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-Hanchen 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 a function of the incidence angle showing that they are strongly enhanced in correspondence of the resonant angle. In particular, we find giant spatial and angular Goos-Hanchen 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] that there are four shifts that can happen when light is reflected. These are the two longitudinal shifts (spatial and angular GH shifts) and the two transverse shifts (spatial and angular IF shifts). Recently, the predicted GH spatial shift [8] of a light beam on a metallic mirror has been measured [9], showing a 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 in this paper we analyze theoretically 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 ε0 = 2.19; the thin film of gold has complex relative permittivity ε1 = −29.02 + 2.03i for a wavelength λ = 830 nm [9]; the air has relative permittivity ε2 = 1.

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

\[
rs = \frac{r_{s}^{01} + r_{s}^{12}e^{2iδ}}{1 + r_{s}^{01}r_{s}^{12}e^{2iδ}}, \quad \text{and} \quad rp = \frac{r_{p}^{01} + r_{p}^{12}e^{2iδ}}{1 + r_{p}^{01}r_{p}^{12}e^{2iδ}},
\]

where

\[
r_{s}^{01} = \frac{k_{z0} - k_{z1}}{k_{z0} + k_{z1}}, \quad r_{s}^{12} = \frac{k_{z1} - k_{z2}}{k_{z1} + k_{z2}}, \quad r_{p}^{01} = \frac{\epsilon_1 k_{z0} - \epsilon_0 k_{z1}}{\epsilon_1 k_{z0} + \epsilon_0 k_{z1}}, \quad r_{p}^{12} = \frac{\epsilon_2 k_{z1} - \epsilon_1 k_{z2}}{\epsilon_2 k_{z1} + \epsilon_1 k_{z2}},
\]

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

\[
k_{z0} = \frac{2\pi}{\lambda} \sqrt{\epsilon_0 \cos(\theta)}, \quad k_{z1} = \frac{2\pi}{\lambda} \sqrt{\epsilon_1 - \epsilon_0 \sin^2(\theta)} = \frac{\delta}{d}, \quad k_{z2} = \frac{2\pi}{\lambda} \sqrt{\epsilon_2 - \epsilon_0 \sin^2(\theta)}
\]

are the z components of the wavevectors of the light. Notice that kz1 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 rs and rp of Eqs. 1 and 2 are complex numbers. Thus one usually writes them as

\[
r_\alpha = R_\alpha^{1/2} e^{i\phi_\alpha},
\]

where \( R_\alpha \) is the α-wave (α = s, p) reflectivity (0 ≤ \( R_\alpha \) ≤ 1) and \( \phi_\alpha \) is the corresponding reflection phase. In the upper panel of Fig. 1 we report the reflectivity \( R_\alpha \), 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 λ = 830 nm and choosing the thickness d = 30 nm for the gold film. The panel shows the well-known surface plasmon resonance at θ = θR ≃ 43.7° [12]. This strong reduction of the p-wave reflectivity \( R_p \) around the resonant angle θR is due to the formation of an evanescent
wave which propagates along the interface between gold and air \[d = 30 \text{ nm}\]. Both the reduction of reflectivity and the position of resonant angle \(\theta_R\) depend on the thickness \(d\) of the metal. Our choice \(d = 30 \text{ nm}\) gives a p-wave reflectivity \(R_p\) close to zero at the resonant angle \(\theta_R\). The figure clearly shows that the s-wave reflectivity is a monotonic increasing function of \(\theta\). Instead the p-wave reflectivity has two local minima: one at \(\theta = \theta_m \approx 41.4^\circ\) where \(R_p \approx 0.77\) and another at \(\theta = \theta_R \approx 43.7^\circ\) where \(R_p \approx 0.15\). Close to the local minimum at \(\theta = \theta_m\) there is a local maximum at the (quasi-) total-reflection angle \(\theta = \theta_0 \approx 42.6^\circ\) where \(R_p = 0.98\). The very deep local minimum at \(\theta_R\) is due to the surface plasmon resonance \[d = 10 \text{ nm}\], while the behavior of the extrema at \(\theta_m\) and \(\theta_0\) 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 \(\theta_m\) and it goes to one at \(\theta_0\) (total reflection). These effects are clearly shown in Fig. 2 where we plot \(R_p\) vs \(\theta\) for different values of the thickness \(d\) of the gold film.

In the lower panel of Fig. 1 we plot the phase \(\phi_p\) of the complex reflection coefficient \(r_p\) as a function of the incident angle \(\theta\), using the same system parameters of the upper panel. The figure shows that, contrary to the phase \(\phi_s\) of s-wave light (dashed line), the phase \(\phi_p\) of p-wave light (solid line) changes abruptly near the resonant angle \(\theta_R\).

