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Giant Goos–Hänchen shift in scattering: the role of interfering localized plasmon modes

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The longitudinal and transverse beam shifts, namely, the Goos–Hänchen (GH) and the Spin-Hall (SH) shifts are usually observed at planar interfaces. It has recently been shown that the transverse SH shift may also arise due to scattering of plane waves. Here, we show that analogous in-plane (longitudinal) shifts also exist in the scattering of plane waves from micro/nano systems. We study both the GH and the SH shifts in plasmonic metal nanoparticles/nanostructures and dielectric micro-particles employing a unified framework that utilizes the transverse components of the Poynting vector of the scattered wave. The results demonstrate that the interference of neighboring resonance modes in plasmonic nanostructures (e.g., electric dipolar and quadrupolar modes in metal spheres) leads to great enhancement of the GH shift in scattering from such systems. We also unravel interesting correlations between these shifts with the polarimetry parameters, *diattenuation* and *retardance*. © 2014 Optical Society of America

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The longitudinal and transverse shifts of a physical light beam at planar dielectric interfaces, namely, the Goos–Hänchen (GH) and the Imbert-Fedorov (IF) shifts, have been under investigation for many years [1–5]. Such in-plane (in the plane of incidence) and transverse (perpendicular to the plane of incidence) shifts have been typically observed in reflection/refraction, total internal reflection of a light beam at planar interfaces, and have accordingly been modeled using various theoretical treatments [6–13]. While the GH shift originates from the angular gradient of the complex reflection/refraction coefficients, the IF shift has its origin in spin–orbit interaction (SOI) and conservation of total angular momentum [4,5,11–13]. The latter also leads to the so-called Spin Hall (SH) effect of light [4,8,11–13]. These shifts depend on the polarization state of the incident beam; the eigenmodes of the GH shift are TM (p) and TE (s) linearly polarized waves and that of the SH shift are left and right circularly polarized (LCP and RCP) waves, respectively [4,5]. Note that the IF shift is more general than the SH shift in the sense that its eigenmodes are both LCP/RCP states and $+45^\circ/-45^\circ$ linear polarization states [4]. It has recently been shown that the transversal spin transport (transverse SH shift) may also arise because of the scattering of plane waves from objects having higher dimensionality (e.g., sphere) [14]. The question therefore naturally follows—is there an analogous in-plane (longitudinal) shift in the scattering of plane waves? We show here that indeed such longitudinal GH shift can be mediated in the scattering of plane waves from micro/nano systems. We study both the scattering-mediated GH and SH shifts utilizing the transverse components of the Poynting vector of the scattered wave. The role of the plane of incidence (for the planar interface) is played

here by the scattering plane. Consequently, the two transverse components of the Poynting vector of the scattered wave, the in-plane (along the direction of the polar scattering angle) and the out-of-plane (along the direction of the azimuthal angle) components are responsible for the longitudinal (in the plane of scattering) and the transverse (perpendicular to the plane of scattering) shifts, respectively. Importantly, we demonstrate that the interference of neighboring localized plasmon resonance modes in metal nanostructures/nanoparticles leads to great enhancement of the GH shift. We also derive interesting correlations between the GH and the SH shifts with the scattering polarimetry parameters, namely, *retardance* δ (phase shift between orthogonal polarization states) and *diattenuation* d (differential attenuation of orthogonal polarization states) [15,16].

In order to derive expressions for the GH and the SH shifts, we consider the scattering of plane waves by a spherical particle [17]. We chose the Cartesian coordinate system with the incident plane wave propagating in the Z direction, and the two orthogonal axes X and Y representing the polarization axes. The polar angle of the scattering θ and the azimuthal angle ϕ are assigned with respect to the Z and X axes, respectively. Since, the eigenmodes of the GH shift are linearly polarized waves, we first consider scattering of the X -polarized wave. The radial, angular and the azimuthal components of the scattered electric and magnetic fields can be derived using the Mie theory [17]. These can then be utilized to obtain the corresponding radial (P_r), angular (P_θ), and azimuthal (P_ϕ) Poynting vector components. Note that the radial component of the Poynting vector signifies energy flow along the direction of the propagation of the scattered wave, whereas both the angular and the

