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A dynamically tunable plasmonic multi-functional device based on graphene nano-sheet pair arrays

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ABSTRACT

Dynamically tunable plasmonic multi-functional is particularly desirable for various nanotechnological applications. In this paper, graphene nano-sheet pair arrays separated by a substrate, which can act as a dynamically tunable plasmonic band stop filter with transmission at resonance wavelength lower than 1%, a high sensitivity refractive index sensor with sensitivity up to 4879 nm/RIU, figure of merit of 40.66 and a two circuit optical switch with the modulation depth up to 0.998, are proposed and numerically investigated. These excellent optical performances are calculated by using FDTD numerical modeling and theoretical deduction. Simulation results show that a slight variation of chemical potential of the graphene nano-sheet can achieve significant resonance wavelength shifts. In additional, the resonance wavelength and transmission of this plasmonic device can be tuned easily by two voltages owing to the simple patterned graphene. These studies may have great potential in fabrication of multi-functional and dynamically tunable optoelectronic integrated devices.

1. Introduction

Much efforts have been made to achieve miniaturization and high-density integration of optical circuits during the past decade. Surface plasmon polaritons (SPPs) is the main approach to solve this problem [1]. SPPs are light waves propagating along the interface between a dielectric and a metal that can be laterally confined below the diffraction limit [1,2]. Due to their potential to control light in nanoscale, an amount of surface plasmon devices based on metal have been investigated. However, these devices cannot be made tunable since the devices fabricated. Graphene, a single layer carbon atoms arrayed in honeycomb lattices, has becoming a new research hotspot in physics and engineering owing to its unique optical and electronic features such as tunability via external gate voltage, subwavelength light confinement, exceptionally high carrier mobility, and low losses [3–5]. It has become a promising candidate for the surface plasmon devices at nanoscale. Various graphene based optical devices have been theoretically explored or experimentally demonstrated, such as splitters [6], terahertz modulator [7], dynamically electrically tunable absorber [8–12], biological sensor [13], tunable filters [14–18]. high sensitivity refractive index sensor [19], and plasmonic switches [20,21]. However, most graphene based optical devices are single functional since devices fabricated and the optical performances are not good enough. For example, modulation depth (*MD*) is lower than 90% for most switches, the minimum transmission is higher than 5% for many band stop filters and the sensitivity is relatively low for most refractive index sensors. Moreover, the optical devices with complicated graphene structure not only increase the device fabrication technique difficulty but also result in their optical performances tuning difficulty via gate voltage. Compared with the above studies, achieving a multi-functional, dynamically tunable optical plasmonic devices with excellent performances based on a simple patterned graphene is very necessary for the optical multi-facility usage.

Inspired by the above elementary investigations, we proposed a multi-functional plasmonic device based on graphene nano-sheet pair arrays which can act as active tunable band stop filter, high sensitivity refractive index sensor and two circuit optical switch. The transmission and resonance wavelength of this multi-functional device can be tuned easily by two voltages which applied on graphene. The optical performances of this multi-functional device are excellent and optical performances are calculated by theoretical deduction and FDTD numerical modeling. Simulation results show the resonance wavelength has a significant shift up to 1.62 μm when we only increase the chemical

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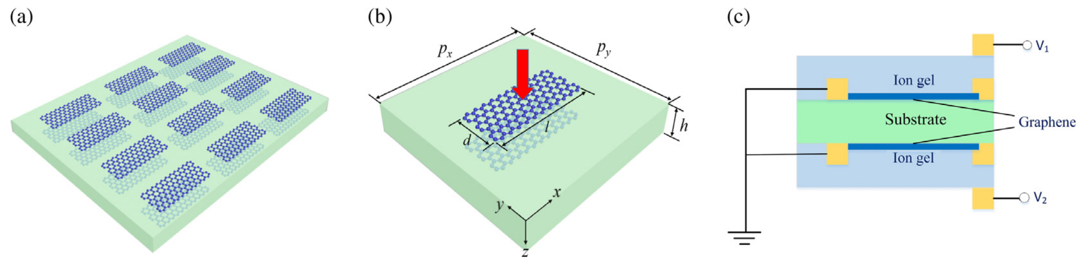

Fig. 1. (a) Schematic model of graphene nano-sheet pair arrays on a substrate. (b) A linearly x-polarized plane wave propagates along the z axis direction. The graphene are located on the upper and lower surfaces of the substrate. Periodicities $P_x = P_y = 300$ nm and the width of substrate $h = 1$ μm. (c) Side view of the device.

potential of the upper or lower graphene nano-sheet from 0.41 eV to 0.5 eV. The transmission dips at resonance wavelength are lower than 1%. The structure can be used as a high-sensitivity refractive index sensor with sensitivity up to 4879 nm/RIU (refractive index unit) as a result of the resonance wavelength highly sensitive to the background refractive index. Moreover, a two-circuit optical switch with the *MD* up to 0.998 regulated by the graphene's chemical potential is realized. These studies may have great potential in fabrication of multi-functional and dynamically tunable optoelectronic integrated devices.

