Main and third harmonic Goos-Hanchen shift analysis at the interface between LHM and RHM

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The effect of optical nonlinearity on lateral Goos-Hanchen shift at the LHM and RHM interface in both main and third harmonic is studied by an analytical method in a 1-D structure. In main harmonic beside negative shift, the shift amplitude increases and decreases by increasing nonlinearity when incident nonlinear medium is LHM and RHM respectively and in third harmonic, negative shift is obtained. Also by changing incident angle and increasing LHM losses and nonlinearity, negative shift turns into positive one which indicates all optically switching between RH and LH property via two parameters of nonlinearity and incident angle of the light.

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1. Introduction

In 1968 Veselago introduced some extinct properties of materials which have simultaneously negative electrical permittivity and magnetic permeability and therefore negative refractive index [1] which are called metamaterial or LHM. One of these interesting properties is the negative Goos-Hanchen shift happening at the interface between a LHM and RHM. This means that at such an interface the light turns back after incidence on the interface where total internal reflection happens and then reflects into the dense material in forward direction. But Veselago didn't introduce any real material in world that exhibited such properties. After that, many attempts were carried out to find or at least engineer a metamaterial until 2000 when D. R. Smith et al. could engineer a material showing negative electrical permittivity and magnetic permeability in a narrow microwave frequency region [2]. In fact they composed the metal rods structure of J. B. Pendry et al. [3] reducing plasma frequency of metals and split ring resonator structure of J. B. Pendry et al. [4] giving negative permeability in order to obtain this metamaterial. Also in 2001, R. A. Shelby et al. [5] experimentally showed negative refraction in microwave frequency by similar structure. Until now many experiments and simulations have been done in microwave and even optical frequency which confirm Veselago metamaterial [6-9]. Recently many researches have been focused on nonlinearity effect in metamaterials and also several of them have been done on Goos-Hanchen displacement in them [10-13].

One can see in these papers that researchers want to control this lateral shift by using metamaterial slab parameters or by using heat as the control signal to change and control the shift. Also they have shown the conditions for reversibility of the shift in a linear optical structure. [14-17]. On the other hand in recent years some efforts are carried out to enter metamaterials to optical processing. For example in [18] the idea of optical memory by use of negative Goos-Hanchen shift has been proposed. These shows intense motivation to control metamaterial optical properties by researchers. It is an essential need to achieve all optical structures and systems to reach THz communication speed in future. Hence here we want to control this lateral shift by use of the intense light as the controlling parameter. In [19] the Goos-Hanchen shift from a RHM into a nonlinear LHM has been analyzed but only main harmonic has been investigated and the effect of losses along with light intensity has not been analyzed. In this letter we investigate the effect of nonlinearity on Goos-Hanchen shift at the interface between a semi-infinite RH and LH materials. We consider both main and third harmonic in both parallel and perpendicular polarizations and by use of a full analytical method we investigate all possible cases of total internal reflection and show how nonlinearity and metamaterial losses can affect the Goos-Hanchen shift. In all of the paper we use [7] for metamaterial and use $\exp(i\omega t)$ time dependence for plane waves in the main harmonic and $\exp(-i\omega t)$ time dependence for plane waves in the third harmonic. Also we utilize Sellmeyer equation everywhere we apply GaAs for RHM. Although the metamaterial in [7] is anisotropic in nature but we suppose the same characteristics of that metamaterial exist in any direction and any polarization of light.

2. Goos-Hanchen shift calculation

We calculate Goos-Hanchen shift both for the main and third harmony. We suppose in the main harmonic the nonlinearity is produced by the intense pump light in incident or first medium so that signal will see nonlinearity in only first medium. In third harmonic calculations we suppose the signal in main harmonic is intense enough to produce third harmonic light in the first medium. For main harmonic analysis we consider GaAs as the incident medium and LHM as the second medium and vice versa, but in third harmonic analysis we must only select GaAs as the incident medium and LHM as the second medium and in addition we must choose main harmonic in non-propagating region of metamaterial so that the third harmonic signal is fallen in the propagating region of it. If we choose main harmony in metamateral propagating region, the third harmony is set in $\varepsilon_{rl} < 0$ and $\mu_{rl} > 0$ region of it which is non-propagating range and therefore no third harmonic signal is produced in metamaterial. On the other hand in third harmony calculations we can not consider metamaterial as the first medium. In fact there are two cases here. If we generate main harmony in metamaterial at its propagating region therefore third harmony is created in the non-propagating region of it and if the third harmonic signal is produced in metamaterial propagating region the main harmonic signal should be exist in non-propagating region of it that they are both impossible. So in the third harmonic calculations only the case of choosing GaAs as the first medium is analysed. The effect of Intensity of control light or optical nonlinearity and metamaterial losses is illustrated too. Ultimately we analyze the results for GaAs-vaccum to compare with GaAs-metamaterial case.

