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TUNABLE LATERAL SHIFT THROUGH NONLINEAR COMPOSITES OF NONSPHERICAL PARTICLES

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Abstract—The Goos-Hänchen (GH) shifts of the reflected waves from nonlinear nanocomposites of interleaved nonspherical metal and dielectric particles are investigated both theoretically and numerically. First, based on spectral representation theory and effective medium approximation, we derive the field-dependent effective permittivity of nonlinear composites. Then, the stationary phase method is adopted to study the GH shifts from nonlinear composites. It is found that for a given volume fraction, there exist two critical polarization factors L_{c1} and L_{c2}, and bistable GH shifts appear only when $L < L_{c1}$ or $L > L_{c2}$. Moreover, both giant negative and positive GH shifts accompanied with large reflectivity are found, hence they can be easily observed in experiments. The reversal of the GH shift may be controlled by adjusting both the incident angle and the applied field. Numerical simulations for Gaussian-type incident beam are performed, and good agreement between simulated data and theoretical ones is found especially for large waist width.

1. INTRODUCTION

Goos-Hänchen (GH) effect, which refers to the lateral shift deviated from the position predicted by geometrical optics when a light beam is totally reflected at a dielectric interface [1, 2], has received much attention because of its potential applications in the design of optical devices such as optical waveguide switch [3], optical sensors [4], etc. This phenomenon was theoretically explained by Artmann using stationary phase method [5], and was observed in

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experiments [6, 7]. In the past, the GH shifts were mainly associated with the total reflection, and later they were also predicted in partial reflection [8–10]. In fact, large positive or negative GH shifts for both reflected and transmitted beams were found for oblique incidence in different media or structures such as dielectric slabs [11, 12], metal surfaces [13, 14], chiral materials [15–17], multilayered structures [18], photonic crystals [19, 20], and negative refractive materials [21–23]. More recently, lateral shift of a normally incident beam reflected from an antiferromagnet was predicted [24].

On the other hand, the realization of the tunable lateral shift or the manipulation of the spatial beam position in a fixed configuration were proposed. For instance, tunable refraction and reflection of self-confined light beams at the interface between two regions of a nematic liquid crystal were reported, and large nonlinear GH lateral shifts were demonstrated [25]. Kerr-type nonlinear layers were introduced in the one-dimensional photonic crystal and Kretschmann configuration to control the bistable lateral shift [26, 27]. Wang et al. [28] proposed the manipulation of the GH shift by a coherent control field. Later, electric control of the lateral shifts for the reflected and transmitted beams was realized due to the electro-optic effects [29, 30]. Chen et al. reported the possibility of constructing an optical sensor for temperature monitoring based on the Goos-Hänchen effect [4].

In this paper, we shall study a tunable Goos-Hänchen shift of the reflected wave from nonlinear metal-dielectric composites. Both metal and dielectric nanoparticles are assumed to be spheroidal in shape and randomly distributed. For simplicity, we further assume that the nanoparticles are identically aligned with the principal axis parallel to x-axis [see Fig. 1]. Similar to the treatment in [31, 32], the nonlinear composites can be regarded as a homogeneous effective material with field-dependent effective permittivity. Therefore, through the adjustment of the applied field, particles' shape and volume fraction, it is possible to change the field-dependent effective permittivity. As a consequence, one can further control the lateral shift of the light beam reflected from nonlinear nanocomposites.

The paper is organized as follows. In Section 2, we first adopt spectral representation approach [33–35] and effective medium approximation [36] to calculate effective field-dependent permittivity of nonlinear composites. Then, we obtain the lateral shift according to the stationary-phase approach [5]. Theoretical calculations and numerical simulations for the lateral shifts are, respectively, presented in Sections 3 and 4. Our conclusions and discussions are summarized in Section 5.

