Low-threshold optical bistability with multilayer graphene-covering Otto configuration

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Abstract

In this paper, we propose a modified Otto configuration to realize tunable and low-threshold optical bistability at terahertz frequencies by attaching multilayer graphene sheets to a nonlinear substrate interface. Our work demonstrates that the threshold of optical bistability can be markedly reduced (three orders of magnitude) by covering the nonlinear substrate with multilayer graphene sheets, due to strong local field enhancement with the excitation of surface plasmons. We present the influences of the Fermi energy of graphene, the incident angle, the thickness of air gap and the relaxation time of graphene on the hysteresis phenomenon and give a way to optimize the surface plasmon resonance, which will enable us to further lower the minimal power requirements for realizing optical bistability due to the strong interaction of light with graphene sheets. These results are promising for realization of terahertz optical switches, optical modulators and logical devices.

Keywords: graphene, optical bistability, Otto configuration

(Some figures may appear in colour only in the online journal)

1. Introduction

Due to its unique and useful optical and electronic properties, graphene has attracted considerable attention from the photonics and optics community. As a next-generation material with the potential to replace traditional materials in electrical and optical devices, graphene has many fascinating optical properties [1–3], such as strong light–graphene interaction, mobility, broadband and high-speed operation, etc. It seems to be an ideal optical material candidate for designing controllable optical devices that operate in terahertz and other optical frequency ranges due to the tunability of the charge carrier density and conductivity of graphene [4]. Surface plasmons (SPs) are coherent delocalized electron oscillations that exist at a metal surface. In the past few decades, the subwavelength optics of SPs have been extensively studied by a wide range of scientists [5]. However, even precious metals, which are widely studied and treated as the best effective plasmonic materials, are hardly tunable and exhibit large losses that restrict their flexibility in optical communication and signal processing devices. Naik et al provided some alternative plasmonic materials beyond gold and silver [6]. Moreover, graphene SPs are an appropriate alternative to metal SPs because the former provide strong light–matter interaction and controllability, with the advantage of being highly tunable by some methods.
Optical bistability (OB) is a light control method using another light source [7, 8]. Bistability in nonlinear optical systems refers to an optical effect where one input intensity can induce two steady transmission light intensities, depending on the history of the input. The phenomenon of OB demonstrates a pragmatic method to optical memory [9], optical information processing [10], optical transistors [11] and so on. In general, OB can be realized at the interface between a linear and a nonlinear material, with the reflected light intensity showing hysteresis [12]. However, the possibility of realizing the hysteresis effect with one atom thick materials such as graphene seems to be emerging.

In the past few decades, there have been numerous researches on SPs in the field of biochemistry [13], physics [14], communication [15] and so on, but seldom reports about graphene SPs with the phenomenon of OB at terahertz frequencies. The investigation of SP modes in air–graphene–SiO2–Si structures showed that graphene-based transverse magnetic (TM) (or transverse electric (TE)) SPs are bound modes, which decay into the air in the range of tens of micrometers [16]. By depositing graphene with silicon photonic crystal cavity, Gu et al achieved an effective nonlinear optical device that could enable ultra-low-power resonant OB, self-induced regenerative oscillations and coherent four-wave mixing [17,18]. Bao et al demonstrated that graphene nanobubbles offer a new and promising type of optical nonlinear medium to overcome the optical path length limitation of atomically thin 2D films, so that OB and all optical switching are obtained in such graphene nanobubbles [19]. He et al made manifest an active tunable device in which the resonance of transmitted or reflected curves can be tuned in a wide range [20]. We have reported a tunable OB at the graphene-covered nonlinear interface, but the threshold for OB is high due to the shortage of effective feedback mechanisms [4]. Peres et al found that a single layer of graphene shows OB in the terahertz range in aerial suspension [21]. He et al showed that for graphene MM structures, the resonant transmission curves can be tuned over a wide range by controlling applied electric fields. As the Fermi level of the graphene layer increases, the resonant transmission becomes stronger, and the resonant dips shift significantly to higher frequency [22]. By considering the nonlinear conductivity of graphene, we established the theoretical relation of nonlinear optical response with respect to dielectric/nonlinear graphene/dielectric heterostructures and further demonstrated tunable OB at terahertz frequencies; however it seems that the threshold for OB is still high where SPs cannot be excited [23]. Recently, we proposed a modified Kretschmann–Raether configuration to realize low threshold optical bistable devices at terahertz frequencies [24]. It is found that the switching-up and switching-down intensities required to observe optical bistable behavior are lowered markedly due to the excitation of the graphene SPs, but the influence of the layer-number of graphene on the hysteresis effect is not significant. In this paper, we propose a modified Otto configuration to realize tunable and low-threshold OB at terahertz frequencies by attaching multilayer graphene sheets to the nonlinear substrate interface. Our work demonstrates that the threshold of OB can be markedly reduced (three orders of magnitude compared to monolayer graphene) by covering the nonlinear substrate with multiple layers of graphene sheets, due to the strong local field enhancement with the excitation of the SPs.

