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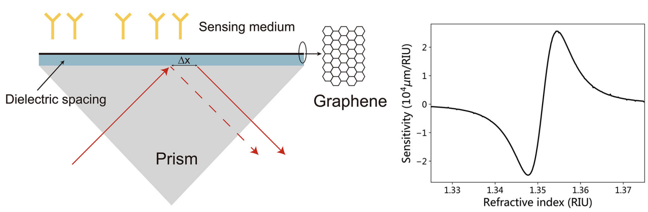

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High Sensitivity Terahertz Biosensor Based on Goos-Hänchen Effect in Graphene

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Abstract: Terahertz biosensing provides a suitable method to identify biomolecules due to their rich spectral fingerprint in this electromagnetic region. However, owing to the limitations of terahertz sources and detectors, the signal is weak and requires to be enhanced by particular technologies. In this paper, we propose a terahertz plasmonic biosensor based on Goos-Hänchen effect in graphene. Sample sensing can be realized by measuring the Goos-Hänchen shift of the reflected light. Numerical simulations show that the sensitivity of this biosensor can reach a high value up to $2.5 \times 10^4 \mu$m/RIU. This graphene plasmonic configuration combined with Goos-Hänchen effect provides a novel high-sensitivity approach for future terahertz biosensing applications.

Index Terms: Graphene, biological sensing, and Goos-Hänchen effect.

1. Introduction

Surface plasmon resonance (SPR) biosensors, which probe biomolecules by surface plasmon polariton waves, have various applications in life science, environmental monitoring, and pharmaceutical industry [1]–[3]. Compared with the fluorescence optical biosensor, the SPR biosensor can detect at high speeds and with high sensitivity [4]. However, for conventional noble metal-based SPR biosensors, there are two limitations in application. On one hand, the noble metal films support surface plasmon polariton (SPP) at the visible region, which can not work in the emerging terahertz fields. On the other hand, in these SPR sensors, the intensity of the reflected wave is measured to get the incident angle of SPR. The intensity changes not as rapidly as the phase, which may have limitations in sensitivity [5]. More recently, graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has shown the potential to develop new terahertz SPR biosensor [6]. Graphene supports the propagation of high confined surface plasmon polariton in the terahertz regime, which can be used to overcome the first limitation [7], [8]. For the second limitation, the Goos-Hänchen (GH) effect of graphene can be utilized to improve the sensitivity.

The Goos-Hänchen effect is firstly observed by Goos and Hnchen, where lateral shift exists between the reflected and the incident beams in totally internally reflection [9]. The lateral shift can be explained by the geometrical optics [10]. Before totally reflected back to high refractive index

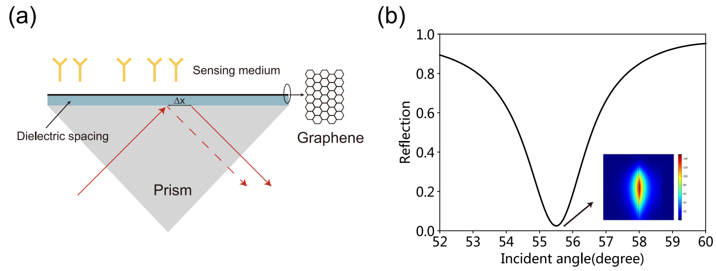

Fig. 1. (a) Schematic diagrams of the proposed biosensor. The incident wave is totally reflected on the interface of the prism and dielectric spacing layer. A lateral shift Δx occurs between the reflected wave and incident wave. (b) The reflection for various incident angles and the electric field distribution around the graphene layer at the resonance angle.

medium, the evanescent wave in low refractive index medium has traveled along the interface. In general, the shift is small due to the scale of the penetration depth. However, when surface plasmon polariton is excited at the interface, the GH shift can be enhanced by the strong field. Thus, the new terahertz plasmonic material, graphene, provides a feasible way for applying GH effect in terahertz fields [11]. Specifically, graphene has two advantages. The first advantage is that graphene supports giant GH shifts due to abrupt phase change by SPP [12]. The second advantage is that both the value and sign of GH shifts are tunable, which can be modulated simply with gate voltage [13]. These two features make graphene a suitable material to construct terahertz high sensitivity biosensor.