2. Theory and model design

A normally incident linearly polarized perpendicular to the ribbons wave along z axis direction is used to excite the surface plasmon mode [22,23]. The surface plasmon polaritons (SPPs) for TM waves can propagate perpendicular to the direction of ribbons with low loss and the plasmon modes form a standing wave in the graphene nanostrips. For a graphene with N-layers, the conductivity is taken as $\sigma_N(\omega) = N\sigma(\omega)$ [24,25], the dispersion relationship of SPPs for TM mode is given by [26–28]:

$$k_{SPP} = \frac{i\left(\varepsilon_{med} + \varepsilon_{sub}\right)\varepsilon_0 c}{N\sigma(\omega)} k_0 \quad (1)$$

where k_{SPP} is wave vector of plasmonic wave in graphene, N represents the layers of graphene. k_0 is the free-space wave vector, ε_{sub} and ε_{med} are the relative dielectric permittivity of the substrate beneath graphene and the medium above graphene, respectively, ε_0 is the permittivity of vacuum, c is the speed of light in vacuum, and $\sigma(\omega)$ is surface conductive of monolayer graphene. $\varepsilon_{med} = {n_b}^2$, n_b represent the refractive index of background.

The surface conductive of monolayer graphene is governed by Kubo formula [29] which depends on the momentum relaxation time τ, incident wavelength λ (angular frequency ω), temperature T and chemical potential u_c. The scattering rate can be expressed by $\Gamma = \tau^{-1}$. At room temperature $T = 300$ K and for mid-infrared wavelengths, the surface conductivity of graphene may be approximated with a Drude-like expression [24]

$$\sigma(\omega) \approx \frac{ie^2\mu_c}{\pi\hbar^2\left(\omega + i\tau^{-1}\right)} \quad (2)$$

where e is the elementary charge and $\hbar$ is the reduced Planck's constant. Combining Eqs. (1) and (2), the wavevector of plasmonic wave can be expressed as:

$$k_{SPP} \approx \frac{\pi\hbar^2\varepsilon_0\left(\varepsilon_{med} + \varepsilon_{sub}\right)}{Ne^2\mu_c}\omega\left(\omega + i\tau^{-1}\right) \quad (3)$$

In general, the relationship between wave wavevector of plasmonic wave k_{SPP} and L_{eqv} can be described by [30,31]

$$\mathrm{Re}\left(k_{SPP}\right) \propto \frac{1}{L_{eqv}} \quad (4)$$

where L_{eqv} represents the equivalent resonant length of rectangle graphene nanostructure [31]. From Eq. (4), the resonance wavelength can be expressed by:

$$\lambda_{res}^2 \propto \frac{\varepsilon_{med} + \varepsilon_{sub}}{N\mu_c} \quad (5)$$

Combine the Scale factor k which deduced from the simulation result, Eq. (5) can be written as:

$$\lambda_{res}^2 = k\frac{\varepsilon_{med} + \varepsilon_{sub}}{\mu_c} \quad (6)$$

The schematic diagram of graphene nano-sheet pair arrays separated by a substrate is showed in Fig. 1(a) and the unit cell structure of this model is depicted in Fig. 1(b). The graphene sheets with N-layers are located on the upper and lower surfaces of the substrate, respectively. In these calculations, a linearly x-polarized plane wave propagates along the z axis direction. The periodic boundary conditions are used along x and y direction and perfectly matched layer boundary conditions is employed in z direction. The refractive index of substrate is 1.5. The period of the structure along x and y direction $P_x = P_y = 300$ nm. Here, we consider that the upper and lower graphene nanostrips are represented by graphene 1 and graphene 2. The d and l are the width and length of graphene sheet respectively. The geometric parameters of graphene 1 and graphene 2 are same. We set the substrate width h is 1 μm. The carrier concentration (n) in patterned graphene layers is controlled using an ion-gel top gate [23], which is shown in Fig. 1(c). The chemical potential can be described as $\mu_c = \hbar v_F(\pi n)^{1/2}$ [23], where the Fermi velocity of the graphene v_F is 10^6 m/s.

3. Results

3.1. Dynamically tunable plasmonic band stop filter

First, we investigate the geometric parameters on the transmission and wavelengths with monolayer graphene. Fig. 2(a) and (b) show the transmission spectra under different values of geometric parameters with the graphene sheet chemical potential as $U_{C1} = 0.47$ eV and $U_{C2} = 0.1$ eV. As expected, a perfect filter with the transmission lower than 1% is obtained owing to surface plasmon resonance which produced at graphene/dielectric interfaces. From the transmission spectra, we observe that the resonance wavelengths are dominated significantly by the geometric parameters l and d. As increase the width d of graphene sheet from 40 nm to 60 nm, the wavelengths are clearly blue-shifting with $l = 150$ nm. While, the wavelengths are red-shifting obviously as the length l increases of 20 nm under $d = 50$ nm. It is remarkable that the transmission and wavelengths tuning via d and l are very useful in designing a band stop filter with specific requirement.

The transmission properties of this proposed filter not only depend on geometric parameters but also material parameters of graphene, especially the graphene conductivity σ_g. From the Kubo formulas, the graphene conductivity is relate to the chemical potential which can be changed by gate voltage. By this way, the fabricated filters with dynamic tunability can be obtained. Transmission spectra under different chemical potential are studied with the $l = 150$ nm and $d = 50$ nm. Fig. 3(a) shows the simulated transmission spectra under chemical potential of the lower graphene $U_{C2} = 0.1$ eV and the upper graphene's chemical