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SPECIAL TOPIC — Nanophotonics

Giant Goos–Hänchen shifts of waveguide coupled long-range surface plasmon resonance mode*

Qi You(游琪), Jia-Qi Zhu(祝家齐), Jun Guo(郭珺), Lei-Ming Wu(吴雷明), Xiao-Yu Dai(戴小玉), and Yuan-Jiang Xiang(项元江)†

SZU-NUS Collaborative Innovation Center for Optoelectronic Science & Technology, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, *China*

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A hybrid structure based on a planar waveguide (PWG) mode coupling a long-range surface plasmon resonance (LRSPR) mode is proposed to enhance the GH shift. Both the PWG mode and LRSPR mode can be in strong resonance, and these two modes can be coupled together due to the normal-mode splitting. The largest GH shift of PWG-coupled LRSPR structure is 4156 times that of the incident beam, which is 23 times and 3.6 times that of the surface plasmon resonance (SPR) structure and the LRSPR structure, respectively. As a GH shift sensor, the highest sensitivity of $4.68 \times 10^7 \lambda$ is realized in the coupled structure. Compared with the sensitivity of the traditional SPR structure, the sensitivity of our structure is increased by more than 2 orders, which theoretically indicates that the proposed configuration can be applied to the field of high-sensitivity sensors in the future.

Keywords: Goos–Hänchen (GH) shift, planar waveguide (PWG), long-range surface plasmon polartons (LRSPPs)

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1. Introduction

The Goos–Hänchen (GH) effect refers to a lateral spatial shift that an electromagnetic wavepacket experiences in its incident plane when it is reflected from a surface. It can be traced back as early as the era of Newton, but it was not until 1947 that Goos and Hänchen first observed it.[1,2] A theoretical explanation of the effect was given by Artmann who used the stationary phase method.[3] In the past few decades, the lateral shift has been widely studied in optical,[4,5] chemical,[6] and biomedical fields.[7] Usually, GH shift was studied at the interface of the structure containing two homogeneous materials with different optical characteristics, and the GH shift is very small in this case, almost comparable to the wavelength of the incident beam.[8–11] For better research, measurement, and application, thus, how to obtain a giant GH shift has always been the goal pursued by researchers.

Currently, researchers are working on the enhancing of the GH shift via various methods, and one of the effective ways is to excite the surface plasmon polaritons (SPPs). As described by Yin *et al.*,[12] a lateral spatial displacement that is greater than 50 wavelengths for the reflected beam due to the surface plasmon polaritons (SPPs), was observed experimentally. The SPP is a perpendicularly confined evanescent electromagnetic wave that occurs at the metal-dielectric interface,[13–15] and it can be excited by attenuated total reflection (ATR) configuration, where the wave vector mismatch between vacuum and SPP is compensated for by using high-index prisms. When SPPs are excited at the metal–dielectric interface, there will be a reflectance dip in the SPR reflectivity curve, and the electromagnetic fields near the interface will become very strong, which can lead to a giant GH shift.

After that, a new mode called long-range surface plasmon resonance (LRSPR) has been proposed to enhance the GH shift.[16] When the metal in the ATR structure is thin enough and clamped by two kinds of dielectrics $(\varepsilon_1, \varepsilon_2)$ with similar refractive indices $(|\varepsilon_1 - \varepsilon_2| \ll \varepsilon_1, \varepsilon_2)$, the SPRs on the upper and lower surfaces of the metal can be coupled together to form an LRSPR. The lateral beam shift at the resonance of LRSPR can be two orders of magnitude greater than the wavelength. Similarly, a dielectric planar waveguide (PWG) coupling system consisting of a high refractive index core layer and two low refractive index cladding layers is another effective way to enhance the GH shift.[17–20] Although the amplified shift has been widely studied and applied, the larger GH shift is always pursued by researchers.

In recent years, hybrid configurations with two different electromagnetic modes have received a lot of attention.[21–23] When the strong resonance formed by the two modes can be coupled together, a stronger resonance is formed. This phenomenon is known as the normal-mode splitting.[24] There-

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†Corresponding author. E-mail: xiangyuanjiang@126.com

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fore, inspired by the above, a coupled structure of the PWG mode and the long-range surface plasmon resonance (LRSPR) mode is proposed to enhance the GH shift in this paper. Both PWG and LRSPPs modes can form a strong resonance, and once the two modes are coupled together, a new strong resonance based on PWG–LRSPP will occur.