2. Model and method

Recently, researches have shown that graphene can also support well-confined SP modes in mid-infrared and terahertz ranges [25, 26]. As their electronic transport properties can be readily tuned via a gate voltage, graphene structures present an attractive alternative material for supporting SPs. However, due to the relatively large momentum mismatch between the SPs and the light photons, their excitation on graphene still remains a challenging issue. We investigate the excitation of SPs on highly doped graphene sheets with attenuated total reflection (ATR) via the modified Otto configuration. The geometrical setup is shown in figure 1, graphene is attached on a nonlinear substrate of refractive index $n_2 = 1.6$, which is separated from the Germanium prism ($n_p = 4$) by a small thickness air gap $d$ ($n_1 = 1$). In the following, the substrate is taken to be nonpolar so that effects of remote phonon scattering may be neglected. The graphene sheets sandwiched between two dielectric media support a single bound SPs mode, which is different from metallic thin films where the SPs dispersion splits into two beams. The applied electrode is also shown in figure 1, here we choose p-type transparent conducting oxide CuAlO2 thin film as the electrode due to its good conductivity and transparency in the terahertz range. The refractive index of CuAlO2 is about 2.0 in the mid-infrared and terahertz spectra [27]. If the nonlinear substrate is thick enough, the insertion of the transparent electrode will have no impact on the behavior of OB. Moreover, the refractive index of CuAlO2 is very near the linear refractive index of the nonlinear substrate.

Graphene is characterized by a complex surface conductivity $\sigma$, which is a function of angular frequency $\omega = (2\pi c)/\lambda$, Fermi energy $E_F$, electron–phonon relaxation time $\tau$ and absolute temperature $T$ of the environment. The complex surface conductivity $\sigma$ is contributed by intraband and interband terms $\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}$, which can be expressed according to the Kubo formula [4, 28].
\[ \sigma_{\text{intra}} = \frac{\text{i}e^2 k_0 T}{\pi \hbar (\omega + i\tau^{-1})} \left[ E_p k_0 T + 2 \ln(e^{ - E_p / k_0 T} + 1) \right] \]  
\[ \sigma_{\text{inter}} = \frac{\text{i}e^2}{4\pi \hbar} \ln \left[ \frac{2k_0 T}{2k_0 T + (\omega + i\tau^{-1})} \right], \]  
where \( e \) and \( \hbar \) are universal constants related to the electron charge and reduced Planck constants respectively, \( E_p \) is the Fermi energy (or chemical potential) and \( k_0 \) is the Boltzmann constant. In the following studies, we find that the graphene electron–phonon relaxation time can modify the hysteresis behavior markedly, and OB cannot be excited if the value for the relaxation time is too low. But if the structure is fixed, it is not easy to change the relaxation time \( \tau \). In the present work, as an example, we choose \( \tau = 0.5 \) ps. Moreover, we use the wavelength \( \lambda = 100 \) μm in the terahertz range. For short wavelengths, such as in near-infrared light (for example, \( \lambda = 1.0 \) μm), there is no OB phenomenon as a result of lack of the SPs in this wavelength. For the mid-infrared light (for example, \( \lambda = 10 \) μm), OB can occur, however the graphene will be broken down due to the very high power requirements for exciting OB.