2.1 Main harmonic Goos-Hanchen shift

Here we remind the calculations for main harmonic Goos-Hanchen shift and finally we insert nonlinearity in the relations. Lateral Goos-Hanchen shift in linear case is the derivation of the phase of reflection coefficient with respect to the tangential component of the wave vector.

$$\frac{\partial\phi}{\partial\beta} = \frac{(2\alpha)\beta(k_1^2 - k_2^2)}{[(\alpha^2 - 1)\beta^2 + k_1^2 - \alpha^2 k_2^2]\sqrt{\beta^2 - k_2^2}\sqrt{k_1^2 - \beta^2}}, \quad (1)$$

Here β is the tangential component of the wave vector, k_1 is wave vector in the first space and k_2 is wave vector in the second space. For parallel polarization $\alpha = \varepsilon_{r1} / \varepsilon_{r2}$ and for perpendicular polarization $\alpha = \mu_{r1} / \mu_{r2}$ and ϕ is the phase of reflection coefficient. If one of the spaces is LHM, it's clear that α will become negative and therefore the shift will become negative too. Now we suppose here the intensity of the pump light is so high that GaAs can show nonlinear properties. According to the Kerr effect the refractive index of the dielectric is generally related to the intensity of the pump light and third order susceptibility by this relations

$$\varepsilon_r = (n_l + \Delta n)^2 \quad (2)$$

$$\Delta n = \frac{3}{8n_l}\mathrm{Re}(\chi_{xxxx}^{(3)})|E|^2 - \frac{j\alpha_2}{2k_0} \quad (3)$$

$$\alpha_2 = \frac{3k_0}{4n_l}\mathrm{Im}(\chi_{xxxx}^{(3)}), \quad (4)$$

where n_l is the linear refractive index and E is the electric field vector and k_0 is the free space wave vector.

If χ^3 is supposed positive, increasing in E and χ^3 will result in increasing in refractive index. In analyzing nonlinearity effect on Goos-Hanchen shift whenever nonlinear medium is LHM, we assume negative χ^3 for metamaterial as Y. Hu et al. have done the same in [20].

2.2 Third harmonic Goos-Hanchen shift

In this section we suppose the signal light is intense itself so that it can produce third harmonic signal in incident medium which is RHM here.

This is the nonlinear electromagnetic wave equation that can be found in any nonlinear books and papers:

$$\vec{\nabla}\times\vec{\nabla}\times\vec{E} - \frac{\varepsilon_{rl}}{c^2}\omega'^2\vec{E} = \mu_0\omega'^2\vec{P}^{NLS} \quad (5)$$

Here $\vec{P}^{NLS}$ is nonlinear polarization in 3ω frequency which is produced by mixing three waves in ω frequency. $\vec{P}^{NLS}$ acts as a electromagnetic source and makes the electromagnetic wave in 3ω frequency. In this literature we regard only third harmonic generation and therefore we can replace ω' with 3ω in (5). ε_{rl} is the relative permittivity in the linear case, c is the light speed in the free space and μ_0 is free space permeability.

The solution of this equation is in the form of the summation of homogeneous response and inhomogeneous response due to $\vec{P}^{NLS}$ which could be found in [21]

$$\begin{aligned}\overline{E_3^i} &= \hat{e}_3^i\overline{E_3^i}\exp i(\overrightarrow{k_3^i}.\vec{r} - 3\omega t) - \\ &\frac{\mu_0 P_3^{NLS} 9\omega^2}{(k_3^i)^2 - (k^{si})^2}(\hat{p} - \frac{\overline{k^{si}}(\overline{k^{si}}.\hat{p})}{(k_3^i)^2})\exp i(\overrightarrow{k^{si}}.\vec{r} - 3\omega t).\end{aligned} \quad (6)$$

