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GOOS-HÄNCHEN SHIFT AT THE SURFACE OF CHIRAL NEGATIVE REFRACTIVE MEDIA

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Abstract—The Goos-Hächen (GH) shift at the surface of chiral negative refractive media is analyzed theoretically. GH shifts are observed for both perpendicular and parallel components of the reflected field near the respective critical angles. It is found that positive and negative shifts can be attained when the incident angle is larger than the first critical angle, whereas if the angle of incidence exceeds the second critical angle, only positive shifts can be observed. In addition, a Gaussian beam is further adopted to illustrate the effect of the GH shifts.

1. INTRODUCTION

As is known, when a light beam is totally reflected at the boundary of two different media, the reflected light beam experiences a lateral shift in the incidence plane from the position predicted by the geometrical optics, because each plane wave component undergoes a different phase change. This lateral beam shift is referred to as Goos-Hänchen(GH) shift [1], which was explained theoretically in terms of stationary-phase approach [2] and investigated in experiment [3–5]. Due to its potential applications in optical devices, such as optical sensors [6] and optical waveguides [7], the GH shift has been studied for a wide range of materials, including absorptive media [8, 9], nonlinear media [4, 10], multilayered structures [11] and photonic crystals [12]. Recently, the GH shift associated with negative refractive media attracts much attention. For instance, Berman [13], Lakhtakia [14], Qing *et al* [15], and Hu *et al* [16] extensively studied the lateral shift at an interface between positive and negative refractive media. Shadrivov *et al* [17] further investigated a giant GH shift in reflection from a layered structure containing a layer of left-handed material. Kong *et al* [18] elaborated the lateral displacement of a Gaussian beam reflected from a left-handed slab. They concluded that the shift is always negative. On the other hand, Grzegorczyk *et al* [19] showed that the GH shift induced by left-handed isotropic slabs could be positive when the second interface of the slab supports a surface plasmon. Furthermore, The lateral shift for an electromagnetic beam reflected from an uniaxial anisotropic slab coated with perfect conductor was studied [20].

In recent years, negative refraction in the chiral medium has aroused great interest within the scientific communities [21, 22, 23]. Actually, Electromagnetic properties in normal chiral materials have been studied for a long time, and a chiral medium can be implemented as a collection of helices [24]. To achieve a chiral medium with negative refraction, Pendry [25] proposed a Swiss roll structure. In addition, negative refractive chiral metamaterial, based on the Y structure, has been designed and tested in the microwave and terahertz frequencies [26]. Physically, it was demonstrated that when the chirality parameter is greater than the square root of the product of permittivity and permeability [27], the backward wave will occur at one of the two circularly polarized eigenwaves, making negative refraction in the chiral media possible. Then many new exciting phenomena related to electromagnetic propagation appear in chiral materials with negative refraction and should be reconsidered theoretically.

The aim of the present paper is to consider the reflection and refraction properties of plane electromagnetic waves in a chiral negative refraction medium, and to investigate the GH lateral shift dependence on the angle of incidence in such a chiral medium, with attention mainly focused on the GH effect on the basis of stationary-phase approach. The numerical results section will compare the data obtained from the negative refraction chiral medium to those obtained by the normal chiral medium. We further present a detailed analysis of the shift from a Gaussian beam to verify the conclusions drawn from the stationary-phase approach. Finally, we summarize our results in the last section.

2. GH SHIFTS IN TERMS OF STATIONARY-PHASE APPROACH

In this paper, we consider only TE polarized wave (the electric field in the x direction) and the case for a TM polarized wave can also be discussed in the similar manner. The geometry for the problem of interest is shown in Fig. 1, where a TE polarized wave is incident on the interface from the dielectric side at an angle θ_i and, as a consequence of the chirality of the second medium, it splits into two transmitted waves (one is right-handed circularly polarized (RCP), and the other is left-handed circularly polarized (LCP)) propagating into the chiral medium and a reflected wave with both parallel and perpendicular components propagating back into the dielectric. Two reflected field components can to first order be represented as two separate reflected beams, each with its own magnitude, lateral shift in the plane of the interface.