Now, let us model each graphene monolayer as a surface conducting sheet with \( T = 300 \) K. Under the random-phase approximation, intraband scattering dominates in highly doped graphene, and its conductivity takes on a Drude-like [29] form \( \sigma = n e^2 / m \), where \( n \) is the carrier density. Obviously, \( \sigma_{\text{intra}} \) is highly dependent on the work frequency and Fermi energy. And the carrier density \( n_{2D} \) can be electrically controlled by an applied gate voltage, thereby leading to a voltage-controlled Fermi energy \( E_F \) and hence voltage-controlled surface conductivity \( \sigma \)—these could provide an effective route to achieving controlled OB in graphene-covered substrate interfaces.

Considering the monolayer graphene and the boundary condition, we can get the total reflection coefficient and total transmission coefficient for the light reflected and transmitted from the substrate interface covered by the graphene

\[ r = \frac{r_{1p} + r_{12} e^{2i k_0 d}}{1 + r_{1p} r_{12} e^{2i k_0 d}}, \quad t = \frac{t_{p1} e^{ik_0 d}}{1 + r_{1p} r_{12} e^{2i k_0 d}}, \]  
where \( r_{1p} \) and \( t_{p1} \) are the reflection coefficient and transmission coefficient at the interface of the Germanium prism and air gap,

\[ r_{1p} = \frac{k_p e_p - k_1 e_1}{k_p e_p + k_1 e_1}, \quad t_{p1} = \frac{2 k_p e_p}{k_p e_p + k_1 e_1}, \]  
where \( k_p = k_0 \cos \theta - \sqrt{\varepsilon_p}, k_1 = k_0 \sqrt{\varepsilon_1 - \varepsilon_p \sin^2 \theta}, \) \( k_0 = \omega / c, \) \( \varepsilon_p \) is the dielectric constant of the prism, \( e_1 \) is the dielectric constant of the air gap. \( r_{1p} \) and \( t_{p1} \) are independent of the graphene and nonlinear response, and hence have the same form as the Fresnel formula at the interface of conventional materials. However, \( r_{12} \) and \( t_{12} \), the reflection coefficient and transmission coefficient at the interface of the air gap and the substrate, are completely different from the ordinary Fresnel formula due to the presence of the graphene sheet and nonlinear effect in the substrate. According to our previous work [4], \( r_{12} \) and \( t_{12} \) can be expressed as

\[ r_{12} = \frac{k_1 e_1 (1 + \sigma k_2 e_2 / \varepsilon_0 \omega) - k_2 e_2}{k_1 e_1 (1 + \sigma k_2 e_2 / \varepsilon_0 \omega) + k_2 e_2}, \]  
\[ t_{12} = \frac{k_1 e_1}{k_1 e_1 (1 + \sigma k_2 e_2 / \varepsilon_0 \omega) + k_2 e_2}. \]

3. Results and discussions

The excitation of SPs with monolayer or multilayer graphene in the modified Otto configuration under lower incident power (linear substrate) is demonstrated with the reflection spectra in figure 2(a). In absence of graphene on the substrate surface, SPs cannot be excited due to the shortage of the negative permittivity at the interface of the air gap and dielectric substrate for the TM polarization. But with the addition of graphene sheets, the conditions for SPs can be satisfied owing to the negative imaginary part of the optical conductivity of graphene [30]. In order to excite SPs, we have adopted an Otto configuration by adding a high-index prism on the air gap. The properties of TM-polarized SPs in the Otto configuration have been investigated in detail in [30]. But what is most interesting is that the reflectance dips are moving to small incident angle rapidly and the angular widths of SP resonance (SPR) are becoming very narrow with the increase of the layer number of graphene sheets, which is pretty good for realizing low-threshold OB or optical switching—as we discuss in the next section. Moreover, SPR is very sensitive to the thickness of the air gap and the Fermi energy of graphene.
The dependences of the reflectance on the incident angle at the different thickness of the air gap and Fermi energy of graphene have been shown in figures 2(b) and (c) respectively. From these figures, we find that it is very important to optimize the SPR conditions to obtain the minimum reflectance and the narrowest angular width of SPR (in order to acquire the maximal local field enhancement), which is advantageous in obtaining low-threshold OB. It should also be noted that the large values of Fermi level—as large as $E_F = 0.9 \text{ eV}$—have been chosen in order to effectively excite SPs, here the reflection dip closes to but does not equal zero, as shown in figure 2(c). Moreover, it is found that Fermi energies as high as $E_F = 1 \text{ eV}$ have been achieved experimentally [31]. The Fermi energies can be further increased if patterned graphene is used, such as ribbons or plates.