azimuthal components imply transversal energy flow and accordingly lead to shifts (parallel and perpendicular to the scattering plane, respectively) in the perceived location of the source (scatterer) [14,18,19]. These may be interpreted as the longitudinal GH and the transverse SH shifts mediated by the scattering process. Apparently, nonzero magnitudes of the radial components of the electric and the magnetic fields in the near field (or in the intermediate zone, depending upon its strength) [14], are the origin of these shifts. The GH shift in scattering (for the X -polarized incident wave) can thus be defined using the angular component of the Poynting vector as:

$$\vec{\Delta}_{\text{GH}} = \lim_{r \rightarrow \infty} r \left(\frac{P_{\theta} \hat{\theta}}{|P_r|} \right), \quad (1)$$

$$\Delta_{\text{GH}} = -\frac{1}{k} \left(\frac{\left| \text{Im} \left(S_2^* \left[\sum_{n=1}^{\infty} (2n+1) a_n \pi_n \right] \cos^2 \varphi - S_1 \left[\sum_{n=1}^{\infty} (2n+1) b_n \pi_n \right]^* \sin^2 \varphi \right) \right|}{|S_1|^2 \sin^2 \varphi + |S_2|^2 \cos^2 \varphi} \right) \sin \theta. \quad (2)$$

Here $\rho = kr$; k is the wave vector in the medium and r is the radial distance; a_n and b_n are the well-known coefficients of the normal scattering modes [TM (electric) and TE (magnetic) modes, respectively], and τ_n , π_n are the corresponding angle (θ) dependent functions. S_2 and S_1 are the amplitude scattering matrix elements [17], defined as

$$\begin{aligned} S_1 &= \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} (a_n \pi_n + b_n \tau_n), \\ S_2 &= \sum_{n=1}^{\infty} \frac{(2n+1)}{n(n+1)} (a_n \tau_n + b_n \pi_n). \end{aligned} \quad (3)$$

Note that the expressions for the GH shifts Δ_{GH} for X , Y linear polarization states (henceforth noted as $|H\rangle$ and $|V\rangle$ states) exhibit symmetry with respect to the azimuthal angle (shift for $|H\rangle$ state at $\varphi = 0$ is equal to the shift

introduced by the TM and TE scattering modes. Second, in such a case, the magnitude of the shift can be determined by the interference of the neighboring modes. For example, for small metal spheres (radius $a \ll \lambda$), scattering is primarily dominated by the lowest order TM modes (e.g., electric dipolar a_1 and quadrupolar a_2 modes) [15,20]. The magnitude of the GH shift may be enhanced by the interference of the neighboring plasmon resonance modes. For small dielectric Rayleigh scatterers ($a \ll \lambda$), on the other hand, where the scattering can be treated in dipole approximation the angular component of the Poynting vector (P_{θ}) is $\sim$ zero, and accordingly the GH shift vanishes.

As previously noted, while the eigenmodes of IF shift are both LCP/RCP states and $+45^\circ/-45^\circ$ linear polarization states, the eigenmodes of SH shift are solely the LCP/RCP states [4]. To derive expressions for the SH shift, we thus consider the scattering of LCP/RCP

incident wave. The radial, angular and azimuthal components of the Poynting vector for LCP/RCP wave can also be obtained employing Mie theory. This yields the same magnitude and opposite signs of the azimuthal component of the Poynting vector (P_{ϕ}) for the LCP/RCP states. In contrast, the angular component (P_{θ}) is independent of the polarization state (LCP/RCP). We thus define the SH shift as the circular polarization-dependent transverse shift in the perceived location of the source, via the azimuthal component of the Poynting vector as:

$$\vec{\Delta}_{\text{SH}} = \lim_{r \rightarrow \infty} r \left(\frac{P_{\phi} \hat{\phi}}{|P_r|} \right), \quad (4)$$