3. FIGURES

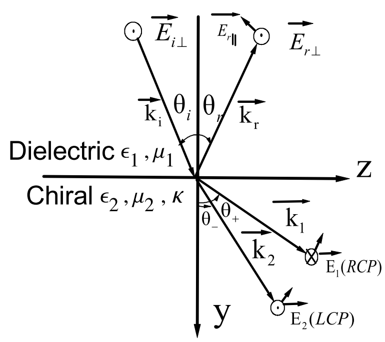

Figure 1. Orientation of the wave vectors at an oblique incidence on a dielectric-chiral interface. Subscripts $\|$ and $\perp$, respectively, stand for parallel and perpendicular with respect to the plane of incidence. In the chiral medium k_1 and k_2 waves represent RCP and LCP waves, respectively.

The constitutive relations used for the chiral medium are defined as [22]:

$$\mathbf{D} = \varepsilon_2\varepsilon_0\mathbf{E} - i\kappa\sqrt{\varepsilon_0\mu_0}\,\mathbf{H} \tag{1}$$
$$\mathbf{B} = \mu_2\mu_0\mathbf{H} + i\kappa\sqrt{\varepsilon_0\mu_0}\,\mathbf{E} \tag{2}$$

where ε_2 and μ_2 are the relative permittivity and permeability of the chiral medium, respectively (ε_0 and μ_0 are the permittivity and permeability in vacuum). The chirality parameter κ measures the degree of the handedness of the material. It gives the angle of polarization rotation of a plane wave with respect to the phase angle of the wave in free space, and the sign of κ is positive (negative) if the rotation is left-handed (right-handed) in the direction of propagation [28]. A monochromatic time-harmonic variation $\exp(i\omega t)$ is assumed throughout this paper, but omitted. Inside the chiral medium there are two eigenmodes of propagation: a RCP wave with phase velocity ω/k_1 and a LCP wave with phase velocity ω/k_2, where the wave numbers are given by

$$k_{1,2} = k_0(\sqrt{\varepsilon_2\mu_2} \pm \kappa) \tag{3}$$

where $k_0 \equiv \omega/c$ denotes the wavenumber in vacuum. The electromagnetic field in the chiral medium can be expressed as [22]:

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 \tag{4}$$

$$\mathbf{H} = \mathbf{H}_1 + \mathbf{H}_2 \tag{5}$$

The relations between electric fields and magnetic fields are

$$\mathbf{H}_{1,2} = \pm j\mathbf{E}_{1,2}/\eta_2 \tag{6}$$

where $\mathbf{E}_1$ and $\mathbf{E}_2$ associated with these two eigen-modes can be expressed by [23]

$$\mathbf{E}_1 = E_{01}\,(-i\mathbf{x} - \sin\theta_+\mathbf{y} + \cos\theta_+\mathbf{z})\,e^{-ik_{1y}y}e^{-ik_{1z}z} \tag{7}$$

$$\mathbf{E}_2 = E_{02}\,(i\mathbf{x} - \sin\theta_-\mathbf{y} + \cos\theta_-\mathbf{z})\,e^{-ik_{2y}y}e^{-ik_{2z}z} \tag{8}$$

E_{01} and E_{02} denote the amplitudes of the electric fields for RCP and LCP transmitted waves, respectively, and $\theta_\pm$ are the refracted angles of the two eigen-waves (see Fig. 1). The refractive indices are thus given as

$$n_{1,2} = \sqrt{\varepsilon_2\mu_2} \pm \kappa \tag{9}$$

It is evident that if $\kappa > \sqrt{\varepsilon_2\mu_2}$, the refractive index $n_2 \equiv \sqrt{\varepsilon_2\mu_2} - \kappa$ will become negative. Correspondingly, nagative refraction will occur to LCP wave and the LCP wave in the chiral medium is transmitted into another side of the normal axes.

