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A Plasmon Modulator by Directly Controlling the Couple of Photon and Electron

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Abstract: As a strong couple mode of photon and electron collective oscillation, the movement of an electron can affect the collective plasmon behaviors efficiently. In this paper, we proposed a novel method for modulating the plasmon by directly controlling the movement of the electron but independent of the properties of the medium. This method is demonstrated by a hybrid graphene-dielectric-interdigital electrode structure in the mid-infrared range. It is possible to regulate the confinement of the graphene carrier and stimulate the plasmon in real-time by using the potential wells created by interdigital electrodes. Furthermore, the plasmon frequency can also be modulated utilizing changing the confined area and the density of the carrier. As a result. the frequency has been tuned over a range of ~ 33 cm^{-1} by applying voltage, and the maximum extinction ratio we measured is 8%. Due to the movement of the electron can also be driven optically, these findings may define a new approach to the all-optical modulator with low pump power.

The optical modulator is a device that modifies the polarization, frequency, amplitude, or phase of light, and it plays a very important role in high-end communication systems [1-3]. The traditional optical modulation mainly includes electro-optic crystal, semiconductor, microring resonator, M-Z interference, and photonic crystal[4-10]. They are generally modulated by controlling the optical properties of the dielectric or the physical structure, leading to its modulation efficiency that is highly dependent on the medium. Herein, the performance of the optical modulator has the potential to be further optimized owing to the weak light-matter interaction.

Surface plasmon polaritons (SPPs) are modes of electromagnetic waves propagating along a metal surface by the interaction of light waves and surface charges. In this mode, the light wave is localized at the interface between metal and dielectric, and there is a strong coupling between the light field and the free electrons on the metal surface, which offers a unique way to concentrate optical fields down to nanometer-sized regions and to achieve a significant field enhancement[11-15]. Various plasmonic optical components, including lenses, reflectors, and waveguides, have demonstrated the potential capabilities of plasmonics to shrink the photonic circuits below the diffraction limit[16-20]. As the movement of electrons can affect the collective plasmon behaviors efficiently, if we can find a method that directly controlling the properties, such as the movement or density distribution, of the electron, the modulation efficiency can be further improved. However, due to the large disparity in electron density, it is difficult to modify the characteristics of the

electron in metal but possible in some two-dimensional materials[20-25]. Graphene is a promising material in photonic and optoelectronic applications due to its superior properties of high carrier mobility, broadband optical response, and facile electrical tunability, which originate from its unique linear dispersion of massless Dirac fermions[26-30]. It was predicted that highly-doped graphene can support surface plasmons (SPs) from mid-infrared to terahertz frequencies with a much higher degree of spatial confinement and relatively lower losses concerning the noble metal plasmons. Because of its unique electronic characteristics, graphene is a viable foundation for developing highly integrated active plasmonic devices and systems, which have applications in the photodetector, modulator polarizer, and biosensor fields [30-33].

In this letter, we report a new method to modulate the plasmon by directly controlling a couple of electrons and photons. This method is demonstrated by a hybrid graphene-dielectric-interdigital electrode structure. The carrier movement of graphene is directly controlled in micrometer-sized regions by the potential wells formed from the interdigital electrode, and the excitation of SPPs is demonstrated experimentally. The frequency of plasmon is modulated utilizing controlling the confined area and density of carrier, whose frequency has to be tuned over a range of ~ 33 cm^{-1} by the applied voltage, and the maximum extinction ratio we measured is 8%. In addition, due to the movement of the electron can also be driven optically, this method paved the way to the all-optical modulator with low pump power. Compared with the traditional plasmon modulator, this new type of modulator is independent of the properties of medium but directly controlled the couple of photon and electron, which has the potential to improve the modulation efficiency and be used for future plasmonic devices, integrated sensor and photonic circuits[34-35].

In Fig. 1. We illustrate the overall design of our hybrid system. The central part is a graphene monolayer-dielectric-interdigital electrode structure. The interdigital electrode is designed to control the movement of the carrier on the graphene surface, and the poly(methyl methacrylate) (PMMA) acts as a dielectric layer. The electron in graphene will reflect when its energy is smaller than the potential well-formed by the applied voltage from the interdigital electrode, thus, the plasmon can be actively excited and controlled owing to the confined electron[36]. Its energy is absorbed in the graphene layer because the excited plasmon when the polarized infrared (IR) beam incident to the structure, which introduced a resonant dip in the transmission spectrum and can be detected. Additionally, the plasmon frequency can also be modulated utilizing changing the confined area and the density of the electron.