$$\Delta_{\text{SH}} = \frac{\sigma}{k} \left(\frac{\left| \text{Re} \left(S_1^* \left[\sum_{n=1}^{\infty} (2n+1) a_n \pi_n \right] + S_2 \left[\sum_{n=1}^{\infty} (2n+1) b_n \pi_n \right]^* \right) \right|}{|S_1|^2 + |S_2|^2} \right) \sin \theta, \quad (5)$$

for $|V\rangle$ state at $\varphi = \pi/2$ and vice versa). In general, the GH shift depends upon both the incident linear polarization state and on the azimuthal angle ϕ (orientation of the scattering plane). Several interesting trends can be predicted from the expression for shift. First, for scattering dominated by one particular type of mode (either a TM mode with $b_n \sim 0$; or a TE mode with $a_n \sim 0$), the shift corresponding to one of the linear polarization states (e.g., $|H\rangle$ state, a_n mode) at a chosen scattering plane ($\phi = 0$) is significant whereas the other ($|V\rangle$ state, b_n mode at $\phi = 0$) is negligible. We thus treat these as shifts

where $\sigma = \pm 1$ for the LCP and RCP states.

Unlike the GH shift, for the LCP/RCP states, the SH shift has the same magnitude and opposite signs and is independent of ϕ (choice of scattering plane). The shift is determined by both the strength of the individual scattering modes and the interference of different modes (e.g., $|a_1|^2$, $|a_2|^2$ and $\text{Re}(a_2 \cdot a_1)$ when two TM modes contribute). Thus, the effect of the interference of the modes is expected to be weaker on the SH shift as compared to the GH shift. Moreover, unlike the GH shift, the SH shift exists even when the contribution is from a single mode

(e.g., a_1 mode) [18,19]. In what follows, we study the role of the interfering modes on both the GH and the SH shifts with illustrative examples of resonant localized plasmon modes (TM- dipolar a_1 and quadrupolar a_2 modes) in metal nanospheres ($a \ll \lambda$), and nonresonant higher order TM and TE (a_n and b_n) modes in dielectric microspheres ($a \geq \lambda$).

Figure 1(a) shows the GH shifts (Δ_{GH} , Eq. (2) in the scattering from a metal (silver, Ag) nanosphere of radius $a = 50$ nm with surrounding medium as water. The scattering angle (θ) dependence of Δ_{GH} in the scattering plane $\phi = 0$ for incident X-polarized (|H) state) and Y-polarized (|V) state) light are shown in the figure and its inset, respectively. The results are shown for two wavelengths, $\lambda = 380$ and 430 nm. The observed trends can be summarized as—(a) the magnitudes of Δ_{GH} for |V) state (for $\phi = 0$) are much weaker than that observed for |H) state. (b) The shifts exhibit strong dependence on scattering angle and wavelength. For incident |H) state, $|\Delta_{\text{GH}}|$ achieves its maximum value at $\theta \sim 62^\circ$ for $\lambda = 380$ nm, whereas the corresponding maximum for $\lambda = 430$ nm is at $\theta \sim 90^\circ$. (c) Interestingly, the |H) polarized light exhibits a giant shift at 380 nm for $\theta \sim 62^\circ$ ($|\Delta_{\text{GH}}| \sim 6\lambda$) (usually the GH shift is in the sub-wavelength domain). Moreover, the signs of Δ_{GH} are reversed [21] between 380 and 430 nm wavelength.

Note that the 50 nm Ag sphere exhibits two prominent plasmon resonances corresponding to the electric dipolar (a_1) and the quadrupolar (a_2) modes with resonance peaks at ~ 500 and 380 nm, respectively [14,19]. The negligible contributions of the magnetic or TE modes ($b_n \sim 0$) leads to weak magnitudes of the GH shift for |V) polarized light [Fig. 1(a), inset]. As previously anticipated, the observed giant enhancement of the shift at $\lambda = 380$ nm for incident |H) polarization state is a manifestation of the interference of the two neighboring plasmon resonance modes. This can be comprehended from Fig. 1(b), where the wavelength dependence of the strength of the interference of the two plasmon modes