In order to study the GH shift for total internal reflection between normal and chiral negative refractive medium, the reflection coefficients will be calculated according to the boundary conditions at $y = 0$. From

Ref. [23] and Ref. [24], the coefficients associated with perpendicular R_{11} and parallel R_{21} components of the reflected wave are obtained:

$$R_{11}=\frac{2\eta_1\eta_2(\cos^2\theta_i-\cos\theta_+\cos\theta_-)+(\eta_2^2-\eta_1^2)\cos\theta_i(\cos\theta_-+\cos\theta_+)}{G} \tag{10}$$

$$R_{21}=\frac{i2\eta_1\eta_2\cos\theta_i(\cos\theta_- -\cos\theta_+)}{G} \tag{11}$$

with

$$\begin{aligned} G \;=\; & (\eta_2\cos\theta_+ + \eta_1\cos\theta_i)(\eta_1\cos\theta_- + \eta_2\cos\theta_i) \\ & + (\eta_2\cos\theta_- + \eta_1\cos\theta_i)(\eta_1\cos\theta_+ + \eta_2\cos\theta_i) \end{aligned}$$

where $\eta_i = \sqrt{\mu_i}/\sqrt{\varepsilon_i}\,(i = 1,\,2)$ are wave impedances in the normal and chiral medium. From the boundary conditions, we have $k_i\sin\theta_i = k_r\sin\theta_r = k_1\sin\theta_+ = k_2\sin\theta_-$.

According to the stationary-phase approach, GH shifts (Δ) for both perpendicular component (R_{11}) and parallel component (R_{21}) in total internal reflection can be calculated in terms of the phase shift of reflection coefficients as [2, 25]

$$\Delta = d\Phi/dk_z \tag{12}$$

where Φ is the phase difference between the reflected and incident waves. In generally, at the interface between normal material and left-handed materials, the phase of R is constant for angles of incidence less than the critical angle, no GH shift is observed until the critical angle of total reflection is reached. While for the case of a dielectric-chiral interface, there exists two eigenwaves inside the chiral medium, thus one or two critical angles $\theta_{c+,\,c-} = \arcsin\left((\sqrt{\varepsilon_2\mu_2}\pm\kappa)/\sqrt{\varepsilon_1\mu_1}\right)$ [23], corresponding to RCP and LCP waves, may exist [26]. A general point should be quite clear: one corresponding to the refractive index n_2 (smaller critical angle) and the other to the refractive index n_1 (larger critical angle). Only beyond the latter occurs a "true" (complete) total reflection. While between those two critical angles, RCP wave would still be propagating through the interface into the chiral medium. Only when the angle of incidence increases to $\theta > \theta_{c-}$, the reflection coefficients become complex. The phase of the reflected wave experiences change with respect to the incident wave, and the GH lateral shifts for parallel component and perpendicular component in the reflected wave as a function of the angle of incidence can be obtained.

The numerical results section will compare the data obtained from the negative chiral medium to those obtained by the normal chiral medium using the stationary-phase approach. Different situations where one or two critical angles exist will be examined respectively.

4. DISCUSSION AND NUMERICAL RESULTS

4.1. $\varepsilon_2\mu_2 > \varepsilon_1\mu_1$ Case

In this case, the chiral medium is denser than the dielectric. No critical angles of total internal reflection exist when $\kappa = 0$. As κ increases, a single critical angle exists only for LCP when $\sqrt{\varepsilon_2\mu_2} + \sqrt{\varepsilon_1\mu_1} > \kappa > \sqrt{\varepsilon_2\mu_2} - \sqrt{\varepsilon_1\mu_1}$. The LCP wave becomes evanescent wave, thus we choose $k_{2y} = ik_2\sqrt{\frac{k_i^2\sin^2\theta}{k_2^2} - 1}$ for the chiral negative refraction medium and $k_{2y} = -ik_2\sqrt{\frac{k_i^2\sin^2\theta}{k_2^2} - 1}$ for the normal chiral medium), while the RCP wave still transmits into the chiral medium, $k_{1y} = k_1\sqrt{1 - \frac{k_i^2\sin^2\theta}{k_1^2}}$. The phase of both reflection components can be solved:

$$\Phi^1_{R_{11}} = \tan^{-1}\frac{A_1}{B_1} \tag{13}$$

$$\Phi^1_{R_{21}} = \tan^{-1}\frac{C_1}{D_1} \tag{14}$$

with

$$\begin{aligned}
A_1 =& -2\cos^2\theta\cos\theta_+\cos\theta_-\left(4\eta_1^2\eta_2^2 + \eta_2^4 - \eta_1^4\right)\\
&-4\eta_1\eta_2^3\cos\theta\cos\theta_-\left(\cos^2\theta + \cos^2\theta_+\right)\\
B_1 =& \ 4\eta_1\eta_2^3\cos\theta\cos\theta_+\left(\cos^2\theta - \cos^2\theta_-\right)\\
&+\left(\eta_2^4 - \eta_1^4\right)\cos^2\theta\left(\cos^2\theta_+ - \cos^2\theta_-\right)\\
&+4\eta_1^2\eta_2^2\left(\cos^4\theta - \cos^2\theta_+\cos^2\theta_-\right)\\
C_1 =& \ 4\eta_1^2\eta_2^2\cos\theta\cos\theta_+\left(\cos^2\theta_- - \cos^2\theta\right)\\
&+2\cos^2\theta\eta_1\eta_2\left(\eta_1^2 + \eta_2^2\right)\left(\cos^2\theta_- - \cos^2\theta_+\right)\\
D_1 =& \ 4\eta_1^2\eta_2^2\cos\theta\cos\theta_-\left(-\cos^2\theta - \cos^2\theta_+\right)\\
&-4\cos^2\theta\cos\theta_+\cos\theta_-\eta_1\eta_2\left(\eta_1^2 + \eta_2^2\right)
\end{aligned}$$

where $\cos\theta_- = \sqrt{\frac{k_i^2\sin^2\theta}{k_2^2} - 1}$, $\cos\theta_+ = \sqrt{1 - \frac{k_i^2\sin^2\theta}{k_1^2}}$ in this situation. The GH lateral shifts of perpendicular component and parallel component in the reflected wave are calculated according to (12)

$$\Delta = \frac{d\Phi}{dk_z} = \frac{d\Phi}{k_i\cos\theta d\theta} \tag{15}$$

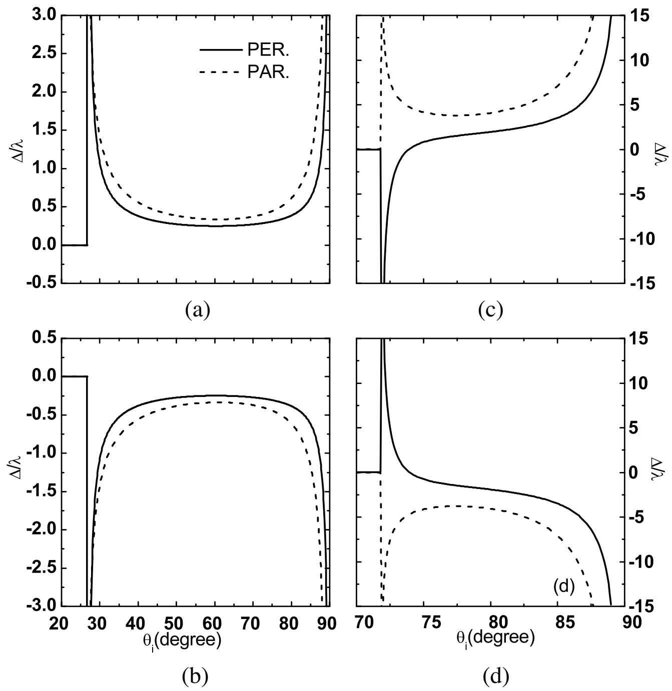

Figure 2. The GH shifts for the perpendicular component and the parallel component of the reflected field as a function of the incident angel with $\varepsilon_1 = 1$, $\mu_1 = 1$, $\varepsilon_2 = 4$, $\mu_2 = 1$, at different values of chirality: (a) $\kappa = 1.55$, (b) $\kappa = 2.45$, (c) $\kappa = 1.05$, (d) $\kappa = 2.95$.

