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A symmetric terahertz graphene-based hybrid plasmonic waveguide

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ABSTRACT

A graphene-based hybrid plasmonic waveguide (GHPW) structure, which works on the terahertz frequency and includes two identical cylinder robs symmetrically put on each side of graphene sheet with gaps *g*, has been proposed and investigated. The present waveguide not only significantly improves the propagation length but also maintains a compact mode area, which is due to the coupling between the dielectric waveguide mode and plasmonic mode. The graphene plasmons particularly differ from plasmons in noble metals of which propagation loss can be tuned by adjusting the Fermi energy level or carrier mobility. With a very good Fermi energy level and carrier mobility, a typical propagation length of 26.7 mm, and mode area of optical field of approximately 4 μm^2 at 10 THz are achieved. This waveguide structure shows great promise for designing kinds of functional elements in actively tunable integrated optical devices.

1. Introduction

Surface plasmon polaritons (SPPs), the collective oscillation arising from the coupling between the incident field and the collective plasma excitations of metals [1–3], have been identified in a many research fields, ranging from thin metallic films [4], down to nano-scale structures [5], and more recently in graphene [6–10]. The incident light can drive a collective spring motion of free charges back and forth between the opposite ends of the patterned metal structures [5]. The motion is capable of focusing light and enhancing the electric field magnitude over several orders [9]. Nano-scale gaps or slots in metallic films [11–13] give a rise to a large field enhancement, which can now be reliably manufactured at less than 10 nm [11]. New metal-based plasmonic waveguide structures with designed functionalities spring up, such as optical modulator [14–15], plasmonic nano-antenna [16–17], plasmonic filter [18–19]. Noble metals, for example, gold and silver, are usually served to support SPPs from the visible to infrared frequency. Compared with SPPs at visible frequency, terahertz (0.1–10 THz) SPPs are very weakly confined on the metal surface, making them unsuitable for compact integration. The SPPs supported by graphene can be confined down to volumes that are several orders of magnitude smaller than plasmons in noble metals [20]. Graphene, a unique 2D carbon atoms arranged in a honeycomb lattice [21–22], has been considered as a promising plasmonic material for light-matter interactions from terahertz to the infrared region [23].

Recently, graphene plasmonics has attracted tremendous attention in optoelectronic field. Generally, SPPs are difficulty to manipulate without changes in the geometry or component of the metal-based waveguide structures on which they are supported [24–26]. Fortunately, the scientific prediction and experimental observation of graphene plasmons (GPs), which provide a new approach to control SPPs by electric methods or by chemical doping [6–10,27].The direct interaction of infrared confined GPs has been showed with employing a stacked graphene micro-disks, which enable the plasmons to be dynamically controlled by changing the disk diameter, the filling factor, the number or the doping of graphene layers [28]. The most exciting was the recent observation of intrinsic GPs [9]. An excess of electrons or holes in doped graphene can produce collective plasmons oscillation, similar to that in traditional noble metals (silver and gold) [29–30]. However, compared to traditional plasmonic materials, graphene presents more appealing features, involving tunability, strong confinement, low loss and crystallinity [31–32]. Due to these striking characteristics, graphene has recently been served as an effective plasmons waveguiding platform in the terahertz and infrared frequencies. The combination graphene and silicon-based waveguides, for instance, making it is possible to design a graphene-based, waveduide-interated optical broadband modulator [33].

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Manipulating the optical field is at the heart of optical modern information processing. But, photons do not possess charge, an effective way to control them by electrical methods has so far proved elusive. A promising approach for realizing electric control of light could be through SPPs—coupled excitations of photons and charge carriers—in graphene. It is expected that SPPs and their related optical fields can easily be tuned electrically by changing the carrier density of graphene. Here, we describe a symmetric terahertz graphene-based hybrid plasmonic waveguide to flexibly control SPPs by adjusting model parameters and graphene properties. In previous works, literatures [34] and [35] are based on a single microfiber structure, the employment of two microfibers give a strong coupling, achieving a better performance. In addition, graphene properties, for example, Fermi energy level and carrier mobility, which have a great influence on the waveguides, are not considered. Literatures [36] and [37] have proposed a rectangular waveguide and a dielectric wedge waveguide, respectively. Again graphene properties are not fully considered. And different from traditional metal-based plasmonic waveguides, the present GHPW provides more freedom to manipulate SPPs by gate voltage, electric method, magnetic method, or chemical doping. It is of great significance to achieve tunability of the GHPW. Benefit from the combining the dielectric cylinder waveguide mode with graphene plasmonic mode, a much larger optical force with low propagation loss is achieved as we expected.