Fig. 1. (a) Scattering angle θ dependence of the computed GH shift Δ_{GH} for Ag nanosphere ($a = 50$ nm), at two wavelengths, $\lambda = 380$ nm (red solid line), 430 nm (black-dotted line). The shifts are shown for incident X-polarized light (|H) state) in the scattering plane $\phi = 0$. The inset shows the corresponding shifts for incident Y-polarized light (|V) state). (b) The wavelength dependence of the strength of the interference of the dipolar a_1 and the quadrupolar a_2 plasmon modes ($\text{Re}(a_2 * a_1)$) (blue-dotted line, left axis) and the corresponding phase difference (in radian) between them (red solid line, right axis). The inset shows the variation of retardance parameter of scattering δ (in radian) as a function of θ at two wavelengths, $\lambda = 380$ and 430 nm for the same Ag nanosphere.

($\text{Re}(a_2 * a_1)$), and the corresponding phase difference between them are shown. The interference appears to be maximal at $\lambda \sim 380$ nm and decays sharply beyond 400 nm (significantly weak at 430 nm). Accordingly, the magnitude of the shift is significantly larger at 380 nm as compared to 430 nm [Fig. 1(a)]. The apparent reversal of phase differences explains the observed reversal of signs of Δ_{GH} between 380 and 430 nm. Since the enhancement of the GH shift is controlled by the interference of the modes and the phase differences between them, and it might be useful to derive correlations between the shift and the experimentally measurable scattering polarimetry parameter, *retardance* δ . The parameter δ also deals with relative phases of the scattered wave and can be defined as [15,16]

$$\delta(\theta) = \tan^{-1} \left[\frac{\text{Im}(S_2^*(\theta)S_1(\theta))}{\text{Re}(S_2^*(\theta)S_1(\theta))} \right]. \quad (6)$$

The scattering angle dependence of δ at two wavelengths $\lambda = 380$ nm and 430 nm for this Ag nanosphere is shown in the inset of Fig. 1(b). A comparison of $\delta(\theta)$ and $\Delta_{\text{GH}}(\theta)$ [Fig. 1(a)] reveals that a large magnitude of GH shift is associated with a sharp variation of δ with θ . For example, a rapid change in δ when θ approaches 62° for $\lambda = 380$ nm is accompanied with a large value of $|\Delta_{\text{GH}}| \sim 6\lambda$, whereas a relatively smoother variation of δ when θ approaches 90° for $\lambda = 430$ nm leads to a smaller value for $|\Delta_{\text{GH}}|$.

In Fig. 2(a), we show the computed [using Eq. (6)] SH shift Δ_{SH} as a function of θ for the same Ag nanosphere as that of Fig. 1. As predicted, the excitation of one particular type of mode (TM plasmon mode a_1 or a_2) does not lead to a significant enhancement of the shift ($|\Delta_{\text{SH}}| < \lambda$). Moreover, the influence of the interference of these modes on the resulting SH shift is also weaker: $|\Delta_{\text{SH}}|$ at $\theta \sim 62^\circ$ for $\lambda = 380$ nm (a strong interference region) is only marginally larger than that observed at $\theta \sim 90^\circ$ for $\lambda = 430$ nm (a weak interference region). Interestingly, the angular variation $\Delta_{\text{SH}}(\theta)$ exhibits distinct correlation with the other scattering polarimetry parameter, namely, *diattenuation* $d(\theta)$ [shown in Fig. 2(b)]. The parameter d can be defined as [15,16]

$$d(\theta) = \left\{ \frac{|S_2(\theta)|^2 \cos^2 \theta - |S_1(\theta)|^2}{|S_2(\theta)|^2 \cos^2 \theta + |S_1(\theta)|^2} \right\}. \quad (7)$$

Fig. 2. (a) Computed SH shift Δ_{SH} as a function of θ for the same 50 nm Ag nanosphere of Fig. 1, for two wavelengths, $\lambda = 380$ nm (red solid line) and 430 nm (black-dotted line). (b) The angular variation of *diattenuation* d for the Ag nanosphere, at $\lambda = 380$ nm (red solid line) and 430 nm (black-dotted line).