We find that the GH shift in the coupled configuration can be enhanced obviously, which is much larger than the GH shift in the conventional SPR and LRSPR configuration. The GH shift generated by the coupled PWG–LRSPP mode is nearly 3.7 times more than the GH shift produced by the LRSPP mode. We can adjust the thickness of the cytop to improve the GH shift. In the application, the GH shift in our structure is very sensitive to the refractive index of the substrate medium; through the further improvement of the structure, it can be used as a high sensitivity sensor. We believe that this scheme could be potentially valuable for the high-sensitivity sensors, the measurement methodology, etc.

2. Theoretical model and method

The structure analyzed here is shown in Fig. 1. The chalcogenide glass (2S2G) is adopted as the prism because of its high refractive index ($n > 2$), and it also shows the potential applications in making ultra-low loss waveguides among glasses.[25] Under the prism is a sandwiched structure consisting of cytop–Si–cytop, which can work as a PWG. Here, the cytop is an amorphous fluoropolymer with a low refractive index, and it is widely used in LRSPR structure and waveguide structure.[26,27] Then an Au thin film is added, and beneath the Au film is another layer of cytop, the structure of cytop–Au–cytop constitutes the LRSPR configuration. Finally, we couple these two structures to obtain a new structure. Here, the wavelength of the excitation light we adopt is $\lambda = 633$ nm, the incident field is assumed to be transverse magnetically (TM) polarized to analyze the GH shift and reflectance (R_p).

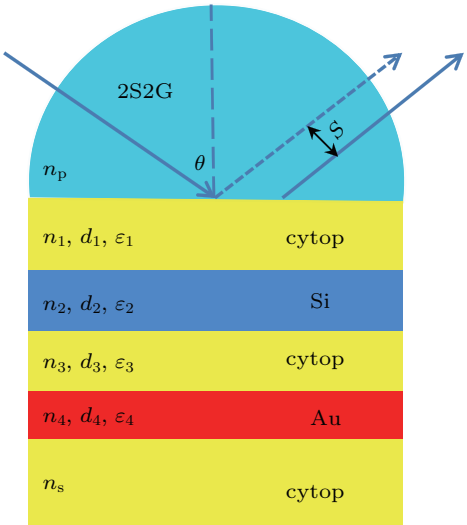


Fig. 1. (color online) Schematic diagram of proposed PWG-coupled LRSPR structure.

In this structure, the refractive index of 2S2G prism is given by the following expression: $n_p = 2.24047 + 2.693 \times 10^{-2}/\lambda^2 + 8.08 \times 10^{-3}/\lambda^4$.[28,29] The refractive index of the cytop layer is $n_1 = n_3 = n_s = 1.34$ at $\lambda = 633$ nm.[26] The third layer is silicon (Si) film and its refractive index is calculated from the expression $n_2 = A + A_1 e^{-\lambda/t_1} + A_2 e^{-\lambda/t_2}$,[30,31] where $A = 3.44904$, $A_1 = 2271.88813$, $A_2 = 3.39538$, $t_1 = 0.058304$, and $t_2 = 0.30384$. The fifth layer is Au film, and its dielectric constant follows the Drude–Lorentz model,[32] $\varepsilon_4 = 1 - \lambda^2\lambda_c/\lambda_p^2(\lambda c + i\lambda)$, where λ_c and λ_p are the collision and plasma wavelength of the metal, respectively. For Au film, $\lambda_c = 8.9342 \times 10^{-6}$ m and $\lambda_p = 1.6826 \times 10^{-7}$ m.[33] In order to calculate the phase (ϕ_p), the thickness values of the upper and mid cytop layer are set to be $d_1 = d_3 = 2100$ nm, and the thickness of silicon is set to be $d_2 = 14.1$ nm. The thickness of Au film is d_4, which needs to be calculated by the dispersion equation. The permittivity of each layer from above down except for the bottom layer is set to be ε_1, ε_2, ε_3, and ε_4.

