Enhancement of four reflection shifts by a three-layer surface-plasmon resonance

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We investigate the effect of a surface-plasmon resonance on Goos-Hänchen and Imbert-Fedorov spatial and angular shifts in the reflection of a light beam by considering a three-layer system made of glass, gold, and air. We calculate these spatial and angular shifts as functions of the incidence angle showing that they are strongly enhanced in correspondence with the resonant angle. In particular, we find giant spatial and angular Goos-Hänchen shifts for the p-wave light close to the plasmon resonance. We also predict a similar but less pronounced resonant effect on spatial and angular Imbert-Fedorov shifts for both s-wave and p-wave light.

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It is now established [1–7] that there are four shifts that can happen when light is reflected: two longitudinal shifts [spatial and angular Goos-Hänchen (GH) shifts] and two transverse shifts [spatial and angular Imbert-Fedorov (IF) shifts]. Recently, the predicted GH spatial shift [8] of a light beam on a metallic mirror has been measured [9], showing good agreement with the theory. Moreover, giant GH spatial shifts have been observed [10] with a three-layer system in the Kretschmann-Raether configuration at the metal-air interface when the surface-plasmon resonance of the metal is excited. Finally, the detection of both GH and IF spatial shifts has been reported [11] for a light beam on a three-layer system totally reflected on the external interface of a dielectric thin film deposited on a high-index substrate.

Motivated by these experimental achievements, we theoretically analyze in this Brief Report the effect of a surface-plasmon resonance not only on GH and IF spatial shifts but also on GH and IF angular shifts. In particular, we investigate the three-layer system glass-gold-air in the Kretschmann-Raether configuration [12,13]. To calculate spatial and angular shifts we use the recently established theory [14] which shows that both spatial and angular GH and IF shifts can be derived in terms of the complex reflection coefficient. We consider the three-layer system glass-gold-air. This is the familiar Kretschmann-Raether configuration [12]: the light beam comes from the prism of glass and reflects with incident angle θ at the interface with air, where there is a thin film of gold with thickness d. In our analysis the prism of glass has relative permittivity $\epsilon_0 = 2.19$; the thin film of gold has complex relative permittivity: $\epsilon_1 = -29.02 + 2.03i$ for a wavelength $\lambda = 830$ nm [9]; the air has relative permittivity $\epsilon_2 = 1$.

The s-wave and p-wave reflection coefficients r_s and r_p of this three-layer system can be written in terms of generalized Fresnel equations [12]

$$r_s = \frac{r_s^{01} + r_s^{12} e^{2i\delta}}{1 + r_s^{01} r_s^{12} e^{2i\delta}}, \tag{1}$$

$$r_p = \frac{r_p^{12} + r_p^{12} e^{2i\delta}}{1 + r_p^{01} r_p^{12} e^{2i\delta}}, \tag{2}$$

where

$$r_s^{01} = \frac{k_{z0} - k_{z1}}{k_{z0} + k_{z1}}, \tag{3}$$

$$r_s^{12} = \frac{k_{z1} - k_{z2}}{k_{z1} + k_{z2}}, \tag{4}$$

$$r_p^{01} = \frac{\epsilon_1 k_{z0} - \epsilon_0 k_{z1}}{\epsilon_1 k_{z0} + \epsilon_0 k_{z1}}, \tag{5}$$

$$r_p^{12} = \frac{\epsilon_2 k_{z1} - \epsilon_1 k_{z2}}{\epsilon_2 k_{z1} + \epsilon_1 k_{z2}} \tag{6}$$

are the reflection coefficient at the 01 and 12 interfaces, and

$$k_{z0} = \frac{2\pi}{\lambda}\sqrt{\epsilon_0}\cos\theta, \tag{7}$$

$$k_{z1} = \frac{2\pi}{\lambda}\sqrt{\epsilon_1 - \epsilon_0 \sin^2\theta} = \frac{\delta}{d}, \tag{8}$$

$$k_{z2} = \frac{2\pi}{\lambda}\sqrt{\epsilon_2 - \epsilon_0 \sin^2\theta} \tag{9}$$

are the z components of the wave vectors of the light. Notice that k_{z1} gives the ratio between the complex phase parameter δ which appears in Eqs. (1) and (2) and the thickness d of the gold film.