2. FORMALISM

Let's assume a transverse-magnetic (TM) polarized wave beam with incident angle θ from vacuum upon a nonlinear two-phase composite (see Fig. 1), in which nonlinear metal ellipsoidal particles with volume fraction p and linear dielectric ellipsoidal particles with volume fraction $1-p$ and permittivity ε_2 are randomly dispersed but identically aligned with each other. The metal particles have the nonlinear displacement-electric field relation with the form [37]

$$\mathbf{D}_1 = \left(\varepsilon_1 + \chi_1|\mathbf{E}_1|^2\right)\mathbf{E}_1, \tag{1}$$

where ε_1 is the linear permittivity of metal components while χ_1 is the third-order nonlinear susceptibility. Here we consider the Goos-Hänchen shift D of the incident wave reflected from the vacuum-composite interface. In this connection, we would like to take two steps to obtain the lateral shift of the reflected beam from nonlinear composites.

First, we calculate effective field-dependent permittivity of the nonlinear composite. In this regard, we indicate that the characteristic particle size is far less than the incident wavelength, and the quasi-static approximation is valid. Moreover, we assume that the dielectric particles and metal particles are uniaxial ellipsoids with the shape characterized by the depolarization factor L along x axis. In this notation, a sphere has $L = 1/3$, while a needlelike particle has $L \to 0$, and a platelike particle has $L \to 1$ [32].

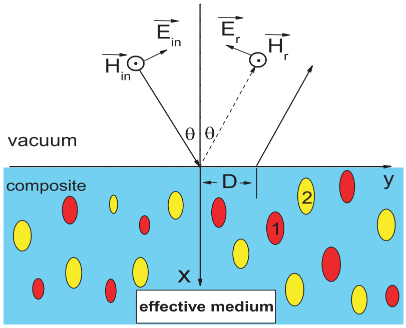

Figure 1. Geometry indicating GH shift of reected wave from vacuum-composite surface. The composite material consists of nonlinear metal particles (the red ones marked 1) and dielectric particles (the yellow ones marked 2). The dashed line is the path of reflection predicted from geometrical optics.

When the nonlinearity is not taken into account, the effective linear permittivity of the composite material can be derived within effective medium approximation [38],

$$p\frac{\varepsilon_1-\varepsilon_e}{\varepsilon_e+L(\varepsilon_1-\varepsilon_e)}+(1-p)\frac{\varepsilon_2-\varepsilon_e}{\varepsilon_e+L(\varepsilon_2-\varepsilon_e)}=0. \quad (2)$$

Eq. (2) admits the solution,

$$\frac{\varepsilon_e}{\varepsilon_2}=\frac{1}{2(1-L)}\left[1-2L+\frac{L-p}{s}\pm\frac{\sqrt{s^2-2(p+L-2pL)s+(L-p)^2}}{s}\right], \quad (3)$$

where $s\equiv\varepsilon_2/(\varepsilon_2-\varepsilon_1)$.

With spectral representation theory [33], ε_e can be written as

$$\varepsilon_e=\varepsilon_2\left[1-\int\frac{m(x)}{s-x}dx\right], \quad (4)$$

where the spectral density function $m(x)$ is defined as

$$m\left(x\right)=\frac{1}{\pi}\lim_{\delta\to0^+}\mathrm{Im}\left[\frac{\varepsilon_e}{\varepsilon_2}(s=x+i\delta)\right]. \quad (5)$$

Substituting Eq. (3) into Eq. (5), we have [38]

$$m\left(x\right)=\frac{p-L}{1-L}\theta(p-L)\delta(x)+\begin{cases}\frac{\sqrt{(x-x_1)(x_2-x)}}{2\pi x(1-L)}, & \text{if} \quad x_1<x<x_2\\ 0, & \text{otherwise,}\end{cases}, \quad (6)$$

where $\theta\left(p-L\right)$ is the step function, and

$$x_{1,2}\equiv p+L-2pL\pm\sqrt{\left(p+L-2pL\right)^2-\left(p-L\right)^2}. \quad (7)$$

Here we would like to mention that for present microstructures, the spectral density function includes two parts [see Eq. (6)]. The first part is δ function at $x=0$ with weight $(p-L)/(1-L)$ for $p>L$. Physically, this reflects the fact that effective medium approximation has the percolation threshold $p_c=L$. The second part denotes the continuous spectrum.