2. Calculation method

Graphene's complex conductivity ($\sigma_g = \sigma_{\text{intra}} + \sigma_{\text{inter}}$) can be referred by Kubo formula [38], depending on the angular frequency ω, temperature T, Fermi energy level E_F, and momentum relaxation time τ. The frequency dependent optical conductivity of graphene considering both intraband (σ_{intra}) and interband (σ_{inter}) optical transitions is calculated by:

$$\sigma_g = i\frac{e^2 k_B T}{\pi\hbar^2\left(\omega + i\tau^{-1}\right)}\left[\frac{E_F}{k_B T} + 2\ln\left(e^{-E_F/k_B T} + 1\right)\right] + i\frac{e^2 k_B T}{4\pi\hbar^2}\ln\left[\frac{2|E_F| - \hbar\left(\omega + i\tau^{-1}\right)}{2|E_F| + \hbar\left(\omega + i\tau^{-1}\right)}\right] \quad (1)$$

In Eq. (1), when $\sigma_{g,i}>0$ ($\sigma_{g,i}$ represents the imaginary part of graphene's complex conductivity σ_g), a graphene sheet performs as an ultra-thin "metal" layer which is capable of supporting a transverse-magnetic (TM) SPPs surface wave [26]. However, when $\sigma_{g,i}<0$, a weakly guided transverse-electric (TE) SPPs surface wave might be only offered. The most attractive feature of graphene is that its Fermi energy level E_F can be tailored ranging from typical −1.0 eV to 1.0 eV through employing a dc-biased device. By using different values of E_F, certain desired graphene conductivity patterns can be achieved. The equivalent permittivity of graphene is defined as [31]

$$\varepsilon_g = 1 + \frac{i\sigma_g\eta_0}{k_0 t} \quad (2)$$

where η_0 is impedance of free space, and k_0 is the wavenumber at the incident wavelength of $\lambda = 10$ μm. General consideration for actual situation, $T = 300$ K. The carrier relaxation time τ depends on the carrier mobility μ and Fermi energy level E_F in graphene. Recently, a carrier mobility of μ=230, 000 cm^2/(V s) has been experimentally obtained in high-quality suspended graphene [39], corresponding to the relaxation time of τ=3.45 ps as the Fermi energy level E_F is tailored to be 0.15 eV due to $\tau = E_F\mu/\left(ev^2{}_F\right)$, where e is the electron charge and $v_F = 10^6$ m/s is the Fermi velocity. Then, the research on graphene terahertz metamaterial shows carrier mobility of μ=1000 cm^2/(V s) has also been achieved in chemical vapor deposition (CVD) grown graphene [40]. In this paper, we use Fermi energy level E_F from 0.1 eV to 1.0 eV and carrier mobility μ from 2000 cm^2/(V s) to 100,000 cm^2/(V s).

3. The GHPW structure and results

The geometric structure of the terahertz GHPW is schematically shown in Fig. 1. A pair of cylinder robs with radius R are deposited onto both sides of graphene sheet with gaps g. Silicon and silica as shown in Fig. 1, are chosen to perform the high-index and low-index dielectric layer for the GHPW, and the permittivity of Si, and SiO_2 is ε_{si} = 12.25 and ε_{SiO_2}=2.25, respectively. The thickness of graphene sheet is set as a typical value t=0.7 nm. The excited SPPs propagate along the z-axis direction for the supported TM electromagnetic mode.

Generally, fundamental mode operation is more preferred for expected applications, as high-order modes would be ignored. The waveguide propagation properties are investigated based on finite-element-method (FEM) using COMSOL. In convergence analysis, the x-direction and y-direction along computational domain is considered to be enough long to make sure a strict eigenvalue.

To quantitatively demonstrate GHPW's potential in offering field confinement along with low mode loss, we modulate the dielectric gap distance, g, and the key parameters (Fermi energy level E_F and carrier mobility μ) of graphene to study the mode field

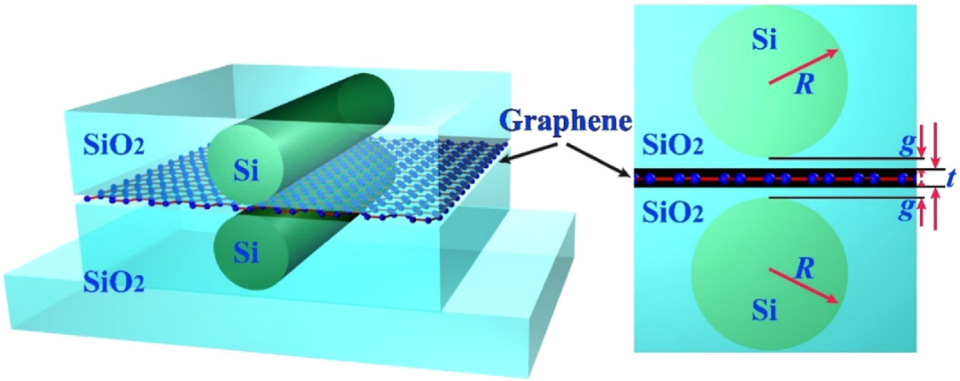

Fig. 1. Schematic structure of a graphene-based hybrid plsamonic waveguide, where two identical cylinder robs of radius R are placed on each side of a graphene sheet (thickness t) with a gap distance of g. The surrounding dielectric layer and substrate are SiO2. The excitation wavelength is 30 μm (10 THz). The radius of dielectric cylinder is R=2 μm. Cross section is inserted on the right.