In this paper, we propose a terahertz SPR-GH biosensor with graphene. We theoretically study SPR performances of the device and obtain the reflective spectrum. Based on transfer matrix method, we calculate the GH shift for the structure. The GH shift is enhanced by SPR and large GH shift is achieved in the terahertz band. Since the GH effect exhibits high sensitivity to the refractive index, the graphene-based configuration is used to design high sensitivity biosensor. Then, we analyze the performance of this biosensor and show the high sensitivity property.

2. Model and Theory

The proposed biosensor is shown in Fig. 1(a), which has four layers: the sensing medium, the monolayer graphene, a dielectric spacing layer, and a high index prism. The sensing medium contracts the monolayer graphene directly. The monolayer graphene is covered on the dielectric layer. As the effective refractive index of the monolayer graphene is very large, it is difficult to excite graphene SPP directly, especially in the terahertz regime. Thus, a modified Otto configuration is used [14]. The prism uses a high refractive index material, and in this paper, its refractive index n_p is set as 4. The dielectric spacing layer uses a low refractive index material and its refractive index n_d is set as 1.5. It should be noted that the design of graphene biosensor fully considers the feasibility of the measurement technique. There are also studies about noble metal GH sensors in experiments [5]. When the incident wave is totally internally reflected in the prism, the evanescent wave exists in the low index spacing layer. When the phase-matching condition is satisfied, SPP is excited in graphene layer. The excitation of SPP is highly affected by the refractive index of the environment. The refractive index of the environment is changed when the sample is changed. Thus, sample sensing can be realized by measuring the properties of the reflected wave.

Before showing the performance of the proposed graphene biosensor, we firstly demonstrate the phenomenon in the biosensor theoretically. Two main physical processes occur in this device. The first process is the excitation of graphene SPP. The second process is the Goos-Hänchen effect in graphene. The graphene can be modeled by a surface conductivity approach. The conductivity expression is formed by two terms, which is interband term and intraband term. Considering that in terahertz regime the angular frequency $\omega \ll 2E_F/\hbar$, where E_F is the Fermi energy, and

$\hbar$ is the reduced Planck constant, the conductivity of graphene is dominated by the intraband transition. So we neglect the interband conductivity contribution and the complex conductivity can be approximated by a Drude-like expression as [15]

$$\sigma(\omega) = \frac{ie^2\mu_c}{\pi\hbar^2(\omega + i\tau^{-1})}, \tag{1}$$

where e is the electron charge, $\mu_c = 0.8$ eV is the chemical potential, $\tau = 3$ ps is the intrinsic relaxation time.

To excite SPP in graphene, the polarization of the incident wave should be transverse magnetic (TM) polarization. The plane of graphene is parallel to the interface of the dielectric medium. We assume that the plane of graphene is perpendicular to the z-axis. The TM plasmonic resonance excitations can be determined by the phase-matching theory, which can be derived from [16]

$$\frac{n_s^2}{k_{zs}} + \frac{n_d^2}{k_{zd}} + \frac{i\sigma}{\omega\epsilon_0} = 0, \tag{2}$$

where $k_{zi(i=s,d)} = \sqrt{k_{sp}^2 - n_i^2 k_0^2}$ is the transverse wavenumber of the surface plasmon, n_s is the refractive index of sensing medium. When the phase-matching condition is satisfied, the energy of the propagating wave is coupled to the graphene surface plasmons via evanescent wave in the dielectric spacing layer. This will lead to a minimum in the reflection spectrum. From (2), this case occurs when the angle of the incident wave is

$$\theta_{sp} = arcsin(Re(n_{eff})/n_p) \approx 55^\circ, \tag{3}$$

where neff is the effective index of the surface plasmon mode and can be calculated by the effective index method [17].

In order to confirm the existence of SPR in the proposed biosensor configuration, the 2D finite-difference domain (FDTD) method is used to get the reflected spectrum. We assume that the frequency of the incident wave is 5 THz. The thickness of dielectric spacing layer is $d = 8\ \mu m$. The refractive index of sensing medium $n_s = 1$. The reflectivity for various incident angles is plotted in Fig. 1(b). In this figure, a dip occurs in 55.6°, which is corresponding to the resonant excitations of graphene plasmons. This numerical result finds consistency with the theoretically predicted results. It is also seen in the figure that the electric field around the graphene layer is enhanced when graphene SPP is excited. Another thing should be noted that the excitation angle of surface plasmon mode should be larger than the angle of total reflection, which is owing to the biosensor's reflective configuration. In the current situation, the angle of total internal reflection between prism and spacing layer,

$$\theta_{TIR} = arcsin((n_d)/n_p) \approx 22^\circ < \theta_{sp}, \tag{4}$$

which satisfies the condition.