For nonlinear composites, since the local field in nonlinear metal components cannot be solved exactly, we shall use mean-field approximation [35] to estimate the field-dependent permittivity of metal,

$$\tilde{\varepsilon}_1\approx\varepsilon_1+\chi_1\langle|\mathbf{E}|^2\rangle_1, \quad (8)$$

where $\langle|\mathbf{E}|^2\rangle_1$ is the spatial average of the local field squared inside the nonlinear metal component and is expressed as [33, 34],

$$\left\langle|\mathbf{E}|^2\right\rangle_1=\frac{|\mathbf{E}_0|^2}{p}\int\left|\frac{\tilde{s}}{\tilde{s}-x}\right|^2m(x)dx, \quad (9)$$

with $\tilde{s} \equiv \varepsilon_2/(\varepsilon_2 - \tilde{\varepsilon}_1)$.

As $\tilde{s}$ is dependent on $\langle|\mathbf{E}|^2\rangle_1$, Eq. (8) is a self-consistent equation for $\langle|\mathbf{E}|^2\rangle_1$ and can be solved, at least numerically. Then, the effective field-dependent permittivity $\tilde{\varepsilon}_e$ is determined by

$$p\frac{\tilde{\varepsilon}_1 - \tilde{\varepsilon}_e}{\tilde{\varepsilon}_e + L(\tilde{\varepsilon}_1 - \tilde{\varepsilon}_e)} + (1-p)\frac{\varepsilon_2 - \tilde{\varepsilon}_e}{\tilde{\varepsilon}_e + L(\varepsilon_2 - \tilde{\varepsilon}_e)} = 0. \tag{10}$$

In the second step, we adopt the standard Fresnel formula to derive the reflection coefficient R for the incident angle θ [8] at the interface between vacuum and nonlinear composite, that is,

$$R(\theta) = |R|e^{i\delta} = \frac{\tilde{\varepsilon}_e \cos\theta - \sqrt{\tilde{\varepsilon}_e - \sin^2\theta}}{\tilde{\varepsilon}_e \cos\theta + \sqrt{\tilde{\varepsilon}_e - \sin^2\theta}}, \tag{11}$$

where the corresponding phase $\delta(\theta)$ is written as,

$$\delta(\theta) = \mathrm{Im}\left\{\ln\left[\frac{\tilde{\varepsilon}_e \cos\theta - \sqrt{\tilde{\varepsilon}_e - \sin^2\theta}}{\tilde{\varepsilon}_e \cos\theta + \sqrt{\tilde{\varepsilon}_e - \sin^2\theta}}\right]\right\}. \tag{12}$$

Once the phase is given, one can apply the stationary-phase method to derive the generalized expression for GH shift D [5],

$$D = -\frac{\lambda}{2\pi\cos\theta}\frac{d\delta(\theta)}{d\theta}, \tag{13}$$

where λ is the incident wavelength.

3. THEORETICAL CALCULATIONS

We are now in a position to perform numerical calculations on GH shift of the reflected waves from the interface between vacuum and the nonlinear composites containing metal and dielectric particles. For simplicity, metal component is assumed to be silver, whose permittivity is $\varepsilon_1 = -7.1 + 0.22i$ (at the wavelength $\lambda \approx 450\,\mathrm{nm}$), and nonlinear susceptibility is $\chi_1 = 10^{-8}$esu. In addition, the permittivity of the linear dielectric component is $\varepsilon_2 = 2.0$ [35]. Actually, the metal/dielectric nonlinear composites have been created by means of conventional melt and heat-treatment processes for several decades [39, 40].