When the angle of incidence is greater than the θ_c, the phase of the reflection coefficient experiences change with respect to the incident wave, the GH lateral shift will appear. In this case there never exists two critical angles. As shown in Fig. 2, GH shift does arise when the incident angles are larger than the critical angle. In this connection, the GH shift is purely a consequence of the chirality. Figs. 2(a) and 2(c) correspond to the case of normal chiral medium ($\kappa < \sqrt{\varepsilon_2\mu_2}$), while Figs. 2(b) and 2(d) correspond to the negative refractive chiral medium ($\kappa > \sqrt{\varepsilon_2\mu_2}$). By comparing Figs. 2(a) with 2(b), it can be easily found that the same critical angle occurs at $\theta_c = 26.8°$, which is mainly due to the fact that the values of $|n_2|$ are identical (similarly in Figs. 2(c) and 2(d)). Note that the shifts for both reflection components in negative refractive chiral medium are negative, indicates that the reflected components will shift to $-z$ direction with respect to the incident wave. These results are directly opposite to those in the normal chiral medium. Further investigation, we find that the signs of GH shift are consistent with that of n_2 except for in the vicinity of the critical angle (see Figs. 2(c) and 2(d)). In that region, the shifts of perpendicular components have opposite signs, which means that the range near the critical angle is quite angle-sensitive. Note that the shifts divergent near θ_c due to the fact that the method of stationary phase fails at the critical angle.

4.2. $\varepsilon_2\mu_2 < \varepsilon_1\mu_1$ Case

In this situation, the dielectric is denser than the chiral medium. If $\kappa = 0$, the medium is simply a dielectric medium, and there is one critical angle for the dielectric-dielectric interface. As κ increases from zero to $\kappa < \sqrt{\varepsilon_1\mu_1} - \sqrt{\varepsilon_2\mu_2}$, two critical angles will arise: smaller critical angle corresponds to LCP wave and larger critical angle corresponds to RCP wave. When the angle of incidence exceeds the larger critical angle, total internal reflection will occur, and both LCP wave and RCP wave become evanescent waves. For each evanescent wave, we will select $k_{2y} = ik_2\sqrt{\frac{k_i^2 \sin^2\theta}{k_2^2} - 1}$ and $k_{1y} = -ik_1\sqrt{\frac{k_i^2 \sin^2\theta}{k_1^2} - 1}$ for the chiral negative refraction medium to ensure the evanescent wave decay away from the interface. The phase of both reflection components can be expressed as:

$$\Phi^2_{R_{11}} = \tan^{-1}\frac{A_2}{B_2} \tag{16}$$

$$\Phi^2_{R_{21}} = \tan^{-1}\frac{C_2}{D_2} \tag{17}$$

with

$$\begin{aligned}
A_2 &= 4\eta_1\eta_2\cos\theta\left(\cos\theta_- - \cos\theta_+\right)\left(-\eta_1^2\cos^2\theta + \eta_2^2\cos\theta_+\cos\theta_-\right)\\
B_2 &= 4\eta_1^2\eta_2^2\left(\cos^4\theta - \cos^2\theta_-\cos^2\theta_+\right) - \cos^2\theta\left(\cos\theta_- - \cos\theta_+\right)^2\left(\eta_1^4 - \eta_2^4\right)\\
C_2 &= 2\eta_1\eta_2\cos^2\theta\left(\cos^2\theta_- - \cos^2\theta_+\right)\left(\eta_1^2 + \eta_2^2\right)\\
D_2 &= -4\eta_1^2\eta_2^2\cos\theta\left(\cos\theta_- + \cos\theta_+\right)\left(\cos^2\theta + \cos\theta_+\cos\theta_-\right)
\end{aligned}$$

here $\cos\theta_- = \sqrt{\frac{k_i^2\sin^2\theta}{k_2^2} - 1}$, $\cos\theta_+ = \sqrt{\frac{k_i^2\sin^2\theta}{k_1^2} - 1}$. From (15), one could obtain the GH lateral shifts of two reflection components. If κ keeps increasing, the larger critical angle will disappear. It implies that by introducing the chirality (e.g., distributing helices) into a dielectric, one could enhance the transmission at large oblique incident angles.