Next, we use the transfer matrix method to analyze Goos-Hänchen effect in the biosensor. We consider the structure that graphene is sandwiched between two dielectric layers with permittivity ϵ_1 and ϵ_2. The transfer matrix T_{12} for TM polarization should be written as [13]

$$T_{12} = \frac{1}{2}\begin{bmatrix} 1+\eta+\xi & 1-\eta-\xi \\ 1-\eta+\xi & 1+\eta-\xi \end{bmatrix}, \tag{5}$$

where $\eta = n_0^2 k_{1z}/n_1^2 k_{0z}$ and $\xi = \sigma k_{1z}/\epsilon_0 n_1^2 \omega$, k_{0z} and k_{1z} are the wave vector components in two dielectric layers, respectively. The system transfer matrix M is given by the propagation matrix of wave in the medium P and the transfer matrix T in the interface, which is expressed by

$$M = T_{01}P(1)T_{12}P(2)T_{23}. \tag{6}$$

The reflection coefficient R can be derived by the elements of transfer matrix

$$R = M_{21}/M_{11}. \tag{7}$$

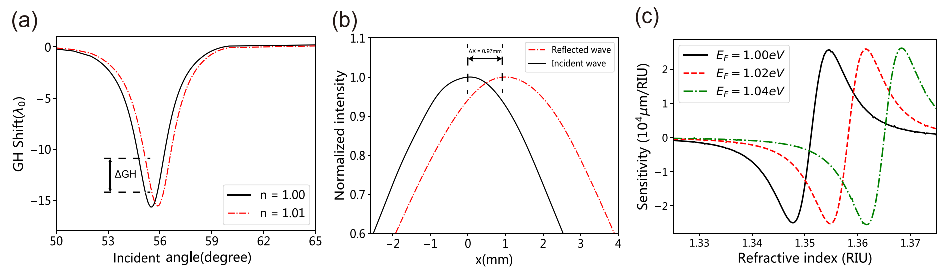

Fig. 2. (a) The GH shifts when refractive index is 1.00 (solid black line) and 1.01 (dashed red line). (b) The field amplitude of incident wave and reflected wave. (c) The sensitivity of different refractive index of sensing medium with different Fermi energy.

The reflection phase ϕ_r can be written as follows:

$$\mathbf{R} = |R| \exp(i\phi_r). \tag{8}$$

The GH shift D_r of reflected wave can be obtained by the stationary-phase method as [18]

$$D_r = -\frac{\lambda}{2\pi}\frac{d\phi_r}{d\theta}. \tag{9}$$

By applying (5)–(8) to (9), we can calculate the GH shift of the system. Then we plot the GH shift as a function of the incident angle, which is shown in Fig. 2(a). From the figure, we can find that the GH shift is negative when Fermi energy Ef = 0.8 eV. The maximum shift can reach $16.1\lambda_0$ at the resonance angle of 55.6° ($n_s = 1$, black line). Thus, the GH shift is significantly enhanced by the SPR compared with non-resonance region. This phenomenon can be explained by the mechanism of SPR. When the resonance condition is satisfied, the incident wave is coupled to the graphene SPP. A drastic phase change will happen for the incident wavevector. In this case, we know that a huge GH shift will happen when the phase changes dramatically from (9).

To verify the calculated results by theoretical analysis, we perform a numerical simulation using the FDTD method. The incident wave is set as TM Gaussian wave and the half-width is $100\lambda_0$. The center of the incident wave arrives at the point (0,0) on the upper interface of the dielectric layer. We can get the lateral shift by comparing the center of the specular reflection between the reflected wave and incident wave. Fig. 2(b) shows the distributions of field amplitude. To show the GH shifts more intuitively, we normalized the incident wave and reflected wave. From the figure, the GH shift is negative as the symmetry axis of the reflected wave is on the right side of symmetry axis of the incident wave. The GH shift for TM incident wave is $\Delta_{GH} = 0.97mm = 16.2\lambda_0$, which agrees well with the theoretical predictions. Furthermore, the Goos-Hnchen shift in graphene has been observed in experiments [19]. Compared with other plasmonic materials, graphene supports large GH shift and the GH shift can be controlled by adjusting Fermi energy of graphene [20], [21].