The structure of PWG consists of cytop–Si–cytop, and the dispersion relation for PWG is calculated from the following formula:[17]

$$\tan k_2 d_2 = \frac{k_2(p_2\alpha_2 + p_3\alpha_3)}{k_2^2 - p_2\alpha_2 p_3\alpha_3}, \tag{1}$$

where $p_2 = \varepsilon_2/\varepsilon_1$, $p_3 = \varepsilon_2/\varepsilon_3$, $k_2 = \sqrt{k_0^2\varepsilon_2 - \beta^2}$, with k being the wave vector in a vacuum, β the wavenumber. Hence, the effective index can be defined as $n_{\text{eff}} = \beta/k_0$. When the effective index of PWG and LRSPP mode are matched, the PWG mode and LRSPP mode can be coupled together. For the LRSPP structure, the dispersion relation can be derived as[34]

$$\tanh(\alpha d_4/2) = -\frac{\varepsilon_4\alpha_d}{\varepsilon_3\alpha}, \tag{2}$$

where $\alpha = \beta^2 - k_0^2\varepsilon_4$ and $\alpha_d = \beta^2 - k_0^2\varepsilon_3$. Similarly, the expression for the effective refractive index is $n_{\text{eff}} = \beta/k_0$.

For a multilayer system, we can use the transfer matrix method (TMM) and Fresnel equations based on an N-layer model to analyse the phase (ϕ_p) and reflectivity (R_p).[35,36] The layers are stacked parallel to the Z direction, perpendicular to the dielectric interface. The total transfer matrix is the multiple multiplication of the transfer matrix for each layer,

$$M = \prod_{K=2}^{N-1} M_K = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}, \tag{3}$$

where N refers to the total number of layers in the structure, and

$$M_K = \begin{bmatrix} \cos\beta_k & (-i\sin\beta_k)/q_k \\ -iq_k\sin\beta_k & \cos\beta_k \end{bmatrix} \tag{4}$$

with

$$q_k = \left(\frac{u_k}{\varepsilon_k}\right)^{1/2}\cos\theta_k = \frac{(\varepsilon_k - n_1^2\sin\theta_1)^{1/2}}{\varepsilon_k} \tag{5}$$

and

$$\beta_k = \frac{2\pi}{\lambda} n_k \cos\theta_k (z_k - z_{k-1}) = \frac{2\pi d_k}{\lambda} (\varepsilon_k - n_1^2 \sin^2\theta_1)^{1/2}, \quad (6)$$

where ε_k, n_k, and d_k represent the dielectric constant, refractive index, and thickness of the k-th layer, θ_1 is the incident angle, and λ represents the wavelength of incident beam. Then we need to calculate the total reflection coefficient (r_p) for the p-polarization from the following expression:

$$r_p = \frac{(M_{11} + M_{12} q_N) q_1 - (M_{21} + M_{22} q_N)}{(M_{11} + M_{12} q_N) q_1 + (M_{21} + M_{22} q_N)}, \quad (7)$$

where q_1 and q_N are the corresponding terms for the first layer (2S2G prism) and the N-th layer. Finally, the phase (ϕ_p) and reflectivity (R_p) of reflection coefficient r_p are obtained from the formulae:

$$\phi_p = \arg(r_p) \quad (8)$$

and

$$R_p = |r_p|^2. \quad (9)$$

After obtaining the phase (ϕ_p), we can calculate the GH shift by the stationary phase method, and it can be expressed as[3]

$$S = -\frac{1}{k_0} \frac{d\varphi_p}{d\theta_1}. \quad (10)$$

3. Results and discussion

Figure 2 shows the effective index of the PWG and LRSPPs mode. From Fig. 2, one can see that the effective index of the PWG mode is 1.3448 (solid red line) when the thickness of Si is $d_2 = 14.1$ nm. Then, for the LRSPR mode, we plot the variation of effective index with the thickness of Au film (solid blue line). In this case, we can see that the solid red line and solid blue line intersect at a point where the thickness of the corresponding Au is 11.4 nm, which means that at the intersection two modes can be coupled together.