It is important to stress that, in general, both s-wave and p-wave reflection coefficients r_s and r_p of Eqs. (1) and (2) are complex numbers. Thus one usually writes them as

$$r_\alpha = R_\alpha^{1/2}\, e^{i\phi_\alpha}, \tag{10}$$

where $R_\alpha = |r_\alpha|^2$ is the α-wave ($\alpha = s,p$) reflectivity ($0 \leqslant R_\alpha \leqslant 1$) and ϕ_α is the corresponding reflection phase. In the upper panel of Fig. 1 we report the reflectivity R_α, obtained directly from Eqs. (1) and (2), as a function of the incident angle θ for s-wave (dashed line) and p-wave (solid line) monochromatic light of wavelength $\lambda = 830$ nm and choosing the thickness $d = 30$ nm for the gold film. The panel shows the well-known surface-plasmon resonance at $\theta = \theta_R \simeq 43.7^\circ$ [12]. This strong reduction of the p-wave reflectivity R_p around the resonant angle θ_R is due to the formation of an evanescent wave which propagates along the interface between gold and air [12]. Both the reduction of reflectivity and the position of resonant angle θ_R depend on the thickness d of the metal. Our choice $d = 30$ nm gives a p-wave reflectivity R_p close to zero at the resonant angle θ_R. The figure clearly shows that the s-wave reflectivity is a monotonic increasing function of θ. Instead the p-wave reflectivity has two local minima: one at $\theta = \theta_m \simeq 41.4^\circ$ where $R_p \simeq 0.77$ and another at $\theta = \theta_R \simeq 43.7^\circ$ where $R_P \simeq 0.15$. Close to the local minimum at $\theta = \theta_m$ there is a local maximum at the (quasi-) total-reflection angle $\theta = \theta_0 \simeq 42.6^\circ$ where

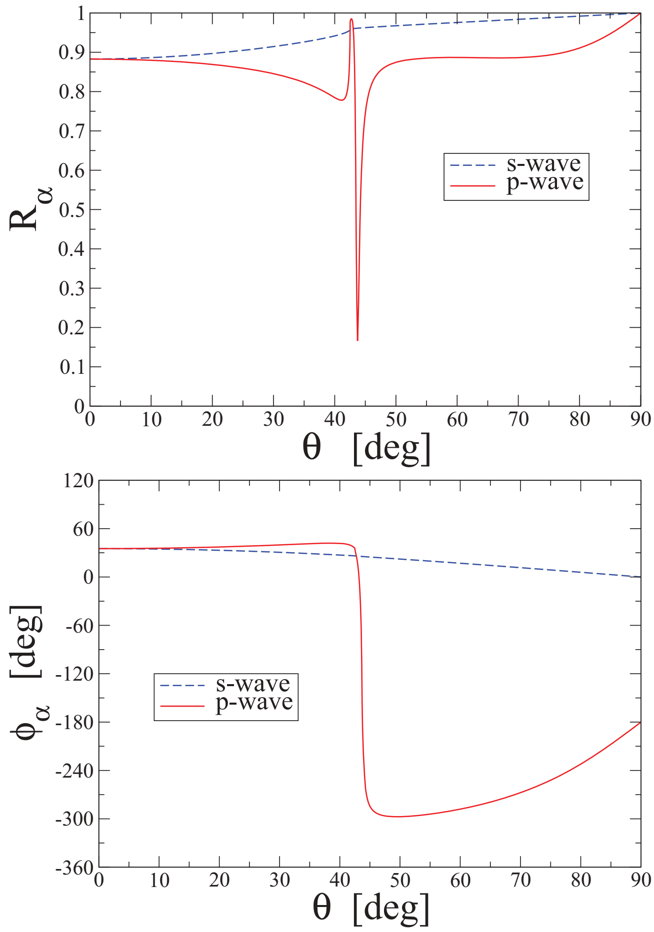

FIG. 1. (Color online) Upper panel: Reflectivity R_α as a function of the incident angle θ for s-wave ($\alpha = s$, dashed line) and p-wave ($\alpha = p$, solid line) monochromatic light. Lower panel: Same as upper panel, but for the phase ϕ_α of the reflection coefficient $r_\alpha = R_\alpha^{1/2} e^{i\phi_\alpha}$. For both panels: Three-layer system with a gold film of thickness $d = 30$ nm as glass-air interface and light with wavelength $\lambda = 830$ nm.

$R_p = 0.98$. The very deep local minimum at θ_R is due to the surface-plasmon resonance [12], while the behavior of the extrema at θ_m and θ_0 is related to the thickness d of the gold film: we have verified that when $d \to 0$ the reflectivity R_p goes to zero at θ_m and it goes to unity at θ_0 (total reflection). These effects are clearly shown in Fig. 2, where we plot R_p vs θ for different values of the thickness d of the gold film.