Here $\overrightarrow{E_3^i}$ is the incident electric field vector in 3ω frequency that is composed of two components, one is $\overline{E_3^i}$ with $\overrightarrow{k_3^i}$ wave vector and the other component with $\overrightarrow{k^{si}}$ wave vector because of phase mismatching between $\overrightarrow{k_3^i}$ and $\overrightarrow{k^{si}}$. Also $\hat{p}$ is the incident nonlinear field unit vector, $k^{si} = 3k_1^i = 3(\omega / c)n_1$, $k_3^i = \sqrt{\varepsilon_{rl}^{3\omega}}3\omega / c$

where $\varepsilon_{rl}^{3\omega}$ is the linear relative electric permittivity of the medium in 3ω frequency and $\hat{e}_3^i$ is the direction of $\overline{E_3^i}$.

By using Maxwell equations and according to Fig. 1 we can calculate incident magnetic field vector and reflected and transmitted electric and magnetic field vectors

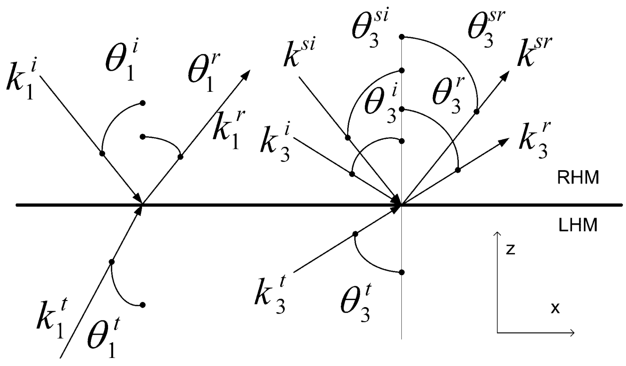

Fig. 1. Reflected and transmitted wave vectors for fundamental (left) and third harmonic (right) frequencies.

$$\overrightarrow{H_3^i} = \frac{1}{3\omega\mu_0}\overline{E_3^i}(\overrightarrow{k_3^i}\times\hat{e}_3^i)\exp i(\overrightarrow{k_3^i}.\vec{r}-3\omega t) - \frac{P_3^{NLS}3\omega}{(k_3^i)^2-(k^{si})^2}(\overrightarrow{k^{si}}\times\hat{p})\exp i(\overrightarrow{k^{si}}.\vec{r}-3\omega t). \quad (7)$$

$$\overrightarrow{E_3^r} = \hat{e}_3^r R\overline{E_3^i}\exp i(\overrightarrow{k_3^{ri}}.\vec{r}-3\omega t) - R\frac{\mu_0 P_3^{NLS}9\omega^2}{(k_3^r)^2-(k^{sr})^2}\left(\hat{p}_r - \frac{\overrightarrow{k^{sr}}(\overrightarrow{k^{sr}}.\hat{p}_r)}{(k_3^r)^2}\right)\exp i(\overrightarrow{k^{sr}}.\vec{r}-3\omega t) \quad (8)$$

$$\overrightarrow{H_3^r} = \frac{1}{3\omega\mu_0}R\overline{E_3^i}(\overrightarrow{k_3^r}\times\hat{e}_3^r)\exp i(\overrightarrow{k_3^r}.\vec{r}-3\omega t) - R\frac{P_3^{NLS}3\omega}{(k_3^r)^2-(k^{sr})^2}(\overrightarrow{k^{sr}}\times\hat{p}_r)\exp i(\overrightarrow{k^{sr}}.\vec{r}-3\omega t) \quad (9)$$

$$\overrightarrow{E_3^t} = \hat{e}_3^t E_3^t \exp(\overrightarrow{k_3^t}.\vec{r}-3\omega t) \quad (10)$$

$$\overrightarrow{H_3^t} = \frac{1}{3\omega\mu_0\mu_{rL}}(\overrightarrow{k_3^t}\times\hat{e}_3^t)E_3^t\exp i(\overrightarrow{k_3^t}.\vec{r}-3\omega t) \quad (11)$$

$\overrightarrow{E_3^r}$ is the reflected electric field vector in 3ω frequency that is composed of $\overline{E_3^r}$ with $\overrightarrow{k_3^r}$ wave vector and the other component with $\overrightarrow{k^{sr}}$ wave vector. $\hat{p}_r$ is the reflection nonlinear polarization unit vector, $k_3^{sr} = k^{si} = 3k_1^i = 3(\omega/c)n_1$, $k_3^r = k_3^i = \sqrt{\varepsilon_{rl}^{3\omega}}3\omega/c$, $\hat{e}_3^r$ is the direction of $\overline{E_3^r}$ and R is the reflection coefficient. Also $\overrightarrow{E_3^t}$ is the refracted electric field vector in 3ω frequency in LHM space, $\overrightarrow{k_3^t}$ is the refracted wave vector in this space and μ_{rL} is the LHM relative permeability.