Numerical results have been presented in Fig. 3. In Figs. 3(a) and 3(c), ($\kappa < \sqrt{\varepsilon_1\mu_1} - \sqrt{\varepsilon_2\mu_2}$ and $\kappa < \sqrt{\varepsilon_2\mu_2}$), it should be noted that the parallel reflected component undergoes a positive shift within two critical angles, while the shift of the perpendicular component is positive near the first critical angle and negative near the second critical angle. When the incident angle is larger than the second critical angle, this shift also becomes positive.

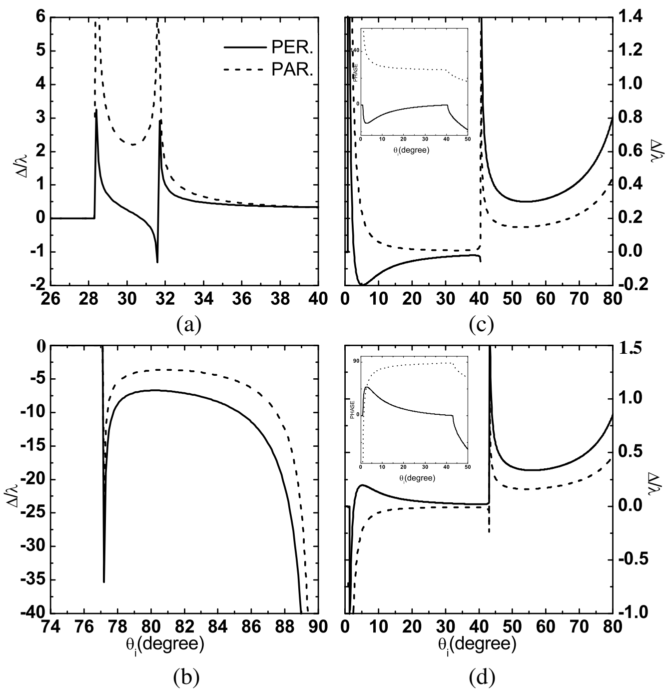

Figure 3. As in Fig. 2 but in different cases. $\varepsilon_2 = 1$, $\mu_1 = \mu_2 = 1$. (a) $\varepsilon_1 = 4$, $\kappa = 0.05$; (b) $\varepsilon_1 = 4$, $\kappa = 2.95$; (c) $\varepsilon_1 = 9$, $\kappa = 0.95$; (d) $\varepsilon_1 = 9$, $\kappa = 1.05$.

For large κ, the refractive index of the chiral medium n_2 will become negative ($\kappa > \sqrt{\varepsilon_2\mu_2}$). Within this category, Fig. 3(b) stands for an example of the case of $\kappa > \sqrt{\varepsilon_1\mu_1} - \sqrt{\varepsilon_2\mu_2}$, in which the second critical angle vanishes and the shifts behave similarly to the case in Fig. 2(b). However, in Fig. 3(d) (representing $\kappa < \sqrt{\varepsilon_1\mu_1} - \sqrt{\varepsilon_2\mu_2}$), there still exist two critical angles even when the negative refraction appears in the chiral medium. Within two critical angles, one may find that the sign of GH shift for the parallel component is consistent with that of n_2, while the perpendicular component experiences a maximum positive (negative) shift for negative (normal) chiral medium, as shown in Figs. 3(c) and 3(d). This unusual phenomenon is also reflected in the observation of the phase of the perpendicular reflection coefficient. It is clear from the inset of Fig. 3(c) that the phase curve has a valley near the first critical angle, and the negative relative minimum corresponds to the maximum negative shift for normal chiral medium. While from the inset of Fig. 3(d), we can see that a distinctive peak appears near those regions in the phase curve of the perpendicular reflection coefficient, and the positive relative maximum corresponds to the maximum positive shift for negative chiral medium. When the incident angle is greater than the second critical angle, both components always experience a positive shift. This can also be seen from the phase curves of respective reflection coefficients. The first derivative of each phase curve is negative ($\Delta = -d\Phi/dk_z$), regardless of the sign of n_2. Additionally, these shifts decrease firstly and then increase with increasing the angle of incidence.