In the lower panel of Fig. 1 we plot the phase ϕ_α of the complex reflection coefficient r_α as a function of the incident angle θ, using the same system parameters of the upper panel. The figure shows that, contrary to the phase ϕ_s of s-wave light (dashed line), the phase ϕ_p of p-wave light (solid line) changes abruptly near the resonant angle θ_R.

In Fig. 2 we report the p-wave reflectivity R_p as a function of the incident angle θ for four values of the thickness d of the gold film. The figure shows that the resonant local minimum clearly appears only for $10 \lesssim d \lesssim 50$ nm. Indeed for both $d \gtrsim 50$ and $d \lesssim 10$ nm, one finds that R_p at θ_R is close to unity.

The results shown in Figs. 1 and 2 are well-known [12] and confirmed by various experiments [12,13]. Nevertheless, their consequences on GH and IF shifts are not yet fully explored. In particular, while the impact of the large derivative of the phase of the reflection coefficient for GH shift value has been previously studied both numerically [15] and experimentally [16], the impact for IF shifts has not yet been explored.

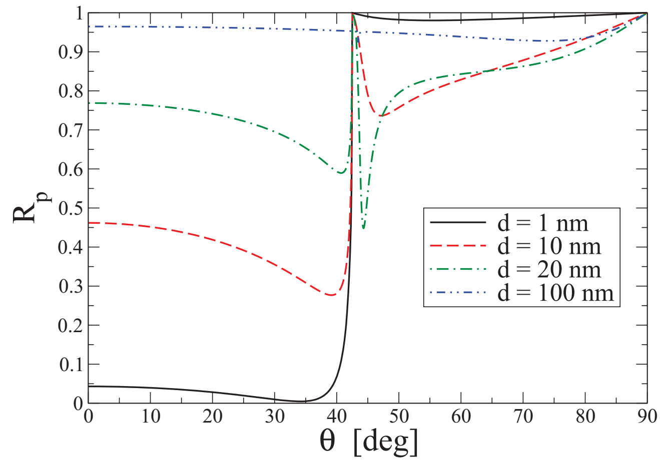

FIG. 2. (Color online) p-wave reflectivity R_p as a function of the incident angle θ for monochromatic light for four values of the thickness d of the gold film. Three-layer system with a gold film as glass-air interface and light with wavelength $\lambda = 830$ nm.

As discussed in detail by Aiello and coworkers [14], for a monochromatic beam of light with polarization α ($\alpha = s,p$) and finite waist, the total beam displacement δ_α observed at distance L from the reflection position is expressible as a linear combination of spatial shift Δ_α and angular shift Θ_α, namely,

$$\delta_\alpha = \Delta_\alpha + L\,\Theta_\alpha, \tag{11}$$

under the condition $\Theta_\alpha \ll 1$. We have seen that when the shift δ_α is parallel to the plane of incidence it is called a Goos-Hänchen shift [1], while when the shift δ_α is normal to the plane of incidence it is called an Imbert-Fedorov shift [3]. Both spatial and angular shifts can be expressed in terms of the reflection coefficient r_α, given by Eq. (10). In particular, in the case of a linearly α-polarized ($\alpha = s,p$) monochromatic light beam, with wavelength λ, incident angle θ, and angular spread θ_0, the shifts are given by [14]

$$\Delta_\alpha = \frac{\lambda}{2\pi}\,\mathrm{Im}[D_\alpha], \quad \Theta_\alpha = \frac{\theta_0^2}{2}\mathrm{Re}[D_\alpha], \tag{12}$$

where

$$D_\alpha = \begin{cases} \frac{d}{d\theta}\ln(r_\alpha) & \text{in the GH case,} \\ 2i\cot\theta\left(\frac{r_p + r_s}{r_\alpha}\right) & \text{in the IF case.} \end{cases} \tag{13}$$

Notice that, as explained in Ref. [14], the IF shifts denote the spatial ($\Delta_\alpha^{\mathrm{IF}}$) and angular ($\Theta_\alpha^{\mathrm{IF}}$) separation between the two right-circularly and left-circularly polarized components of the reflected beam generated by the reflection-induced splitting of the α-wave incident beam (see also [17]). Equations (12) and (13) show that while the spatial shifts depend on the presence of an imaginary component in the reflection coefficient, the angular shifts depend explicitly on the presence of a finite angular spread θ_0 in the incident beam.