Now we discuss the optimization of SPR by changing the thickness of the air gap at different layer numbers of graphene, as shown in figure 3. For $N = 1$ in figure 3(a), the optimal conditions for getting the minimum reflectance dips are situated around $d = 1.5 \text{ \mu m}$ and the resonant angle is about $\theta = 57.5^\circ$. However, the angular width is very wide and a minimum reflectance of less than 5% is hard to achieve, which leads to weak local field enhancement. For $N = 3$ in figure 3(b), the optimal conditions for getting the minimum reflectance dips are situated around $d = 4.5 \text{ \mu m}$ and the resonant angle is about $\theta = 25.5^\circ$. In this case, the angular width is becoming very narrow and the minimum reflectance is less than 1%, which can give rise to strong local field enhancement.

If further increase in the number of layers of graphene is implemented, the angular width of SPR can be narrowed further and the reflectance dip can reach almost perfect zero reflectance, as shown in figure 3(c). For $N = 5$, the optimal conditions for getting the minimum reflectance dips are situated around $d = 4.0 \text{ \mu m}$ and the resonant angle is about $\theta = 24.1^\circ$.

Next, we want to discuss the optical bistable behavior in the modified Otto configuration and demonstrate possible methods to lower the threshold of the optical hysteresis effect. In order to gain larger nonlinear index—as much as $n_2 = 1 \times 10^{-10} \text{ m}^2 \text{ W}^{-1}$—we choose a semiconductor, such as GaAs or InSb, as the nonlinear substrate [8]. In order to simplify the discussion, we also assume that this semiconductor is non-dispersive and the linear optical refractive index is $n_1 = 3.4$. Moreover, compared with common graphene substrates, e.g. Si or SiC, GaAs is a black–gray solid and can be stable in air. Further, the electron mobility of GaAs is 5–6 times larger than silicon. Hence, graphene on GaAs substrate is characterized by a rather high carrier density due to doping, so that we can tune the carrier density in this construction by adding a gate electrode to the surface of the GaAs substrate. At moderate levels of carrier density, the plasmon approaches the surface of graphene and GaAs leading to the effects of graphene SPs.

Without graphene on the nonlinear substrate, the hysteresis effect is hard to observe in our considered incident light power due to the lack of effective feedback mechanisms in the prism-air-nonlinear substrate structure. However, the optical
bistable behavior can be observed immediately if we cover the nonlinear substrate with a single-layer graphene sheet. As shown in figure 4(a), the typical S-shape curve of the relationship between the incident intensity and the reflected intensity has been discovered, and the hysteresis indicates bistability where two stable output powers can be obtained for a given input power. That is to say, OB can be realized by the insertion of graphene in this modified Otto configuration. In order to further understand the optical bistable behavior, we also show the dependence of the reflectance on the incident light intensity. We choose the incident angle $\theta = 80^\circ$ (> the resonant angle $\theta_R = 57.5^\circ$), hence it works in the total internal reflection (TIR) mode where the reflectance is high, as shown in figure 2(a) or figure 3(a). However, with the increases of the incident light intensity, the reflectance reduces gradually and it switches to low reflectance state (attenuated total internal reflection, ATIR) when the incident light intensity approaches the threshold value at $I_{th} \approx 4410$ kW cm$^{-2}$. But on the contrary, the reflectance decreases gradually if we decrease the incident intensity and it can switch from low reflectance state (ATIR mode) to high reflectance state (TIR mode) at the threshold value $I_{th} \approx 3105$ kW cm$^{-2}$. Apparently, this provides us a method to realize all-optical switching by using this novel optical bistable behavior. But there is a huge barrier due to the requirement of very high incident light intensity. Based on the previous discussion, we have known that we could realize optimal SPR conditions with very narrow angular width and very low reflectance dip by covering multilayer graphene sheets on the nonlinear substrate. Here, we choose $N = 3$ and $N = 5$ as examples, and the results have been shown in figures 4(b) and (c). For $N = 3$, we choose the incident angle $\theta = 27.5^\circ$ (> the resonant angle $\theta_R = 25.5^\circ$); and the threshold values are $I_{th} \approx 18.7$ kW cm$^{-2}$ and $I_{th} \approx 14.1$ kW cm$^{-2}$ respectively. Clearly, the threshold values have been reduced nearly 200 times, which is hard to achieve in the structure without SPR. One of the things that fascinate us most about OB is that the threshold values can be reduced further, as shown in figure 4(c) with $N = 5$. Here, we choose the