3. Results

To show how the biosensor works, we choose two different refractive index medium and calculate the GH shifts. When the biomolecules are different, the refractive index of the medium is changed. The difference may be very small, so it is necessary to use high sensitivity biosensors. The refractive index of the two sensing medium is set as $n_s = 1.00$ and 1.01. Fig. 2(a) illustrates the variation of GH shifts with respect to incident angle for two mediums. As the figure shows, the GH shift curve moves towards higher angle of incidence when increasing the refractive index n_s. This result can be understood by the difference between two SPR curves. For the higher refractive index case, the resonance excitation of graphene plasmons takes place at a larger angle of incidence. Therefore, when a slight change in refractive index $\Delta n = 0.01$, a significant shift 690μm is observed.

Next, we discuss the performance of the biosensor. The most important performance parameter of an SPR biosensor is the sensitivity. The sensitivity can be defined as the ratio of the change in

GH shifts (D_{GH}) with the change in the refractive index (n_s) of the sensing layer [22]:

$$S_n = \frac{\delta D_{GH}}{\delta n_s}. \tag{10}$$

Fig. 2(c) illustrates the variation of sensitivity with the refractive index of the sensing medium. The chemical potential of graphene is set as 1.01 eV. The sensitivity shifts from negative to positive as the refractive index increases. The sensitivity coefficients can reach $2.5 \times 10^4 \mu$m/RIU when the refractive index is 1.347 and 1.354. The biosensor can detect the sample of which refractive index ranging from 1.33 to 1.37. Fig. 2(c) also shows the sensitivity changes with different graphene Fermi energy. With the increase of Fermi energy E_f, the maximum sensitivity moves to a higher refractive index. The figure clearly shows that the working range can be changed due to the tunability of graphene. Thus, before the biosensor works, the applied voltage of graphene should be changed to make the sensitivity locate in a suitable range. From the figure, we can also find that the sensitivity coefficient is closely related to the slope of the GH shift. We achieve high sensitivity sensors with the maximum sensitivity reaches up to $2.5 \times 10^4 \mu$m/RIU. It shows that the proposed configuration is much more sensitive than the precious terahertz biosensors [23]–[25]. For example, in Ref. [23], the sensitivity of Fano resonances biosensor is about 5.7×10^4nm/RIU. So the maximum sensitivity of our proposed biosensor is three orders of magnitude larger than that one. With the simple structure and high sensitivity, the graphene SPP-GH biosensor is crucial in developing precision measurement in terahertz sensors. The result shows that graphene is also a suitable material to construct biosensors in the terahertz regime [26].

It is possible to improve the performance of the biosensor. By studying (3), we can use two methods to improve sensitivity. The first method is to adjust the parameters of graphene, such as Fermi energy and scattering time. The purpose is to get large phase change in view of the SPR. The other method is that we can employ structures that can enhance the GH effects, such as graphene ribbons [27]. Furthermore, this graphene plasmonic configuration combined with Goos-Hänchen effect provides a high-sensitivity approach for future terahertz biosensing applications, which is not limited to graphene. Other materials or structures that support surface plasmons in the terahertz region can be used to construct SPP-GH biosensors. Specifically, alternative approaches include other 2D Van der Waals materials, such as black phosphorus, and structures that support spoof surface plasmons, such as metal grating [28], [29].

4. Conclusions

In conclusion, we proposed a high-resolution SPR terahertz sensor based on Goos-Hänchen effect in graphene. Graphene SPP is excited at the sensing interface thereby resulting in a higher sensitivity to the biomolecular. The plasmon resonance also produces phase retardation of the wave, which enhanced the GH shifts. Sample sensing can be realized by measuring the GH shifts of the reflected wave. Our analysis shows that the sensitivity can reach $2.5 \times 10^4 \mu$m/RIU for the refractive index 1.347 and 1.354. This simple ultrasensitive terahertz biosensor makes it possible to detect the small biomolecular more accurately and conveniently.

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