5. LATERAL SHIFT OF A GAUSSIAN-SHAPED INCIDENT BEAM

To demonstrate the validity of the stationary-phase approach, we consider a Gaussian-shaped incident beam located at $y = 0$ in this section. The incident field on the interface at angle θ_i has the form of

$$E_{ix} = \int_{-\infty}^{\infty} A(k_z) \exp(-ik_y y - ik_z z) dk_z \tag{18}$$

where $A(k_z) = \frac{w_z}{\sqrt{2\pi}} \exp[-\frac{w_z^2}{2}(k_z - k_{z0})^2]$, $w_z = w_0 \sec\theta_i$, $k_{z0} = k_i \sin\theta_i$, and w_0 is the beam width. The reflected fields ($E_\perp^r$ and $E_\parallel^r$), determined from the transformation of the incident beam, can be written as:

$$E_\perp^r = \int_{-\infty}^{\infty} R_{11} A(k_z) \exp(ik_y y - ik_z z) dk_z \tag{19}$$

$$E_\parallel^r = \int_{-\infty}^{\infty} R_{21} A(k_z) \exp(ik_y y - ik_z z) dk_z \tag{20}$$

The calculated lateral shift can be obtained by finding the location where $|E_\perp^r|_{y=0}$ or $\left|E_\parallel^r\right|_{y=0}$ is maximal [33, 34]. Numerical results are shown in Fig. 4 for the beam width $w_0 = 10\lambda$. The shift for the parallel reflected field is found to be -5.5λ, while it is 4.5λ for the perpendicular reflected field. In comparison, -8.11λ and 6.07λ for parallel and perpendicular fields are found respectively based

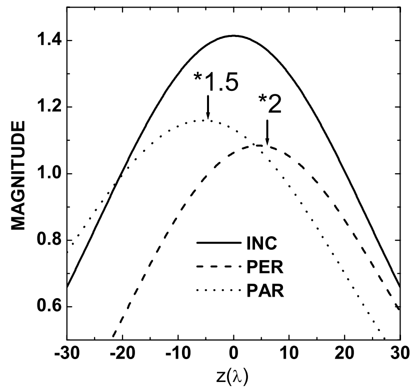

Figure 4. Comparison of the shapes for the perpendicular reflected field $|E_r|_{PER.}$ and the parallel reflected field $|E_r|_{PAR.}$, for a Gaussian beam $|E_i|$ at an incident angle of 72° in $y = 0$ plane. The parameters are the same as in Fig. 2(d). The magnitudes of the two reflected components have been scaled by respective factors in order to make the peak positions more distinguishable in the illustration.

on Artmann formulation Eq. (12) [also see Fig. 2(d)]. Therefore, simulation data for the Gaussian wave in qualitative agreement with numerical results for Artmann formulation, and the discrepancy results from small beam width we choose for the Gaussian approach. Actually, one would expect that the lateral shifts for Artmann formulation will be close to the results for Gaussian approach with sufficiently large beam width [33, 34]. In addition, we predict that the magnitude of the perpendicular reflected field is greater than that of parallel component from both approaches.

6. CONCLUSION

In conclusion, GH shift for both parallel and perpendicular components of the reflected field at the surface of negative chiral medium has been analyzed by the stationary-phase method. We have shown that the sign of the shift is generally consistent with that of n_2 where there exists only one critical angle (corresponds to LCP wave). When there exist two critical angles which correspond to LCP wave and RCP wave, respectively, if the angle of incidence is greater than the first critical angle and less than the second critical angle, both positive and negative GH shifts for perpendicular reflected component are possible, and they are directly opposite to the normal chiral media. While the shift for parallel component is also in consistence with the sign of n_2 within these two critical angles. As the incident angle increases larger than the second critical angle, both components experience a positive shift whether the chiral medium is normal or negative. Therefore, negative refraction, even though very small, has great impact on the GH shift. Furthermore, we perform the numerical results for a Gaussian-shaped incident beam to demonstrate the validity of the stationary-phase approach.

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