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

The results shown in Figs. 1 and 2 are well-known \[d = 1 \text{ nm}\] and confirmed by various experiments \[d = 10 \text{ nm}\]. 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 \[d = 20 \text{ nm}\] and experimentally \[d = 100 \text{ nm}\], the impact for IF shifts has not yet been explored.

As discussed in detail by Aiello and coworkers \[d = 1 \text{ nm}\], for a monochromatic beam of light with polarization \(\alpha\) \((\alpha = s, p)\) and finite waist the total beam displacement \(\delta_\alpha\) observed at distance \(L\) from the reflection position is expressible as a linear combination of spatial shift \(\Delta_\alpha\) and angular shift \(\Theta_\alpha\), namely

\[
\delta_\alpha = \Delta_\alpha + L \Theta_\alpha ,
\]

under the condition \(\Theta_\alpha \ll 1\). We have seen that when the shift \(\delta_\alpha\) is parallel to the plane of incidence it is called Goos-Hanchen (GH) shift \(\Delta_\alpha\), while when the shift \(\delta_\alpha\) is normal of the plane of incidence it is called Imbert-Fedorov (IF) shift \(\Theta_\alpha\). Both spatial and angular shifts can be expressed in terms of the reflection coefficient \(r_\alpha\), given by Eq. (10). In particular, in the case of linearly
\[ \Delta \alpha = \frac{\lambda}{2\pi} \text{Im}[D\alpha], \quad \Theta\alpha = \frac{\theta_0^2}{2} \text{Re}[D\alpha], \]  

(12)

where

\[ D\alpha = \begin{cases} \frac{d\ln(r\alpha)}{dr} & \text{in the GH case} \\ 2i\cot(\theta) \left( \frac{r_s + r_p}{r_s} \right) & \text{in the IF case} \end{cases} \]  

(13)

Notice that, as explained in Ref. [14], the IF shifts denote the spatial \( \Delta\alpha^{IF} \) and angular \( \Theta\alpha^{IF} \) separation between the two right-circularly and left-circularly polarized components of the reflected beam generated by the reflection-induced splitting of the \( \alpha \)-wave incident beam (see also [17]). Eqs. (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 \( \theta_0 \) 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 of the light for our three-layer system.

In the upper panel of Fig. 3 we plot the Goos-Hanchen spatial shift \( \Delta\alpha^{GH} \) as a function of the incident angle \( \theta \) for s-wave \( (\alpha = s, \text{dashed line}) \) and p-wave \( (\alpha = p, \text{solid line}) \) monochromatic light. The s-wave light does not show any GH spatial shift. Instead for the p-wave light there is an extremely large (about 80 wavelengths) GH spatial shift in correspondence of the surface plasmon resonance (where \( \theta = \theta_R \approx 43.7^\circ \)). Our results on the giant GH spatial shift at plasmon resonance angle \( \theta_R \) are in full agreement with previous experimental data [10]: also the presence of a small secondary peak at the total reflection angle \( \theta_0 \approx 42.6^\circ \) is consistent with the p-wave experimental results of Yin, Hesselink, Lin, Fang and Zhang [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-Hanchen angular shift $\Theta^{GH}$ as a function of the incident angle $\theta$ for s-wave (dashed line) and p-wave (solid line) monochromatic light. This quantity, which has been recently measured by Merano, Aiello, van Exter and Woerdman [6] for a Gaussian laser beam at the air-glass interface, has not yet been observed in experiments with metals. The novel results shown in the lower panel of Fig. 3 can be thus quite useful for next future experiments. The figure shows that $\Theta^{GH}_s$ is always zero. Instead, in analogy with the spatial shift $\Delta P^{GH}$, the angular GH shift $\Theta^{GH}_p$ is different from zero around the resonant angle $\theta_R$. Actually, $\Theta^{GH}_p$ is exactly zero at $\theta = \theta_R$ but it displays two positive peaks at $\theta_0$ and just above $\theta_R$, and another very large negative peak just below $\theta_R$. There is a remarkable similarity between our results near the resonant angle $\theta_R$ 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 $\Theta^{GH}_p$.

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 $\theta_R$ for both s-wave and p-wave light. However, this enhancement is much smaller than the GH one (in p-wave). 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 $\theta_R$. Notice that the IF angular shifts are much smaller with respect to the p-wave GH ones. Moreover, for s-waves the GH shifts are close to zero apart near the $\theta_0$ angle while the IF shifts are always nonzero and at resonance larger than the s-wave GH ones. This is due to the fact that IF shifts involve both $r_s$ and $r_p$ reflection coefficients.

In conclusion, we have investigated Goos-Hanchen and Imbert-Fedorov spatial and angular shift 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 suppress the reflectivity at a specific resonant angle of incidence and with a carefully chosen thickness. We have found that in correspondence of this critical angle both spatial and angular Goos-Hanchen 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-Hanchen 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 next future experiments.

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