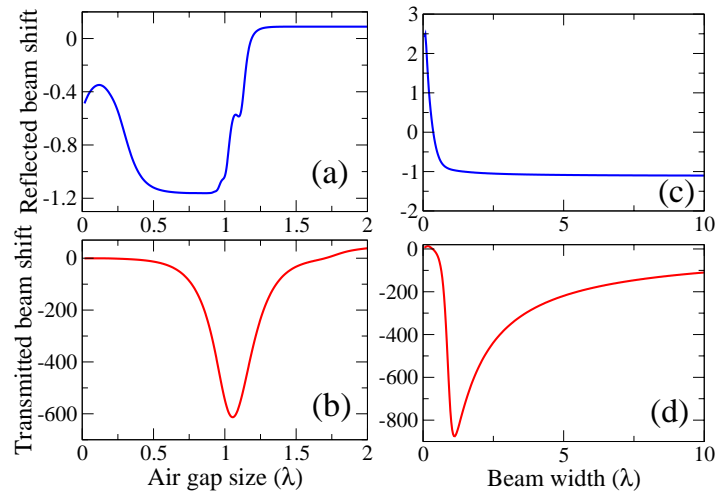


Fig. 8. Dependence of the relative shift of the (a) reflected and (b) transmitted beams versus the thickness d of the air gaps between the DNG slab and the high-index slabs when $L = 5\lambda_0/2\pi$, $a = \lambda_0$, and $k_{x_0} = 1.1862\pi/\lambda_0$. Dependence of the relative shift of the (c) reflected and (d) transmitted beams versus the waist a of the incident beam when $L = 5\lambda_0/2\pi$, $d\lambda_0$, and $k_{x_0} = 1.1862\pi/\lambda_0$.

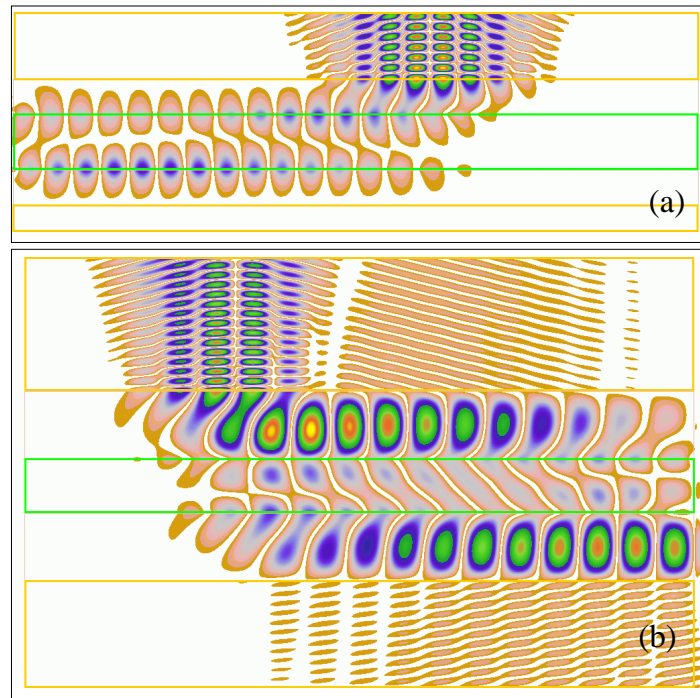


Fig. 9. Intensity distribution of the electric field for the excitation of (a) backward guided waves (430K) and (b) forward leaky waves guided by the air gaps (1.5M).