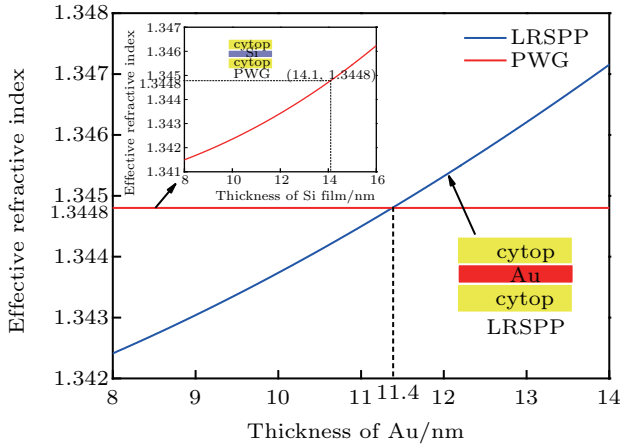


Fig. 2. (color online) Plot of effective refractive indices of PWG mode (solid red line) and LRSPP mode (solid blue line) versus thickness.

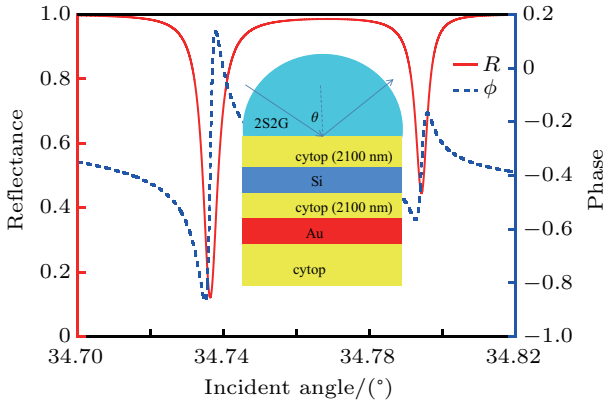


Fig. 3. (color online) Variation of reflectance and phase with incident angle when $d_2 = 14.1$ nm, $d_4 = 11.4$ nm.

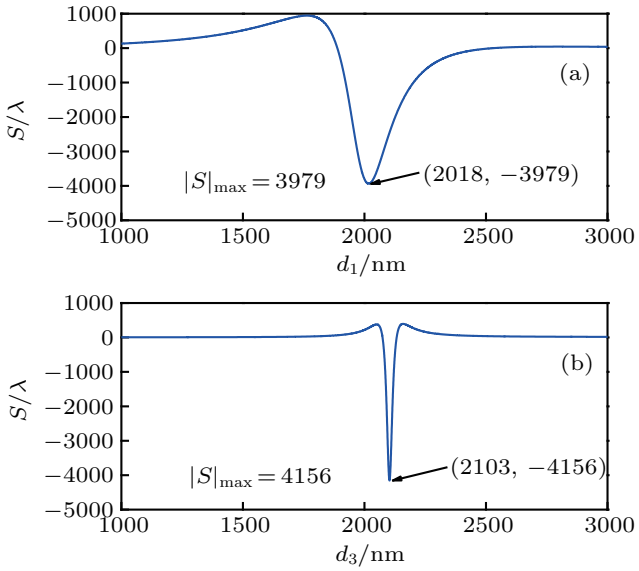


Fig. 4. (color online) Variation of GH shift with thickness of (a) d_1 and (b) d_3.

Using the TMM method, we can obtain the curve of reflectance (solid red line) and phase (blue dotted line) as a function of the incident angle in Fig. 3. The reflectance curve is split into two dips and two resonance angles (34.736° and 34.794°) are obtained. This is due to the PWG structure and the LRSPR structure that are both of narrow resonance; normal mode splitting occurs when two narrow resonances are coupled together, resulting in the splitting of the SPR curve into two resonances.[14] According to Eq. (10), there is a direct relation between phase and GH shift, the sharper the phase jump, the larger the GH shift we can obtain, which indicates that we can obtain the larger shift around 34.736°. In this structure, the cytop layer acts as a dielectric layer, its thickness affects the GH shift. To obtain the largest GH shift, therefore, we plot Fig. 4 to determine the optimal thickness of the cytop layer. The results show that when $d_1 = 2018$ nm and $d_3 = 2103$ nm, the largest GH shift we can obtain is 4156 times that of the incident beam, and $|S|_{max}$ here is obtained at $\theta = 34.736°$. As is well known, in a traditional SPP system, the metal thin film attaches to the prism, the best thickness