By using Eqs. (12) and (13) with the reflection coefficients given by Eqs. (1) and (2) we calculate the four GH and IF shift

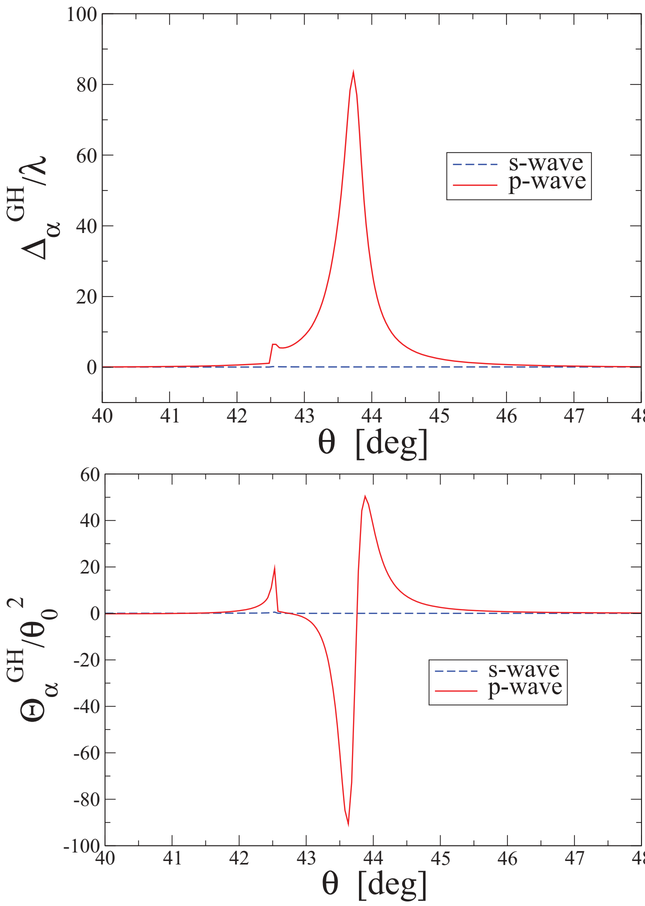

FIG. 3. (Color online) Upper panel: Goos-Hänchen spatial shift $\Delta_\alpha^{\rm GH}$ as a function of the incident angle θ for s-wave ($\alpha = s$, dashed line) and p-wave ($\alpha = p$, solid line) monochromatic light. Lower panel: Same as upper panel, but for the Goos-Hänchen angular shift $\Theta_\alpha^{\rm GH}$. For both panels: Three-layer system with a gold film of thickness $d = 30$ nm at glass-air interface and light with wavelength $\lambda = 830$ nm. θ_0 is the angular spread of the incident beam.