Figure 2 illustrates the GH shifts as a function of the applied field E_0 for different volume fraction p and different depolarization factor L. We find that for given p and θ, the optical bistable behavior occurs only when L is smaller than one critical value L_{c1} or larger than the other critical value L_{c2}. In other words, optical bistable behavior cannot be observed when L is in the range from L_{c1} to L_{c2}. For instance, L_{c1} is

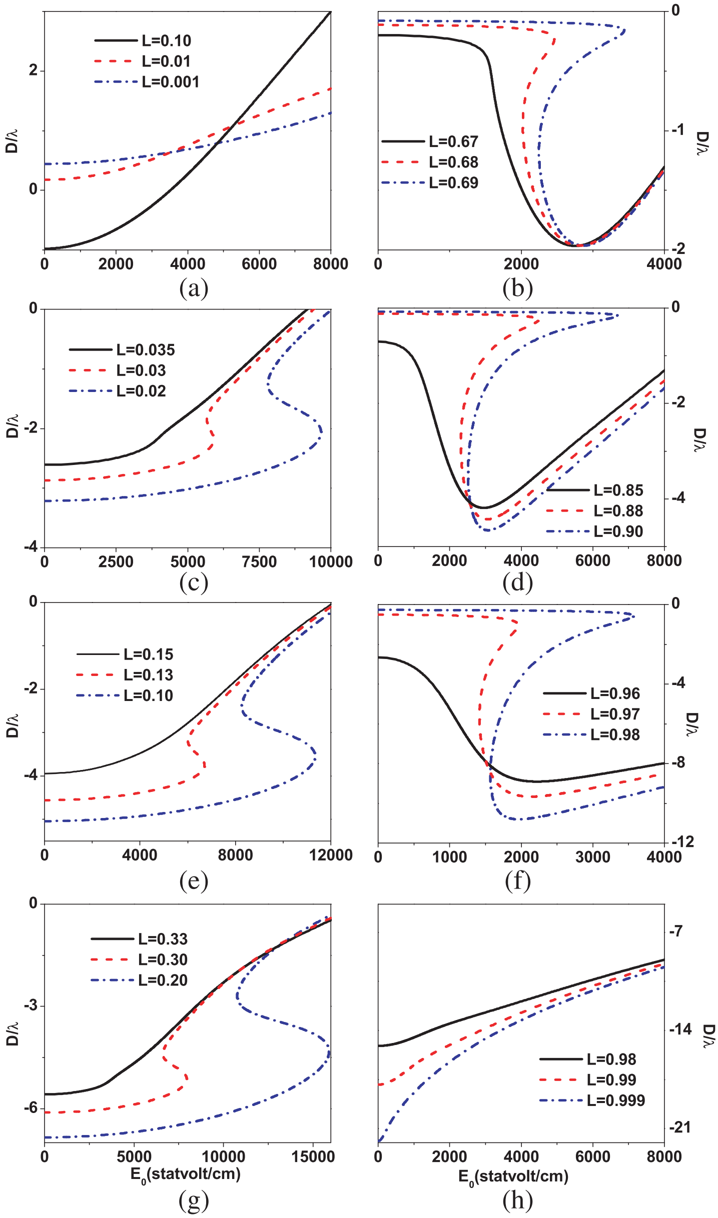

Figure 2. GH shift (in unit of λ) as a function of E_0 for $\theta = 85°$ and for different volume fractions: $p = 0.2$ for (a) and (b); $p = 0.4$ for (c) and (d); $p = 0.6$ for (e) and (f); $p = 0.8$ for (g) and (h).

0.015, and L_{c2} is 0.96 for $p = 0.6$ [see Figs. 2(e) and 2(f)]. This can be well understood if one carefully checks the spectral density function $m(x)$. Actually, since the first part in Eq. (6) is δ-type function with the pole $x = 0$, it does not contribute to the bistable behavior. And the continuous spectrum described by the second part of Eq. (6) tends to be a δ-like function at $x = 0$ too. As a consequence, no optical bistability (OB) appears. For $p > L$ [see the left column in Fig. (2)], it is evident that both the upper and lower threshold fields are strongly dependent on L, and their values are relatively larger than those for $p > L$ [see the right column in Fig. (2)]. Actually, for $p > L$, the metal particles are easily grouped into clusters, and form the connected path through the whole composites due to some connected clusters. Therefore, the local fields in the metal components are averaged out, and to realize the bistable GH shift, one must apply the relatively large field. On the contrary, for $p < L$, the probability that metal particles form the clusters is low, and most of metal particles are isolated. Such behavior is helpful to enhance the local fields due to surface plasmon resonances even for small applied field. Therefore, the threshold applied field is relatively small to realize the optical GH shift. In addition, we note that the GH shift can be greatly enhanced when the applied field decreases from the magnitude larger than the upper threshold field and reaches the negative maximum near the down-switch threshold field [see Figs. 2(b), 2(d), and 2(f)].

