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# Enhancement of spin components' shifts of reflected beam via long range surface plasmon resonance

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ABSTRACT

In this letter, we investigated the impact of long range surface plasmon resonance (LRSPR) on the spatial and angular shifts of left and right spin components of a p-polarization Gaussian beam reflected from a glass-fused silica-gold-fused silica interface, and deduced the formulas of these shifts. We found that the spatial and angular spin splitting of left and right spin components only occur in the direction perpendicular to the plane of incidence (out-of-plane), but not in the direction parallel to the plane of incidence (in-plane). The spatial and angular in-plane shifts of left and right spin components are the same, which are equal to those of the total reflected beam (i.e., angular and spatial Goos–Hänchen shifts). We found that all the in-plane and out-of-plane shifts can be greatly enhanced by LRSPR. The maximum angular and spatial in-plane shifts can be up to $1.060\times10^{-4}$ rad and 249.977 μm, respectively, which are almost equal to half of the divergence angle and beam waist of the incident Gaussian beam. The maximum spatial in-plane shift (about 20.148 μm) is about 5 times larger than the previously reported enhanced value. We also found that the directions and magnitude of angular and spatial in-plane and out-of-plane shifts can be controlled by slightly adjusting the angle of incidence or the thickness of fused silica film or gold film under certain conditions, which may provide a new way for photon manipulation. Furthermore, our work may provide some help for precision measurement of physical and biological parameters and the development of SPR sensing technology.

## 1. Introduction

The behavior of plane wave is ruled by the Snell's law and Fresnel equations when reflected from or transmitted through a planar interface. However, for the bounded beam of light, owing to the occurrence of diffractive corrections, the gravity centers of which will undergo tiny shifts in the directions parallel (in-plane) and perpendicular (out-of-plane) to the plane of incidence [1,2]. The in-plane and out-of-plane shifts are known as the Goos–Hänchen (GH) shifts [3] and the Imbert–Fedorov (IF) shifts [4], respectively. The GH and IF shifts exist both in position space (corresponding to $x$- and $y$-position space, named spatial GH and IF shifts) and angular spectrum space (corresponding to $x$- and $y$- angular spectrum space, named angular GH and IF shifts) [1,2]. The IF shifts originate from the spin–orbit interaction of light thus are spin dependent [5]. Therefore, for a linearly polarized incident beam, their left and right spin components will split in the direction perpendicular to the plane of incidence when reflected from or transmitted through a planar interface, this physical phenomenon is known as photonic spin Hall effect (PSHE) [6–8]. The spin splitting also occurs within the plane of incidence [9]. Similar with GH and IF shifts, the in-plane and out-of-plane spin splitting occur both in position space [8,9] and angular spectrum space [10,11]. The spin splitting depends on the polarization of incident beam and the character of interface, so the four kinds of splitting do not always occur at the same time. For example, when a linearly polarized beam (not including p-polarization) with is reflected from an air–glass interface [9], the spin splitting only occurs in position space, does not occur in angular spectrum space; but when the beam is elliptically polarized [10], the splitting will occur in angular spectrum space. For the incident beam of p-polarization, the in-plane spin splitting will not occur in position space, and the out-of-plane spin splitting will not occur in angular-spectrum space [8,9], but if the glass is replaced by topological insulators [12] or Two-dimensional atomic crystals [11], they will occur. The spin splitting shifts have drawn significant attention [13,14] owing to its enormous potential applications in precision metrology, such as, determining the thickness of nanometal film [15], the number of graphene layers [16], the axion angle of topological materials [12], the magneto-optical constant of Fe films [17], as well as the quantized Hall conductivity and the Berry phase [18].