To find the reflection coefficient we should apply boundary conditions which is the equality of tangential components of electric and magnetic field vectors at z =0 which requires that

$$\omega: \quad k_{1x}^i = k_{1x}^r = k_{1x}^t \quad (12)$$

$$3\omega: \quad 3k_{1x}^i = k_{3x}^{si} = k_{3x}^{sr} = k_{3x}^r = k_{3x}^i = k_{3x}^t \quad (13)$$

and therefore:

$$\theta_3^{si} = \theta_3^{sr} = \theta_1^i \quad (14)$$

$$\sin(\theta_3^i) = \sin(\theta_3^r) = (\sqrt{\varepsilon_{rN}^{\omega}}/\sqrt{\varepsilon_{rN}^{3\omega}})\sin(\theta_1^i) \quad (15)$$

$$\sin(\theta_3^t) = (\sqrt{\varepsilon_{rN}^{\omega}}/\sqrt{\varepsilon_{rL}^{3\omega}\mu_{rL}^{3\omega}})\sin(\theta_1^i). \quad (16)$$

Clearly above relations is independent of polarization.

Here $\varepsilon_{rN}^{\omega}$ is the relative permittivity of the RHM medium in ω frequency, $\varepsilon_{rL}^{3\omega}$ and $\mu_{rL}^{3\omega}$ is the relative permittivity and permeability of the LHM medium in 3ω frequency.

In Fig. 2, we have shown the fields in perpendicular polarization which electric field is in y direction and we have decomposed the incident and reflected tangential magnetic field into two its components according to (7) and (9)

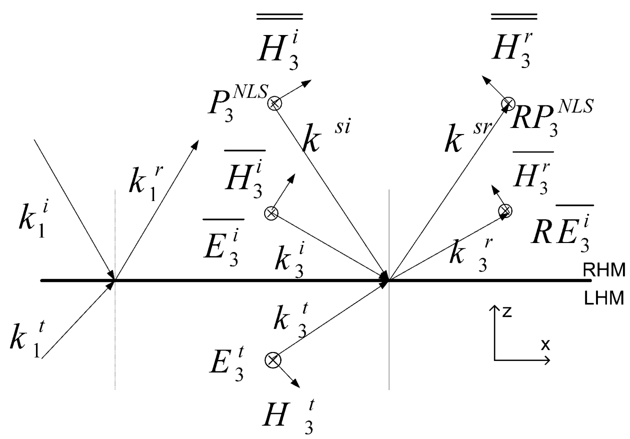

Fig. 2. Reflected and transmitted fields for fundamental (left) and third harmonic (right) frequencies in perpendicular polarization.

$$\vec{H}_3^i = \vec{\bar{H}}_3^i + \vec{\bar{\bar{H}}}_3^i \qquad (17)$$

$$\vec{H}_3^r = \vec{\bar{H}}_3^r + \vec{\bar{\bar{H}}}_3^r . \qquad (18)$$

By using boundary conditions for this polarization after some mathematical manipulation we can find reflection coefficient

$$R = (W - U)/(W + U) \qquad (19)$$

where

$$U = \frac{k_3^t \cos(\theta_3^t)}{3\omega\mu_0\mu_{rL}}\left(\overline{E_3^i} - \frac{\mu_0 P_3^{NLS} 9\omega^2}{(k_3)^2 - (k_s)^2}\right) \qquad (20)$$

$$W = \frac{k_3 \cos(\theta_3)}{3\omega\mu_0}\overline{E_3^i} - \frac{P_3^{NLS} 3\omega k^s}{(k_3)^2 - (k_s)^2}\cos(\theta^s) . \qquad (21)$$

which $k_3 = k_3^r = k_3^i$, $k^s = k_3^{si} = k_3^{sr} = 3k_1$ and $\theta^s = \theta^{si} = \theta^{sr}$ and $\theta_3 = \theta_3^r = \theta_3^i$.