Figure 3. Dependences of the reflectance on the incident angle and thickness of air gap for different layer numbers of graphene sheets, (a) $N = 1$, (b) $N = 3$ and (c) $N = 5$. The other parameters are $\lambda = 100$ $\mu$m, $\tau = 500$ fs and $E_F = 0.8$ eV respectively.
incident angle \( \theta = 24.7^\circ \) (\( \theta > \theta_R = 24.1^\circ \)), the threshold values are \( I_{th} \approx 2.7 \text{ kW cm}^{-2} \) and \( I_{th} \approx 2.1 \text{ kW cm}^{-2} \), and the threshold values have been reduced nearly 1600 times (more than three orders of magnitude).

In addition to the influence of the layer-number of graphene sheets on the hysteresis effect, the Fermi energy of graphene, the incident angle, the thickness of air gap and the relaxation time of graphene are also exerting an important influence on the optical bistable behavior, as shown in figure 5. Figure 5(a) shows the effect of Fermi energy \( E_F \) on the reflectance bistability. Due to the dependence of the optical conductivity of graphene on the Fermi energy \( E_F \), the changing of \( E_F \) will make a great influence on the hysteresis effect. Moreover, the Fermi energy change as \( E_F = \hbar v_F(\pi n_{2D})^{1/2} \), where \( n \) is the carrier density \( n = C_g(V_g - V_{Dirac})/e \), \( C_g \), \( V_g \) and \( V_{Dirac} \) are the gate capacitance, gate voltage, and the gate voltage corresponding to the charge-neutral Dirac-point. Hence, the Fermi energy can be tuned by an external applied voltage, so the hysteresis effect can be electric field controlled. By decreasing the Fermi energy, the imaginary part of optical conductivity is decreased, hence needing less incident intensity to maintain OB, leading to the lower intensity shifts of switch-on and switch-off. However, as Fermi energy \( E_F \) increases both the switch-up and switch-down threshold light intensity shift to higher incident light intensity rapidly and the width of the hysteresis loop is also enhanced markedly. This might be useful to control the threshold value and the hysteresis cycle width of the bistable curve simply by adjusting the Fermi energy of the graphene sheet. Consequently, it provides an effective way of manipulating OB by an external applied voltage.

Besides the dependence of the reflectance on the Fermi energy, it is also influenced by the parameters of the incident light, which are shown in figure 5(b). When the incident angle increases, it needs more light intensity to switch the reflectance from TIR mode to ATIR mode, hence the bistability seems obvious and the switch-on and switch-off are enhanced. What is more, OB is also strongly dependent on the thickness of the air gap, as shown in figure 5(c). It is clear that both the switch-on and switch-off shift to high values with increasing thickness due to the thickness deviating from the optimal thickness and hence needing greater incident light intensity. Furthermore, it is worth studying the influence of the losses (the electron-relaxation time and the losses have an inverse relationship) in graphene on the bistable behavior in THz. Figure 5(d) displays the curves of OB at different relaxation times of graphene. It can be seen that the influence of the losses in graphene on the hysteresis is obvious and significant. As the electron–phonon relaxation time decreases, the loss is...
increased and it needs more incident light intensity to realize the switching from TIR mode to ATIR mode, hence both the switch-on and switch-off threshold shift to higher values, showing the incident intensity should be enhanced to give rise to OB. Moreover, it is presented that if the relaxation time is small enough, the hysteresis loop may disappear and OB does not exist.

4. Conclusion

In summary, we analyzed the hysteresis response of a modified Otto configuration with graphene sheets covering a nonlinear dielectric substrate. Our work demonstrated that the threshold of OB can be markedly reduced by covering multi-layer graphene sheets on the nonlinear substrate due to strong local field enhancement with the excitation of SPs, where the threshold value can be reduced by three orders of magnitude by increasing the layer number of graphene to five. Moreover, we also presented that the OB is dependent on the properties of graphene (such as the Fermi energy and relaxation time), the thickness of air gap, the angle of the incident light and the incident wavelength. The tunability and the low threshold of OB with graphene could prepare the way to optical logic, optical memory, optical transistors and all-optical switching, etc.

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