Figure 3 shows the dependence of the lateral shift on the external electric field. Figs. 3(a) and 3(b) are typical hysteretic curves that have been reported in some papers [26, 27]. From S-shaped bistable curve [see Fig. 3(a)], we can see that the lateral shift increases with the increase of the external field E_0 and discontinuously jumps to the upper branch when the external field reaches upper threshold field $E_{0,upper}$ (about 11340 statvolt/cm). However, when E_0 is reduced to a value larger than $E_{0,upper}$, the lateral shift does not jump back to the lower branch, but continues to decease until E_0 reaches the lower threshold field $E_{0,lower}$ (about 8266 statvolt/cm) and then jumps back to the lower branch. Fig. 3(b) is a Z-shaped curve which is different from Fig. 3(a) for S-shaped curve. These typical curves are distinctive properties of OB of GH shift for nonlinear nanocomposites. We further find that bistable GH shift crosses itself in some microstructures, as shown in Fig. 3(c). This anomalous phenomenon is rarely reported in previous papers [41]. In detail, the curve jumps to the upper branch at the upper threshold field $E_{0,upper}$ (about 8558 statvolt/cm) when E_0 increases from a low value. And the discontinuous jump of the lateral shift occurs when E_0 decreases from a high value to the lower-switch threshold $E_{0,lower}$ (about 2870 statvolt/cm). Note that although large

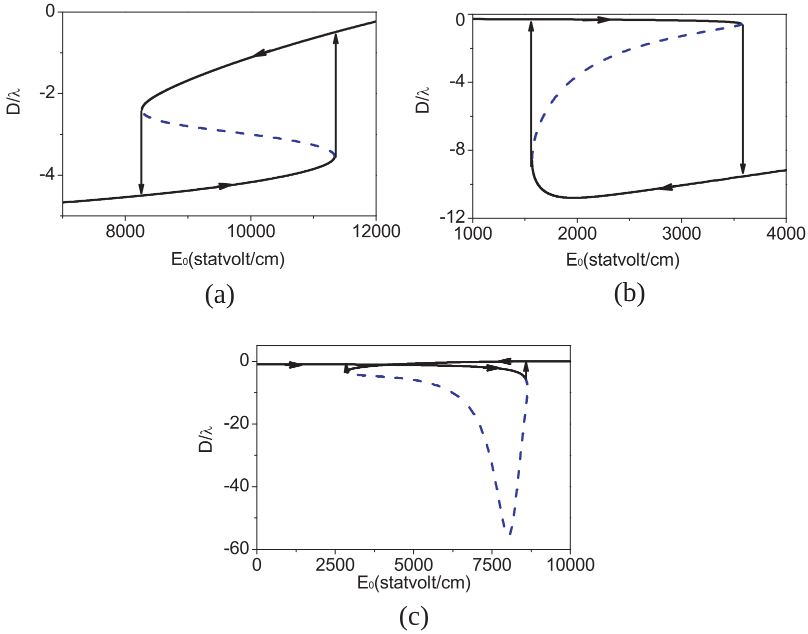

Figure 3. Dependence of the lateral shift (in units of λ) on the external applied field for TM waves. The relevant parameters are chosen to be: $p = 0.6$, $L = 0.10$, and $\theta = 85°$ for (a), $p = 0.6$, $L = 0.98$, and $\theta = 85°$ for (b), and $p = 0.2$, $L = 0.75$, and $\theta = 63°$ for (c). The dashed line represents the unsteady state.

negative lateral shifts exist, they are in unsteady state and cannot be observed in experiments.