Fig. 3, shows the fields in parallel polarization. Here we suppose the magnetic field does not undergo polarization change after reflection. If we change the reflected magnetic field polarization into the opposite direction, the phase of reflection coefficient just will shift π radian and the Goos-Hancken shift will not change.

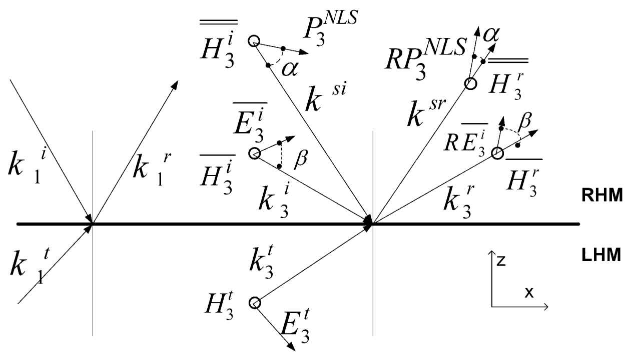

Fig. 3. Reflected and transmitted fields for fundamental (left) and third harmonic (right) frequencies in parallel polarization.

Like the perpendicular case by applying boundary conditions we can obtain reflection coefficient for parallel polarization

$$R = W/U \qquad (22)$$

$$U = \frac{k_3}{3\omega\mu_0}\overline{E_3^i}\sin(\beta) - \frac{P_3^{NLS} 3\omega k^s}{(k_3)^2 - (k^s)^2}\sin(\alpha) + \frac{k_3^t \sin(\theta_3 - \beta)}{3\omega\mu_0\mu_{rL}\cos(\theta_3^t)}\overline{E_3^i} + \frac{k_3^t P_3^{NLS} 3\omega}{(k_3)^2 - (k^s)^2}\frac{\sin(\theta^s - \alpha)}{\mu_{rL}\cos(\theta_3^t)} - \frac{k_3^t P_3^{NLS} 3\omega}{(k_3)^2 - (k^s)^2}\frac{(k^s)^2}{(k_3)^2}\frac{\cos(\alpha)\sin(\theta^s)}{\mu_{rL}\cos(\theta_3^t)} \qquad (23)$$

$$W = \frac{k_3^t \sin(\theta_3 + \beta)}{3\omega\mu_0\mu_{rL}\cos(\theta_3^t)}\overline{E_3^i} - \frac{k_3^t P_3^{NLS} 3\omega}{(k_3)^2 - (k^s)^2}\frac{\sin(\theta^s + \alpha)}{\mu_{rL}\cos(\theta_3^t)} + \frac{k_3^t P_3^{NLS} 3\omega}{(k_3)^2 - (k^s)^2}\frac{(k^s)^2}{(k_3)^2}\frac{\cos(\alpha)\sin(\theta^s)}{\mu_{rL}\cos(\theta_3^t)} - \frac{k_3 \sin(\beta)}{3\omega\mu_0}\overline{E_3^i} + \frac{P_3^{NLS} 3\omega k^s}{(k_3)^2 - (k^s)^2}\sin(\alpha) \qquad (24)$$

After these calculations the only undefined parameters in reflection relations (19) and (22) are $\overline{E_3^i}$ and P_3^{NLS} which could be found from coupled wave equations just like the method in [22].

For cubic crystals that belong to $\bar{4}3m$ symmetry group such as GaAs in perpendicular polarization like here which E is in the y direction, we can write P_3^{NLS} as

$$\overline{P_3^{NLS}} = \hat{a}_y \varepsilon_0 \chi_{yyyy}^3 E_1 E_1 E_1 \exp i[3(k_{1x}x + k_{1z}z) - 3\omega t] \qquad (25)$$

After solving nonlinear wave equation and by use of the slowly-varying amplitude approximation rule, which slowly varying amplitude is a function of both x and z because of oblique propagating wave in nonlinear medium, we can write coupled wave equations such as the following relations

$$2i\left(k_{3x}\frac{\partial \overline{E_3^i}}{\partial x} + k_{3z}\frac{\partial \overline{E_3^i}}{\partial z}\right) = -\mu_0\varepsilon_0 9\omega^2 \chi_{yyyy}^3 (E_1)^3 \times \exp i[(3k_{1x} - k_{3x})x + (3k_{1z} - k_{3z})z] \qquad (26)$$

$$2i\left(k_{1x}\frac{\partial E_1}{\partial x} + k_{1z}\frac{\partial E_1}{\partial z}\right) = -3\mu_0\varepsilon_0\omega^2 \chi_{yyyy}^3 E_1 E_1^* E_1 \qquad (27)$$

Here E_1 is the amplitude of the incident field at ω frequency. We neglect the variation of the E_1 wave and just solve (26).