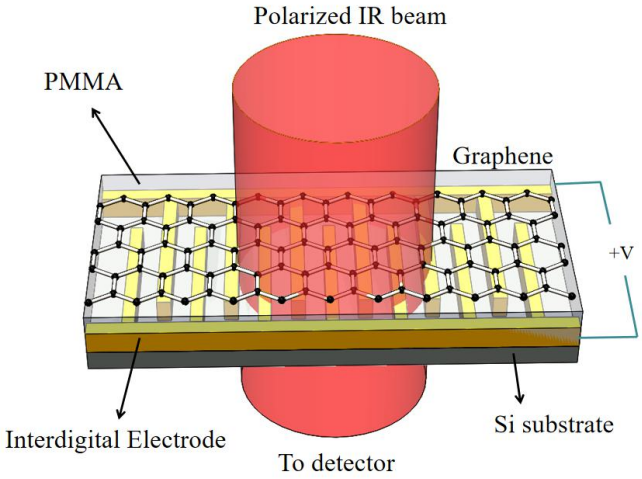


Figure 1 The schematic of the modulator, with a graphene on the interdigital electrode, and the PMMA act as a dielectric layer, the voltage is applied on the interdigital electrode.

A theoretical understanding of the movement of the carrier to the resonant frequency in nano-ribbon arrays is presented. Under a normal-incidence beam, the resonance frequency ω of the graphene nano-ribbons can be expressed as[37]

$$\omega = \sqrt{\frac{2\pi e^2 E_f}{\varepsilon_0 h^2 d}} \tag{1}$$

$$E_f = h v_f \sqrt{\pi |n|} \tag{2}$$

Where h, e and ε_0 are the Planck constant, the charge and the permittivity of vacuum respectively, and E_f is the Fermi energy. It can be obtained from equation 1 and 2 that the resonance frequency ω of the graphene nano-ribbons varies with the width d and carrier density n ($d^{-1/2}$ and $n^{1/4}$). While in the homogeneous graphene, it is related to the confined area and the density of carrier similarly, which can be utilized to build active graphene plasmonic devices in various frequency ranges.

Figures 2(a) and 2(b) show the electrical potential and the electron density distribution of the proposed model to uncover the movement of carrier trend obtained with the FDTD (COMSOL software) method. The electron distributes on the graphene surface periodically when the voltage is applied to the interdigital electrode. Figure 2(c) showed the distribution of electron versus different voltage, the electron is limited in a smaller area with a higher density as the voltage increased from 1V to 5V, results in a shift of plasmon frequency. Figure 2(d) showed the electron distribution versus different periods from 0.8μm to 1.6 μm. The simulated results show that a longer period corresponds to a more confined area. As the important factors that affect the plasmon frequency, both the confined area and the density of the carrier can be used to control the resonant frequency effectively through applying voltage or changing the structure parameter.

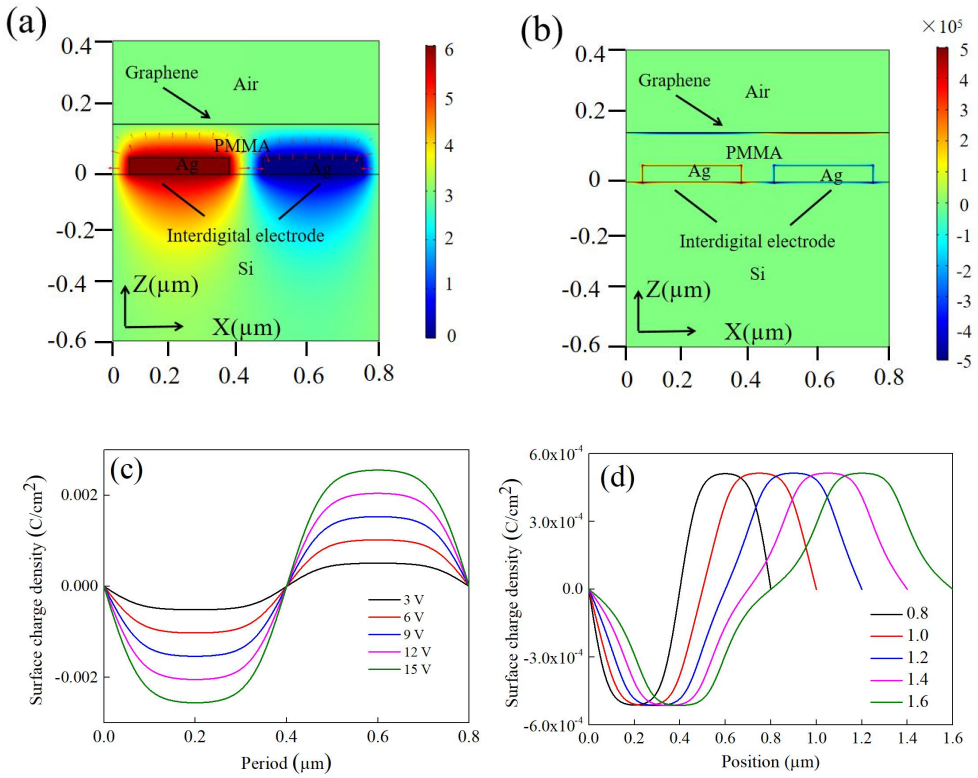
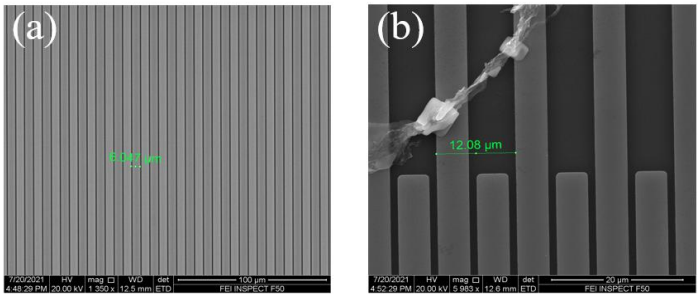