of Au film is usually around 50 nm when Au is used to excite SPPs. Therefore, in order to compare the enhanced shifts based on SPR, LRSPR, and PWG-coupled LRSPR structure, we adopt 51-nm Au film to excite SPPs. The results are shown in Fig. 5. In the SPR structure (three-layer system prism-gold-cytop), the largest GH shift is 178.7, and in the LRSPR configuration (four-layer system prism-cytop-gold-cytop), the largest GH shift we can obtain is 1129. In our proposed coupling structure (six-layer system prism-cytop-silicon-cytop-gold-cytop), S/λ attains 4156, which is the largest GH shift we can obtain. Thus, we can conclude that the new structure of PWG-coupled LRSPR can greatly enhance the GH shift.

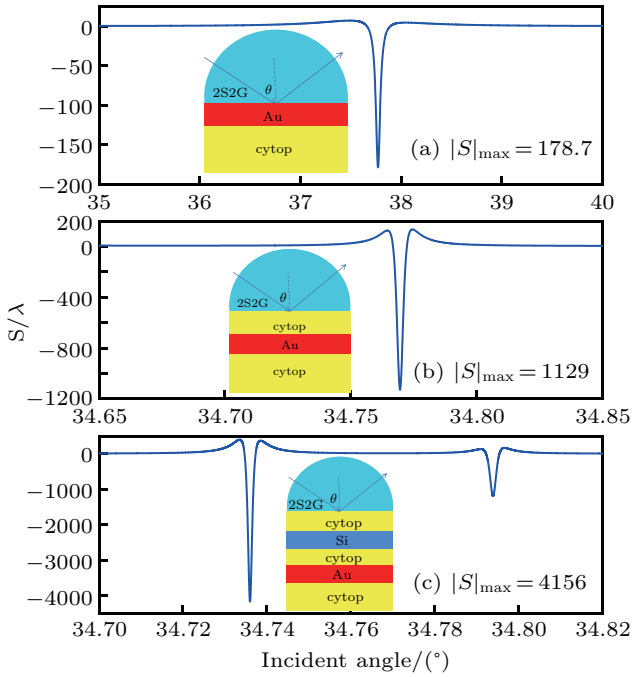


Fig. 5. (color online) Variation of GH shift with the incident angle for the structure based on (a) SPR structure with thickness of Au of 51 nm, (b) LRSPR structure with thickness of Au and cytop being 11.4 nm and 2018 nm, respectively, and (c) PWG–LRSPR structure with thickness being d_1 =2018 nm, d_2 =14.1 nm, d_3 =2103 nm, and d_4 =11.4 nm from above down.

In our theoretical research, we find that the GH shift will present a great red shift when we change the refractive index of the bottom cytop layer (n_s). Therefore, we can use the proposed structure as a high sensitivity sensor based on the changing shift. The underlying cytop (n_s) is replaced by the sensing medium, and in order to ensure that the configuration of the waveguide can be coupled with the LRSPR, it is better for the refractive index of the sensing layer to be about 1.34 (pure water). Here, we define ΔGH as the maximum value of the changed GH shift. From Fig. 6(a), one can see that in the SPR structure, when we change the refractive index of 0.0001, the ΔGH is relatively small, which is about 17.7λ (all "λ" are calculated numerically only), so we can define the sensitivity as $S' = \Delta\text{GH}/\Delta n = 1.77 \times 10^5 \lambda$, where Δn refers to the change of refractive index of the bottom layer (n_s). Similarly, the ΔGH in the LRSPR structure is 461λ, and the changed refractive index is $\Delta n = 5 \times 10^{-5}$, so we can calculate the sensitivity to be $S \approx 9.2 \times 10^6 \lambda$. In the PWG-coupled LRSPR structure, the highest sensitivity we can obtain is $S \approx 4.5 \times 10^7 \lambda$. Compared with the sensitivity of a traditional SPR sensor, the sensitivity of the proposed system is increased by more than 2 orders. Moreover, we plot Fig. 7 to determine the optimum thickness of the cytop layer and to obtain the highest sensitivity, and the result shows that the sensitivity can be obtained to be as high as $4.68 \times 10^7 \lambda$ when $d_1 = 2004$ nm and $d_3 = 2089$ nm.