By solving (26) we obtain

$$\overline{E_3^i} = \gamma\left\{\frac{\exp i(\Delta k_x x + \Delta k_z z)}{i(\Delta k_x + a\Delta k_z)} - \frac{\exp i[\Delta k_x x_0 + \Delta k_z (z - ax + ax_0)]}{i(\Delta k_x + a\Delta k_z)}\right\} + \varphi(z - ax) \qquad (28)$$

where $a = k_{3z}/k_{3x}$, $\gamma = -\mu_0\varepsilon_0 9\omega^2 \chi_{yyyy}^3 E_1^3 / 2ik_{3x}$, $\Delta k_z = 3k_{1z} - k_{3z}$ and $\Delta k_x = 3k_{1x} - k_{3x}$. Also φ is an arbitrary function which is selected from initial conditions. We suppose that there is no $\overline{E_3^i}$ wave in initial point (x_0, z_0) and take φ as zero.

For parallel polarization we can find P_3^{NLS} in the same manner

$$P_{3x} = \varepsilon_0 E_{1z} E_{1z} E_{1x} (\chi^3_{yyzz} + \chi^3_{yzyz} + \chi^3_{yzzy}) + \varepsilon_0 E_{1x} E_{1x} E_{1x} \chi^3_{yyyy} \quad (29)$$

$$P_{3z} = \varepsilon_0 E_{1x} E_{1x} E_{1z} (\chi^3_{yyzz} + \chi^3_{yzyz} + \chi^3_{yzzy}) + \varepsilon_0 E_{1z} E_{1z} E_{1z} \chi^3_{yyyy} \quad (30)$$

After some calculations like for perpendicular polarization and neglecting the variation of E_1, one can find similar equations for both $\overline{E^i_{3x}}$ and $\overline{E^i_{3z}}$ just like (26). These equations could be solved in the same manner for perpendicular polarization. Finally we can get Goos-Hanchen lateral shift by taking derivation of the phase of reflection coefficient with respect to the tangential component of the wave vector.

3. Results and discussion

In all of the simulations we use Sellmayer equation for GaAs refractive index and [7] for metamaterial refrarctive index. We show only perpendicular polarization results here. The same results from qualitative point of view are obtained for parallel polarization.

First we calculate the shift in main harmony where RHM is GaAs and LHM is metamaterial in [7]. Incident medium is GaAs here. Fig. 4-left shows negative shift for linear (thin line) and nonlinear (thick line) case in fundamental frequency. We see that in nonlinear case as the result of increasing first medium refractive index and optical density, the confinement factor of the structure also increases therefore the wave can not leak further into the LHM so the shift is reduced. The wavelength of calculation is $\lambda = 1.410\mu$ where LHM shows $\varepsilon_{rL} = -1 - 0.3i$ and $\mu_{rL} = -1 - 0.3i$. The refractive index of GaAs in this wavelength is 3.3919. We suppose typical value χ^3 = 1.4×10^{-22} $-1.4\times10^{-24} i\ m^2/V^2$ at $E = 3\times10^{11} V/m$ for GaAs. In Fig. 4-right we only neglect the losses.

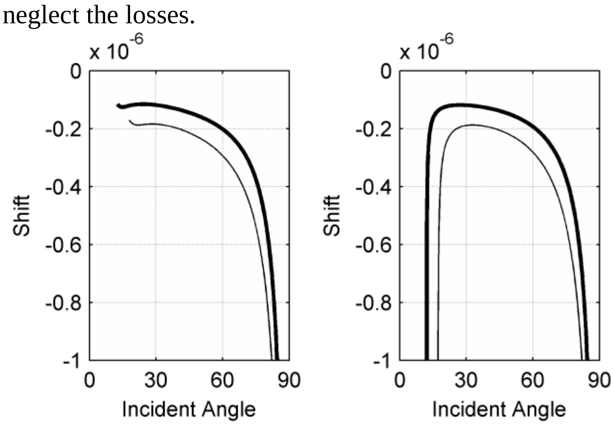

Fig. 4. Goos-Hanchen shifts versus incident angle in ω frequency when incident medium is GaAs and the second medium is metamaterial in [7] for linear (thin line) and nonlinear (thick line) cases and for Right- lossless case and Left- Lossy case.