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However, the photonic spin splitting is extremely weak, it is only a fraction of the wavelength in general cases [7,15–17]. It is normally difficult to detect or measure it directly. Therefore, the research of enhancing PSHE has become especially necessary. Many researchers have done a lot of work in this area [19–24]. For instance, Luo et al. [19] demonstrated that the spatial out-of-plane photonic spin splitting (OPPSS) can be enhanced near the Brewster angle. Zhou et al. [22], Jiang et al. [23] and Xiang et al. [24] theoretically investigate the enhanced spatial OPPSS through considering the surface plasmon resonance (SPR) effect, respectively. However, due to the strong absorption of the interior of the metal, both of the propagation distance and penetration depth of the wave of the surface plasmon polariton (SPP) are very short. In order to solve above problems, the long range surface plasmon polariton (LRSPP) was proposed [25]. Compared with conventional SPP, LRSPP have narrower angular resonance curves, higher surface electric field strengths, and longer surface propagation lengths and depths [26]. Due to these advantages, the long range surface plasmon resonance (LRSPR) has been used to enhance tiny beam shifts [27–29]. Recently, Tan et al. [30] investigate the enhancement effect of LRSPR on spin splitting of the left and right spin components of a p-polarization Gaussian beam reflected from a glass-fused silica-gold-fused silica interface (LRSPR coupling structure) in $y$-position space. They find that the two spin components will undergo symmetrical spin splitting, and LRSPR has an excellent enhancement effect on it. The researchers [22–24,30], including Tan et al. [30], have only studied the performance of spin components of reflected beam in $y$-position space, what are the performances of them in $x$- and y-angular spectrum space, as well as in $x$-position space? Will the spin splitting occur in these three spaces? What are the impacts of LRSPR on them? No one has studied and discussed these questions yet.

In this letter, we will give the answers to the above questions. We make a brief introduction to LRSPR at first, deduce the formulas of the in-plane and out-of-plane spatial and angular shifts of left and right spin components of a p-polarization Gaussian beam reflected from a glass-fused silica-gold-fused silica interface at second, then analyze the impact of LRSPR on these shifts, and summarize our work finally.

## 2. Theoretical analysis

### 2.1. Characteristics of LRSPR

The LRSPP is the special mode of electromagnetic wave formed by the coupling of two SPPs which propagate along opposite interfaces of thin metal film sandwiched between two dielectric mediums with similar refractive index [25]. Therefore, the strength of LRSPP is sensitive to the thickness of the dielectric layer and metal layer. Tan et al. deduced the electric field distribution, rigorous dispersion equation and exciting conditions of LRSPP [30]. The details are no longer repeated here. The conventional LRSPR coupling structure, as shown in Fig. 1, consists of glass prism, dielectric layer, metal layer, and dielectric substrate. In our system, the medium of dielectric layer and substrate is fused silica, and the metal layer is gold. The incident light is a Gaussian beam light whose wavelength is 632.8 nm and beam waist is 500 μm. The relative dielectric constant $\varepsilon_p$ of glass prism is 3.61 at the wavelength of 632.8 nm. The values of the relative dielectric constant of fused silica ($\varepsilon_s = 2.123$) and gold ($\varepsilon_m = -13.073 + 0.997i$) can be obtain by the Sellmeier dispersion equation [31] and the Drude model [32], respectively.

Consider the case of a monochromatic and polarized Gaussian light beam reflected from the glass-fused silica-gold-fused silica interface. As illustrated in Fig. 1, the $z$ axis of the laboratory Cartesian frame $(x, y, z)$ is normal to the glass-fused silica interface ($z = 0$) and directed from the glass to the fused silica space. Cartesian frame $(x_i, y_i, z_i)$ and $(x_r, y_r, z_r)$ are attached to the incident beam and the reflected beam, respectively. Note that the coordinate $x_r$ is associated with the in-plane shifts, while $y_r$ is associated with the out-of-plane shifts. The Gaussian light beam is considered as propagating along the positive $z_i$ axis. According to Snell's law [33], the reflection coefficients of p-polarized and s-polarized light can be expressed as:

$$r_A = R_A e^{i\phi_A} = \frac{r_A^{12} + r_A^{234} e^{2ik_{2z}d_s}}{1 + r_A^{12} r_A^{1234} e^{2ik_{2z}d_s}}. \tag{1}$$