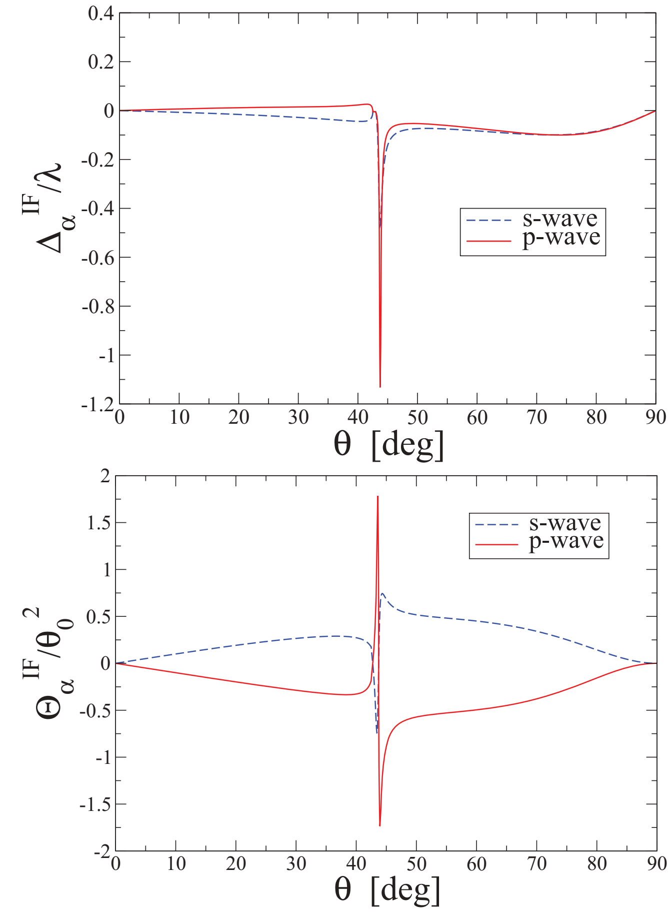

FIG. 4. (Color online) Upper panel: Imbert-Fedorov spatial shift $\Delta_\alpha^{\rm IF}$ as a function of the incident angle θ for s-wave ($\alpha = s$, dashed line) and p-wave ($\alpha = p$, solid line) monochromatic light of wavelength $\lambda = 830$ nm. Lower panel: Same as upper panel, but for the Imbert-Fedorov angular shift $\Theta^{\rm IF}$. For both panels: Three-layer system with a gold film of thickness $d = 30$ nm at glass-air interface and light with wavelength $\lambda = 830$ nm. θ_0 is the angular spread of the incident beam.

of the light for our three-layer system. In the upper panel of Fig. 3 we plot the Goos-Hänchen spatial shift $\Delta^{\rm GH}$ as a function of the incident angle θ for s-wave and p-wave monochromatic light. The s-wave light does not show any GH spatial shift. In contrast, for the p-wave light there is an extremely large (about 80 wavelengths) GH spatial shift in correspondence with the surface-plasmon resonance (where $\theta = \theta_R \simeq 43.7^\circ$). Our results on the giant GH spatial shift at plasmon resonance angle θ_R are in full agreement with previous experimental data [10]; also the presence of a small secondary peak at the total reflection angle $\theta_0 \simeq 42.6^\circ$ is consistent with the p-wave experimental results of Yin*et al.* [10].

Under the same system conditions (gold film of thickness $d = 30$ nm and light with wavelength $\lambda = 830$ nm), in the lower panel of Fig. 3 we plot the Goos-Hänchen angular shift $\Theta^{\rm GH}$ as a function of the incident angle θ for s-wave and p-wave monochromatic light. This quantity, which has been recently measured by Merano *et al.* [6] for a Gaussian laser beam at the air-glass interface, has not yet been observed in experiments with metals. The results shown in the lower panel of Fig. 3 can be thus quite useful for future experiments. The figure shows that $\Theta_s^{\rm GH}$ is always zero. Instead, in analogy with the spatial GH shift $\Delta_p^{\rm GH}$, the angular GH shift $\Theta_p^{\rm GH}$ is different from zero around the resonant angle θ_R. Actually, $\Theta_p^{\rm GH}$ is exactly zero at $\theta = \theta_R$ but it displays two positive peaks at θ_0 and just above θ_R, and another very large negative peak just below θ_R. There is a remarkable similarity between our results near the resonant angle θ_R and the experimental data obtained in Ref. [6] near the Brewster angle at the air-glass interface: in particular, both systems show a sudden change of the sign of $\Theta_p^{\rm GH}$.

In Fig. 4 we report the IF shifts. In the upper panel of the figure we plot the IF spatial shift. This spatial shift is strongly enhanced at θ_R for both s-wave and p-wave light. However, this enhancement is much smaller than the GH one (in p-wave light). In the lower panel of Fig. 4 we show the IF angular shift. Both s-wave and p-wave angular shifts are nonzero for all incident angles (apart $\theta = 0^\circ, 90^\circ$) with a sudden change of sign around θ_R. Notice that the IF angular shifts are much smaller than the p-wave GH ones. Moreover, for s waves, the GH shifts are close to zero apart near the θ_0 angle while the

IF shifts are always nonzero and at resonance larger than the s-wave GH ones. This is because IF shifts involve both r_s and r_s reflection coefficients.

In conclusion, we have investigated Goos-Hänchen and Imbert-Fedorov spatial and angular shifts for s-wave and p-wave light which reflects at the interface between glass and air with a thin film of gold. The presence of the metal induces a surface-plasmon resonance which strongly suppresses the reflectivity at a specific resonant angle of incidence and with a carefully chosen thickness. We have found that in correspondence with this critical angle both spatial and angular Goos-Hänchen shifts are remarkably enhanced in the case of p-polarized light. In addition, we have found a similar, but less pronounced, resonant effect on spatial and angular Imbert-Fedorov shifts for both s-wave and p-wave light. We stress that, up to now, only the spatial Goos-Hänchen shift has been experimentally observed [10] for the three-layer system under consideration. For this reason, we think that our theoretical predictions can be a useful guide for future experiments.

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