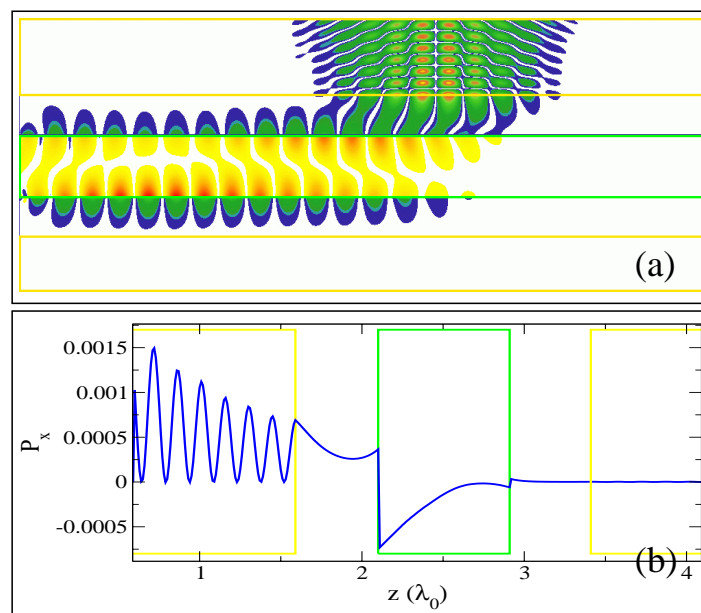


Fig. 10. (a) (365K) Contour plot of the x -component of the Poynting vector (blue corresponds to positive values, while yellow corresponds to negative values), (b) Profile of the x -component of the instantaneous Poynting vector as a function of z (normal to the interfaces) at the middle point of the simulation domain.

of the energy carried by the mirror-like reflected and leaky-wave radiated beams.

We have performed direct numerical FDTD simulations of the temporal dynamics for the excitation of the guided waves in the five-layer structure. Samples of these results are shown in Figs. 9(a,b) where two snapshots in time of the electric field intensity distribution at the end of the simulations are given. In particular, Fig. 9(a) shows the excitation of the backward guided waves. The air gap thickness here was chosen to be $\lambda_0/2$ in order to decrease the quality factor of the guided modes and to obtain a better coupling with the radiative modes. The excited guided wave has a *vortex-like structure* of the energy flow, as predicted earlier in Ref. [17]. The structure of the x -component of the instantaneous Poynting vector is shown as a contour plot in Fig. 10(a). It shows that the energy inside the DNG slab flows in a direction opposite to the energy flow in the dielectrics. Figure 10(b) presents the profile of this component along the cross-section transverse to the interfaces shown in Fig. 10(a) at the middle point of the simulation domain. It shows explicitly *the negative energy flow* inside the DNG slab waveguide.

Finally, Fig. 9(b) shows the snapshot in time of the distribution of the electric field intensity at the end of the simulation in the case when the excitation of the leaky waves is guided by the air gaps. These results demonstrate that the electric field in this case is mostly concentrated in the air gaps. This explains the positive energy flow, and the overall positive shift of the reflected and transmitted beams.

5. Conclusions

We have analyzed the scattering of an obliquely incident Gaussian beam by a multi-layered structure that includes a double-negative (DNG or left-handed) medium. We have demonstrated that a rich variety of surface and guided waves supported by these multi-layered structures having both double-positive (DPS or right-handed) and DNG media can result in a giant lateral shift

of the beam reflected from it. We have emphasized that this effect is due to either the resonant excitation of surface waves (surface polaritons) at the interface between the conventional DPS and the unconventional DNG materials, or due to the resonant excitation of guided and leaky modes in the DNG slabs. For the resonant excitations of guided waves, the reflected beam has a well-defined double-peak structure, where one peak represents the mirror-like reflection, and the second one appears due to a lateral beam shift from the point of the mirror-like reflection, and it is produced by the excited surface waves. The lateral beam shift can be both positive and negative, depending on the type of the surface waves supported by the structure and excited by the incoming beam. Many of these predictions hold in the presence of losses in the DNG material, which have been included in our analysis as well. We have also performed a series of direct finite-difference-time-domain numerical simulations to model the temporal dynamics of the beam scattering in both types of the multi-layered structure guided-wave geometries and have confirmed the major effects predicted analytically for the time harmonic, stationary problem.

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