In Fig. 4, we show the phase diagram for the OB in p-L plot. It is evident that there is a non-OB area between L_{c1} and L_{c2}, and L_{c1} and L_{c2} increase monotonously with the increase of the volume fraction p. According to our calculations, for a given p and $L < L_{c1}$, the optical bistable curves are generally S-shaped curves, and the OB region is found to be enlarged with the decrease of L. However, for $L > L_{c2}$, the hysteresis curves are Z-shaped curves, and the greater L is, the larger the bistable region becomes. We should mention that for small p such as $p < 0.3$, only upper OB region exists, while for large $p > 0.75$, only lower OB region exists.

From the discussions above, we find that the giant negative GH shift may be realized especially near the lower-threshold field in Z-type bistable region (for instance, $D \sim -10\lambda$ as seen from Fig. 2(f)). In what follows, we would like to show that for such a kind of nonlinear composites at large applied field $E_0 \approx 1.5 \times 10^4$statvolt/cm,

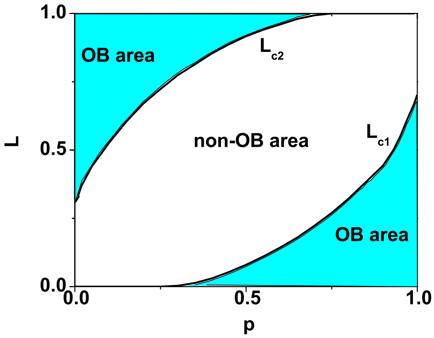

Figure 4. Phase diagram between OB and non-OB region in p-L plot for $\theta = 85°$. Note that L_{c1} and L_{c2} divide the picture into three parts.

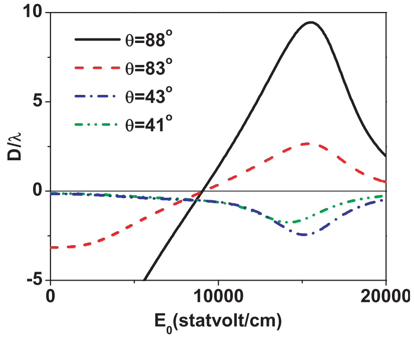

Figure 5. GH shift as a function of E_0 for $p = 0.4$ and $L = 0.7$.

the GH shift may be even giant positive ($D \sim 10\lambda$) at angles most closed to grazing incidence, as shown in Fig. 5. In addition, we observe that the lateral shift can be tuned from negative to positive through the suitable adjustment of the incident angle. As a matter of fact, for $E_0 \approx 1.5 \times 10^4$ statvolt/cm, there is a critical angle of total reflection $\theta_c = \arcsin n \approx 75.4°$, where the refractive index of the complex medium $n = \mathrm{Re}(\sqrt{\tilde{\varepsilon}_e})$ [42], i.e., n, is the real part of $\sqrt{\tilde{\varepsilon}_e}$. When the incident angle is greater than θ_c, the total reflection occurs, and the GH shift is positive which is usually modified by the presence of absorption. On the contrary, the GH shift is negative for $\theta < \theta_c$, and the shift reaches negative maximum at the Brewster angle, which is defined as $\theta_B = \arctan n \approx 44.1°$. Moreover, we note that the reversal of the GH shift from negative to positive values can also be realized by the variation of the applied field.

4. NUMERICAL SIMULATIONS

In the end, we perform numerical simulations of the Gaussian-shaped incident beam to demonstrate the validity of the above stationary-phase method. The incident Gaussian beam has the following Fourier integral [12],

$$\psi_{in}(x, y)|_{x=0} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} A(k_y) \exp(ik_y y) dk_y, \qquad (14)$$

where $A(k_y) = w_y \exp[-(w_y^2/2)(k_y - k_{y0})^2]$ is the Fourier spectrum of the incident beam with $k_{y0} = k_0 \sin\theta$, and $w_y = w_0 \sec\theta$ (w_0 is the waist width of Gaussian beam). Consequently, the field of reflected beam can be written as

$$\psi_r(x, y)|_{x=0} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} R(k_y)A(k_y) \exp(ik_y y)dk_y, \qquad (15)$$

where $R(k_y)$ represents the reflection coefficient, which can be derived as a function of k_y from Eq. (11). For realistic calculations, it is enough to perform the integration from $-k_0$ to k_0. The calculated lateral shift of reflected beam is the value of y where the corresponding field achieves the maximum [12].