Fig. 3. (a) Computed GH shift Δ_{GH} as a function of θ for a dielectric microsphere ($a = 1 \mu\text{m}$, refractive index $n_s = 1.6$, $\lambda = 632.8 \text{ nm}$). (b) The angular variation of retardance δ (in radians) for the same dielectric scatterer.

The correlation between Δ_{SH} and d arises because both of these parameters are related to the SOI of light and the resulting transformation of spin angular momentum (SAM) to orbital angular momentum (OAM) [14,15,22]. Note that for the incident RCP/LCP state, the strength of SAM to OAM conversion depends upon the magnitude of d ($d = 1$, corresponds to complete conversion, the scattered light becomes completely linearly polarized subsequently generating OAM) [15]. Since the SH shift is also known to be large when the transformation of SAM to OAM is complete [14], the local angular maxima of $|\Delta_{\text{SH}}|$ is accompanied with local maxima of $|d|$.

We have carried out similar studies for dielectric scatterers. Figure 3(a) shows the computed GH shift as a function of θ for a dielectric microsphere ($a = 1 \mu\text{m}$, refractive index $n_s = 1.6$, $\lambda = 632.8 \text{ nm}$) with surrounding medium as air. For this large dielectric scatterer ($a \geq \lambda$), several higher order TM and TE (a_n and b_n) modes contribute to the scattering, none of which may be resonant. Δ_{GH} exhibits rather complex θ dependence with its magnitude peaking at several narrow ranges of angles θ . This apparently arises because of the complicated nature of the angular dependences of the contributing higher order modes and the resulting interferences. Despite such complexities, $\Delta_{\text{GH}}(\theta)$ exhibits similar correlation with $\delta(\theta)$ as shown in Fig. 3(b). Note that the spatial extent of the Poynting vector circulation [P_ϕ , in Eq. (5)] in the scattering of the LCP/RCP light may be extended to several λ for larger dielectric scatterers, leading to a large SH shift [13]. In conformity with this, our calculations (for the dielectric microsphere with $a = 1 \mu\text{m}$, $n_s = 1.6$) also yielded a large magnitude of $\Delta_{\text{SH}}(\geq \lambda)$ at several narrow ranges of θ (not shown here). Importantly, the correlation between $|\Delta_{\text{SH}}(\theta)|$ and $|d(\theta)|$ was observed to remain intact. These results highlight the utility of the experimentally measurable retardance and diattenuation parameter of scattering for studying/interpreting GH and SH shifts in the scattering from micro/nano systems.

To summarize, we have shown that the in-plane (longitudinal) Goos-Hänchen shift can also be observed in scattering of plane waves from micro/nano particles. Both the Goos-Hänchen and the Spin Hall shifts in plasmonic metal nanoparticles and dielectric micro-particles were studied utilizing the transverse components of the Poynting vector of the scattered wave. Notable findings of this investigation are: while the magnitude of the GH shift from the dielectric particles is small (in the sub-

wavelength domain), it exhibits a great enhancement in plasmonic metal nanoparticles. This great enhancement of the GH shift originates from the interference of the neighboring plasmon resonance modes. On the other hand, the influence of the interference of the plasmon modes on the SH shift is weaker, leading to a relatively small magnitude of SH shift in plasmonic nanoparticles. We also note that, although the results presented here are for spherical scattering, an extension for non-spherical particles is warranted. For example, for studying the shifts for rods, spheroids, etc., the T-matrix approach [16] (instead of Mie theory) may be used to compute the scattering matrix elements. Regarding experimental realization of the shifts, the measurement of the SH shift in the scattering from dielectric microspheres has been realized by mapping the scattered intensity distributions for incident LCP/RCP states, in a direction transverse to the scattering plane [14]. The GH shift in scattering may also be measured in analogous fashion by mapping the differential scattered intensity distributions for incident orthogonal linear polarization states, in a direction parallel to a chosen scattering plane. Moreover, the observed correlations between the shifts and the retardance and the diattenuation parameters may open up interesting avenues for analysis/interpretation of the shifts via these experimentally measurable scattering polarimetry parameters.

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