Figure 2 (a)The electrical potential and (b) surface charge density distribution of the proposed structure on graphene under the voltage of 6V (c)the surface charge density distribution versus the voltage from 3V to 15 V (d)the surface charge density distribution versus the period from 0.8μm to 1.6 μm.

The following steps are used to build the fabricate the structure shown in Figure 1: (1) Traditional photolithography and lift-off techniques were used to create the interdigital electrodes. The linewidth, period and thickness of interdigital electrodes are 5 μm, 12 μm and 80 nm respectively. (2) A 100nm-thick layer of PMMA was then span on top of the interdigital electrodes as the dielectric layer. (3) Chemical vapor deposition (CVD)-grown monolayer graphene was then transferred on top of the PMMA as the propagation medium of SPPs[38]. The quality of prepared interdigital electrodes and graphene is verified via scanning electron microscope(SEM), the SEM images are shown in Figures 3(a) and 3(b). Although there is some cracking on the graphene, it has a negligible effect on the transmission spectra.



Figur 3 The SEM image of (a) interdigital electrode and (b) graphene.

We performed polarization-dependent transmission experiments on the fabricated devices using Fourier transform infrared spectroscopy (FTIR) in the mid-infrared region (Vertex 80V). SPPs can be excited only when the input light is polarized perpendicular to the interdigital electrode and the carrier is confined by the potential wells, its energy is absorbed in the graphene layer, which introduces a resonant dip in the transmission spectrum ($T_{\perp}$). No resonance features are expected on the transmission spectra of light polarized along the grating lines ($T_{//}$). The transmission spectrum as a function of the applied voltage is shown in Figure 4, demonstrating the effective tuning ability of the carrier density and confined area in the graphene layer. Here $T_{\perp}/T_{//}$ is plotted versus frequency for different voltages in the mid-infrared region. The transmission spectra are smooth when there is no voltage applied to the interdigital electrode, the plasmon can not be excited. The transmission spectra of a sample with a period of 12 μm are showed in figure 4(a), a large blue shift of 33 cm^{-1} of the resonance frequency is observed (807cm^{-1}, 825cm^{-1}, 840cm^{-1}) as the interdigital electrode applied different voltage from 3 to 9 V, it is due to the increase of carrier density and the minimization of a confined area. The transmission spectra of the sample with a linewidth of 5 μm and a period of 14 μm are showed in figure 4(b). Compared with figure 4(a), its absorption peak is located at a lower frequency and has a smaller frequency shift owing to the wider confined area under the same voltage. The maximum extinction ratio (ER) of the proposed structure is shown in figure 4(c), which is approximately 8%. The ER of the resonance varies from device to device, presumably due to sampling uniformity variations. The ER of the resonance can be increased by improving the quality of the graphene layer and the fabrication processes.