In third harmonic case in same structure, nonlinearity variation don't change Goos-Hanchen shift (Fig. 5). We inferred that intense light can not produce ninth harmony for main harmony or on the other words the light is not intense enough to produce third harmonic signal for 3ω frequency signal therefore there is no variation for third harmony refractive index hence the shift remains unchanged. The wavelength of fundamental frequency is $\lambda = 3\times1.410\mu$, therefore metamaterial shows above characteristics in third harmony case. GaAs refractive index in ω and 3ω is 3.3241 and 3.3119, respectively.

We take $\chi^3 = 1.4\times10^{-22} + i10^{-24}\ \ m^2/V^2$ at $E =\ 3\times10^{11} V/m$ (continous line) and $\chi^3 = 1.4\times10^{-25} + i10^{-27}\ \ m^2/V^2$ at $E = 3\times10^{8} V/m$ (dashed line) for GaAs.

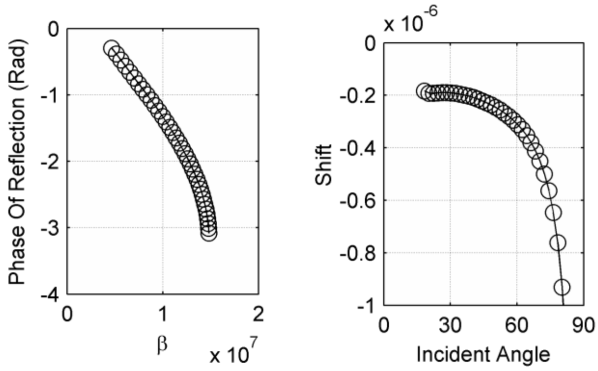

Fig. 5. Right- Goos-Hanchen shifts versus incident angle and Left- Phase of reflection versus tangential component of wave vector, in 3ω frequency when incident medium is GaAs and the second medium is metamaterial in [7] for large nonlinearity (circular line) and small nonlinearity (continous line) cases.

Now we simulate the case that first medium is metamaterial and second medium is free space. We analyze only main harmony case here because as we described before, there is no third harmonic wave in this case. We take $\lambda = 1.425\mu$ which metamaterial shows $\varepsilon_{rL} = -1.5 - 0.1i$ and $\mu_{rL} = -1.4 - i$. First we neglect the metamaterial losses and suppose $\chi^3 = -1.4\times10^{-23} - i10^{-25} m^2/V^2$ at $E = 3\times10^{11} V/m$. We see from Fig. 6, the lateral shift increases with nonlinearity (dashed line) because of negative χ^3 and consequently decreases with the metamaterial refractive index and structure confinement factor.

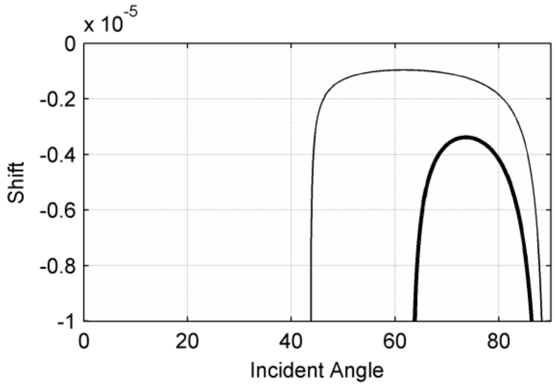

Fig. 6. Goos-Hanchen shifts versus incident angle in ω frequency when incident medium is metamaterial in [7] and the second medium is GaAs for linear (thin line) and small nonlinearity (thick line) cases and by neglecting losses in metamaterial.

For the same structure we change only nonlinearity and take $\chi^3 = -1.4\times10^{-22} - i10^{-24} m^2/V^2$ and again neglect metamaterial losses. We see that by increasing in nonlinearity positive shift could be obtained (Fig. 7).

We should say that although we increase nonlinearity and light intensity but on the other hand losses term in nonlinearity also have been increased and in fact this increasing of losses have caused positive Goos-Hanchen shift. However we can conclude that we are able to switch between RH and LH properties by changing nonlinearity.