Where,

$$r_A^{234} = \frac{r_A^{23} + r_A^{34} e^{2ik_{3z}d_m}}{1 + r_A^{23} r_A^{234} e^{2ik_{3z}d_m}}, \tag{2}$$

$$r_p^{i,i+1} = \frac{(\varepsilon_{i+1} k_{i,z} - \varepsilon_i k_{i+1,z})}{(\varepsilon_{i+1} k_{i,z} + \varepsilon_i k_{i+1,z})}, \tag{3}$$

$$r_s^{i,i+1} = \frac{(k_{i,z} - k_{i+1,z})}{(k_{i,z} + k_{i+1,z})}, \tag{4}$$

$$k_{iz} = k_0 \sqrt{\varepsilon_i - \varepsilon_1 (\sin\theta)^2}. \tag{5}$$

$i \in 1, 2, 3$ and $j = i + 1$. The 1, 2, 3 and 4 correspond to glass prism, fused silica layer, gold layer and fused silica substrate, respectively. $A \in p, s$, $R_A = |r_A|$ and $\phi_A$ represent the modulus and phase of reflection coefficient of the A-polarized light, respectively. $r_p^{i,i+1}$ and $r_s^{i,i+1}$ denote the reflection coefficient of p-polarized and s-polarized light at the interface between $i$th and $j$th layer medium, respectively.

In order to study the impact of the LRSPR on the spin component's shifts of reflected beam, we first analyze the impact of the thickness of fused silica film and gold film on the LRSPR. According to Eqs. (1)–(5), we can obtain the reflection spectrum curves as shown in Fig. 2. It can be seen clearly from Fig. 2(a) that there are two resonant peaks in the reflection spectrum, the stronger one on the left side is caused by LRSPP, and the weak one on the right side is caused by short range surface plasmon polariton (SRSPP) [30].

We find that the thickness of gold film has a great influence on the resonant peak of LRSPR. When the thickness of gold film increases from 60 nm (green dash dotted line) to 70 nm (red dash line) under $d_s = 300$ nm, the resonant angle, depth and shape of the resonant peak of LRSPR have changed greatly. The resonant angle changes from 54.60° to 55.27°, the variation is 0.67°; the minimum $R_p$ decreases from 0.2106 to 0.0557 (the proportion of the variation is 73.6%); the resonant peak becomes much sharper, which indicates that the largest value of $\partial R_p/\partial\theta$ in 70 nm curve (64.44) is larger than that in 60 nm curve (52.85) as shown in Fig. 2(e); the curve of the reflected phase $\Phi_p$ (red dash line) near the resonant angle becomes much steeper as shown in Fig. 2(b), that means $|\partial\Phi_p/\partial\theta|$ becomes much larger near the resonant angle. From Fig. 2(f), we can clearly see that the value of $|\partial\Phi_p/\partial\theta|$ at its resonant angle in 70 nm curve is 1345.3, which far larger than that (441.7) in 60 nm curve.

The thickness of fused silica film also has a certain influence on the resonant angle, depth and shape of the resonant peak. However, compared with gold film, the influence of fused silica film is weaker. As shown in Fig. 2(a), when the thickness of fused silica film increases from 300 nm (green dash dotted line) to 400 nm (blue solid line) under $d_m = 60$ nm, the resonant angle is almost unchanged (the variation is only 0.02°, from 54.60° to 54.58°); the minimum $R_p$ increases from 0.2106 to 0.3607 (the proportion of the variation is only 47.7%); but the width of resonant peak become narrower, the largest value of $\partial R_p/\partial\theta$ increases from 52.85 to 76.86 as shown in Fig. 2(e). Compared with 300 nm, the variation range of the reflected phase $\Phi_p$ near resonant angle and the maximum value of $|\partial\Phi_p/\partial\theta|$ of the curve of 400 nm (blue solid line) becomes small obviously as shown in Fig. 2(b) and (f). The largest values of $|\partial\Phi_p/\partial\theta|$ of the curves of 300 nm and 400 nm are 441.7 and 286.0, respectively. However, unlike $R_p$ and $\Phi_p$, the $R_s$ and $\Phi_s$ are almost unchanged when the LRSPR is excited as shown in Fig. 2(c) and (d). The thickness of fused silica film and gold film has little influence on the $R_s$ and $\Phi_s$. This is because only p-polarized light can excite SPP [34].