We compare the theoretical results with numerical ones for the bistable lateral shift in Fig 6. The waist widths of Gaussian beam are chosen to be 10λ and 20λ. As shown in Fig. 6, the numerical results are in good agreement with the theoretical ones from the stationary phase method, especially when the width of the beam is wide enough. The discrepancy between numerical and theoretical results is due to the distortion of the reflected beam which can be eliminated by enlarging the waist width. Actually, the wider the incident beam is, the closer the numerical results are to the theoretical ones. Further numerical simulations show that the numerical results are almost the same as the theoretical ones when the waist width is 30λ or even larger.

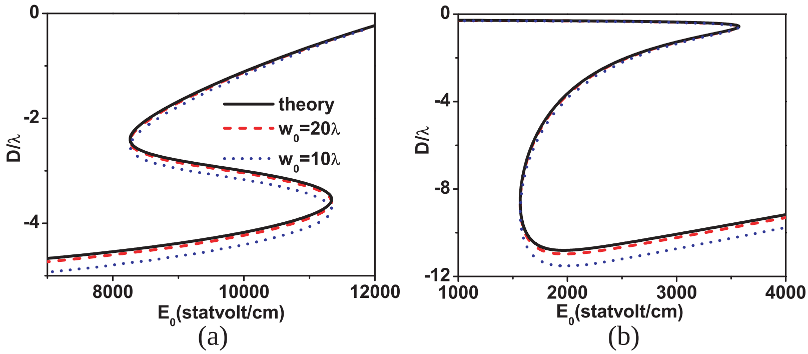

Figure 6. Bistable GH shifts based on the theory and the numerical simulations for $\theta = 85°$. Other parameters are $p = 0.6$ and $L = 0.10$ for (a); $p = 0.6$ and $L = 0.98$ for (b).

5. CONCLUSION AND DISCUSSION

In this paper, we have studied negative and positive GH shifts of reflected waves from the nonlinear composites of nonspherical particles both theoretically and numerically. We adopt spectral representation theory and generalized effective medium approximation to derive the effective field-dependent permittivity of the nonlinear composites. Then, stationary phase method is used to investigate the GH shifts of the reflected wave from the interface between vacuum and nonlinear composite. For a given volume fraction, we predict that there are two critical polarization factors L_{c1} and L_{c2}, and bistable GH shift vanishes when $L_{c1} < L < L_{c2}$. Moreover, giant negative bistable shift is found near the lower threshold field when the applied field larger than the upper threshold field decreases. In addition, the transition from negative GH shift to positive shift takes place by tuning the incident angle or the applied field, and giant positive GH shift is predicted at almost grazing incidence. Numerical simulations confirm our theoretical analysis well, especially when the width of the Gaussian wave is large enough.

Some comments are in order. We would like to point out the observability of bistable GH shift. The magnitude of the reflectivity $|R|^2$ in the bistable region is about $0.3 \sim 0.9$. And the magnitude of the reflectivity for giant positive GH shift is found to be $0.8 \sim 0.9$ for $\theta = 88^\circ$. Therefore, the GH shift reported here should be relatively easy to be observed compared to those discussed previously in [10, 43]. Although our analysis has been performed in the case that the metal particles are nonlinear, it can be generalized to the nonlinear composites in which both metal and dielectric components are nonlinear. In this connection, more complicated bistable GH shift may be predicted. We believe that the nonlinear GH effect could have potential applications for designing new type optical devices such as bistable switches, optical sensors, etc. [25].

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