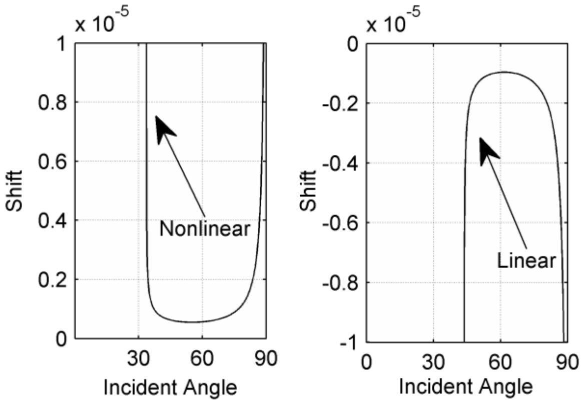

Fig. 7. Goos-Hanchen shifts versus incident angle in ω frequency when incident medium is metamaterial in [7] and the second medium is GaAs, for Right- linear, and Left- large nonlinearity cases and by neglecting losses for metamaterial.

On the other hand we simulate also the same structure in Fig. 6, by regarding losses for metamaterial and see that increasing in amount of losses can decrease the negative shift or even change the negative shift into positive one (Fig. 8) as we saw in previous case. It can be said that losses in LHM vanish the LHM behavior of metamaterial and change it into RHM somewhat. According to Fig. 8 we can conclude that we can adjust and control the shift by using of two parameters of nonlinearity and incident angle of light.

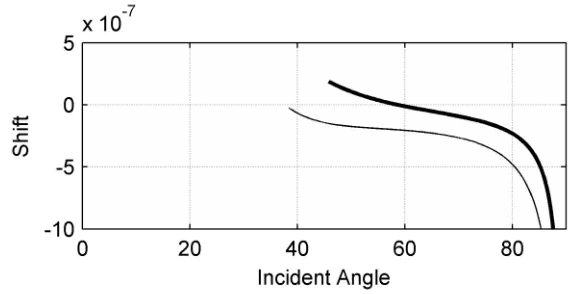

Fig. 8. Goos-Hanchen shifts versus incident angle in ω frequency when incident medium is Metamaterial in [7] and the second medium is GaAs for linear (thin line) and small nonlinearity (thick line) cases and by considering losses for metamaterial.

Ultimately for comparison between RHM-LHM shift and RHM-RHM or LHM-LHM shift we analyze the case which first medium is GaAs and the second medium is free space. We take the wavelength and structure like first case in Figs. 5 and 6 for main and third harmonic frequencies respectively with only this difference that we consider free space as the second medium in stead of LHM. We show the results only for main frequency in Fig. 9 where we see qualitatively there is no difference between them except that the the shift have became positive here. The same result like Fig. 5 could be obtained qualitatively for third harmonic frequency except positive shifts in this case.

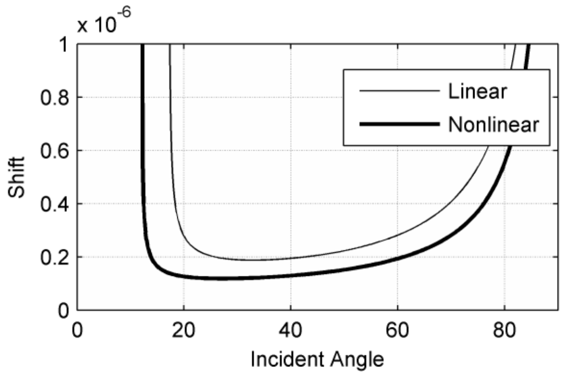

Fig. 9. Goos-Hanchen shifts versus incident angle in ω frequency when incident medium is GaAs and the second medium is free space.

3. Conclusions

We analytically solved nonlinear wave equation for the structure composed of two semi-infinite RHM and LHM both for main harmony and third harmony. For main harmony we showed that Goos-Hanchen shift increases when RHM is incident medium which has positive χ^3 and decreases when LHM is incident medium which we suppose it has negative χ^3 and in this case we showed how increasing in nonlinearity and LHM losses can result in decrease in Goos-Hanchen shift and even can change the sighn of the shift bye controlling light intensity losses and incident angle of light which can be used for All optically switching between RH and LH properties. Also we showed in third harmonic nothing happens in Goos-Hanchen shift by changing in nonlinearity. These effects may be useful in optical switching and processing applications such as negative Goos-Hanchen shift based memories in future and in metamaterial based sensors.

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