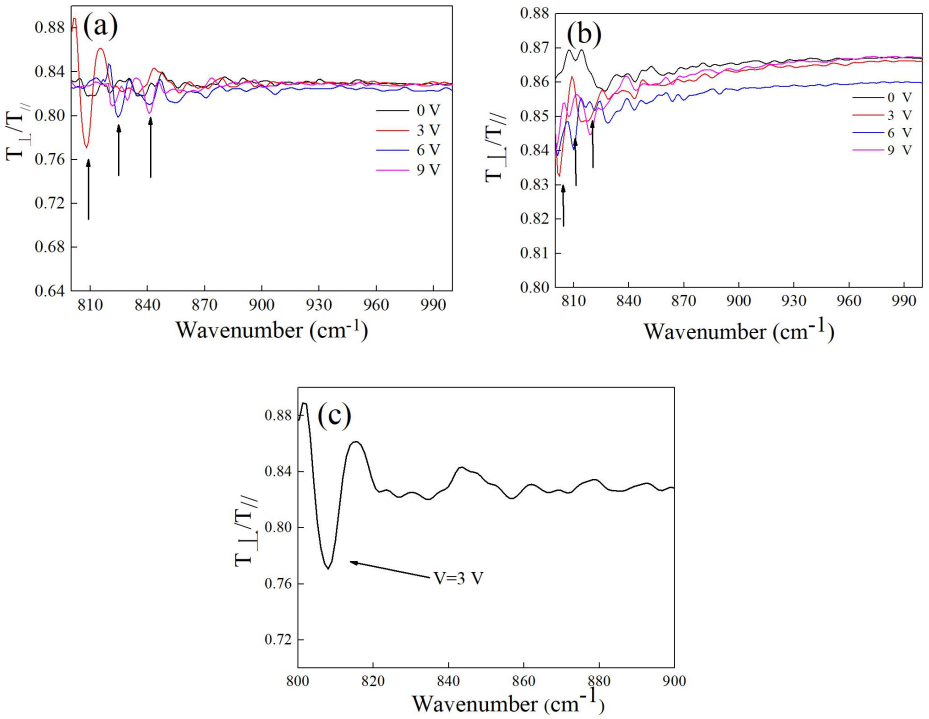


Figure 4 The transmission spectra at different voltage of the sample (a)with a period of 12 um (b) with a period of 14 um (c) the maximum ER of the sample is about 8%.

The influence of the width of graphene nano-ribbon on the transmission spectrum is also simulated, aiming at further verified the tunability of the confined area to the resonant frequency. Figure 5(a) is the schematic of the model we used for simulation, and the transmission spectra versus different frequencies and widths are showed in Figure 5(b). An obvious resonant dip has appeared at the widths of 289 nm, 299nm and 314nm when the laser incident with a frequency of 840, 825 and 807 cm^{-1} respectively, because the carrier oscillated when the laser polarized perpendicular to the graphene nano-ribbons and the plasmon is excited, its energy is absorbed in the graphene layer, leading to a resonant dip in the transmission spectrum. It convincingly proved that a small confined area will lead to a blue shift of the resonant frequency. The increase of carrier density can also lead to the blue shift of the transmission spectrum according to the equation (1) and (2). In our experimental result, the blue shift of the resonant frequency is caused by both reduced area confinement and higher carrier density; these two variables may be used to regulate the plasmon efficiently.

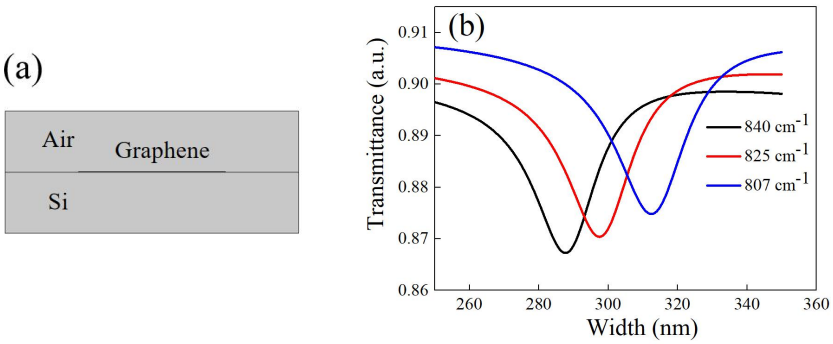


Figure 5 (a)The schematic of simulation (b)The transmission versus the width at the frequency of 840, 825 and 807 cm^{-1} respectively.

In conclusion, we proposed a new type of graphene plasmon modulator by directly controlling a couple of electrons and photons but independent of the properties of the medium. The modulator consists of a hybrid graphene-dielectric-interdigital electrode structure, the confinement of the carrier can be controlled by the potential well-formed by the voltage applied on the interdigital electrode to excite the plasmon. The frequency of plasmon can also be tuned by changing the confined area and the density of the carrier. The experimental results showed that the modulation efficiency can be improved effectively. Additionally, because the elcetron's mobility may be controlled optically, our technique opens up a new direction for all-optical modulators with low pump power.

Data availability

The data relative to the experiments discussed in this work are available upon reasonable request from the corresponding author changgui lu.

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Author contributions

Changgui Lu conceived the idea. Xiangyue Zhao and Shuping jin contributed to the numerical simulation. Xuefang Hu and Yinwei Gu contributed to the experiment. Xuefang Hu and Xiangyue Zhao analyzed the results and contributed to preparation of the manuscript. Yiping Cui supervised the project.

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Ethic

This article does not present research with ethical considerations.

Competing interests

Te authors declare no competing interests.