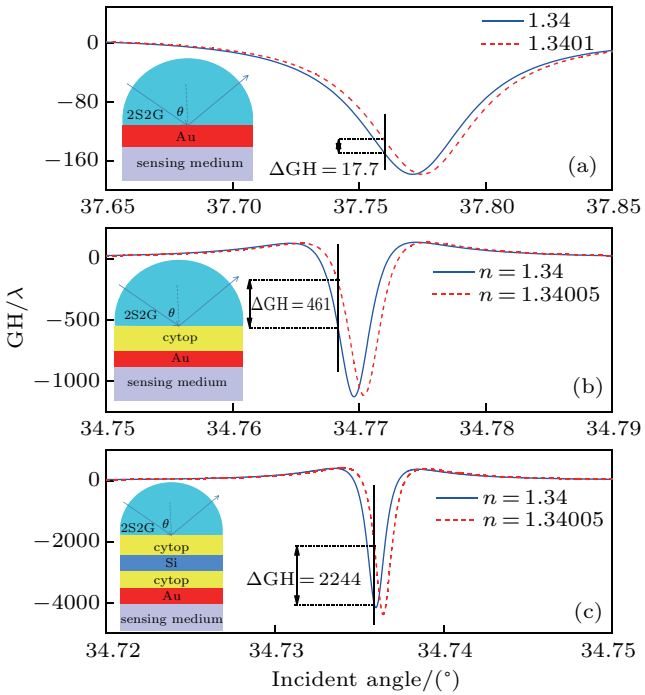


Fig. 6. (color online) Variation of GH shift with incident angle when changing the refractive index of sensing medium in (a) SPR structure, (b) LRSPR structure, and (c) PWG–LRSPR structure.

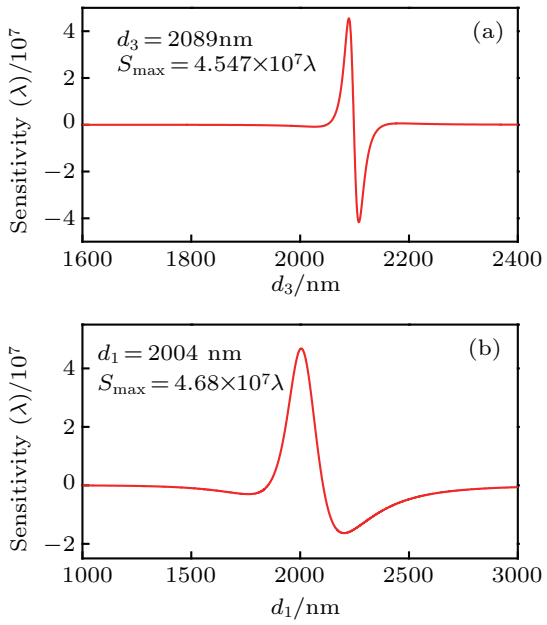


Fig. 7. (color online) Variation of sensitivity with thickness of (a) d_3 and (b) d_1.

4. Conclusions and perspectives

In this study, we have coupled PWG structure and LRSPR structure together to obtain a new structure, where the GH shift based on the PWG-coupled LRSPR structure can be greatly enhanced. By optimizing the thickness of dielectric layers, the largest lateral shift we can theoretically obtain almost attains to the millimeter magnitude. As a GH shift sensor is based on the changing shift, our structure can obtain sensitivity as high as $4.68 \times 10^7 \lambda$. Compared with the sensitivity of a traditional SPR structure, the sensitivity of our structure is increased by more than 2 orders. It should be noted that the refractive index of the dielectric layer is 1.34, so it is applicable to the sensing medium with a refractive index of about 1.34.

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