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Metal-loaded graphene surface plasmon waveguides working in the terahertz regime

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ABSTRACT

A metal-loaded graphene surface plasmon waveguide composed of a thin silica layer sandwiched between a graphene layer and a metal stripe is proposed and the waveguiding properties in the THz regime are numerically investigated. The results show that the fundamental mode of the proposed waveguide is tightly confined in the middle silica layer with an acceptable propagation loss. Compared with most other graphene waveguides proposed in the literature, the realization of this waveguide does not need to pattern or deform the graphene layer, thus retaining the superior properties of bulk graphene material. The tight modal confinement and the ease of fabrication suggest the high potential use of this waveguide in high-density THz photonic integration.

1. Introduction

The use of surface plasmons (SPs) for radiation guiding at a scale beyond the diffraction limit has been widely investigated in the optical frequencies [1,2]. Due to the high level of free electron concentration, noble metals have the plasma frequencies normally in the ultraviolet, making them good plasmonic materials in the optical regime. However, in the lower frequency bands such as Terahertz (THz) or microwave frequencies, where the frequency is far below the plasma frequency of metals, noble metal usually cannot be used to support SPs due to the near-zero skin depth. Although the concept of spoof surface plasmons (SSPs) [3,4] have been proposed in the THz/Microwave band to support the propagation of artificial surface wave, recently another material of graphene has emerged as a good candidate to support SPs in those frequencies. The energy band structure of single-layer graphene is linear with no band gap [5–7], making graphene possess unique properties which other substances do not have, such as zero effective carrier mass near the Dirac point and tunable carrier density by chemical potential or Fermi level [8]. As a result, the plasma frequency of graphene can be tuned to be in the THz regime and graphene can work as a good plasmonic material. Compared with noble metals, graphene has many advantages, such as extreme confinement in the THz band, and high tunability [9] by electrostatic gating. Actually graphene as a one-atom-thick plasmonic material [1] has achieved wide applications in THz metamaterials and plasmonics [2]. To date various graphene based plasmonic waveguides working in the far infrared or lower frequencies have been proposed, with the graphene in the form of ribbons [10–13], nanowire [14,15], rings [16], wedge/groove waveguide [17] and graphene on the dielectric [18]. However in most of those proposed structures the two dimensional (2D) material of graphene layer needs to be either deformed or structured, which may not only add much complication to the fabrication process but also deteriorate the original unique properties of bulk graphene because the new boundaries in structured graphene may introduce some defect states into the energy band of graphene. The effect will be more evident at lower frequencies because the period of electromagnetic wave is long enough and the moving electrons in graphene will suffer from additional scattering from the new edges. Many waveguides proposed in the literature based on structured graphene may be too optimistic in terms of propagating loss when the theoretical estimation is based on the property of bulk graphene material. Besides the tunability, graphene also shows other interesting optical properties such as high nonlinear kerr effect [19] and saturable absorption [20], etc.

In this paper a new type of waveguide referred to as the metal-loaded graphene surface plasmon (MLGSPP) waveguide, is proposed and numerically investigated. Quite similar to the dielectric-loaded surface plasmon polariton waveguide (DLSPPW) [21] in the optical frequencies, this waveguide does not need one to change the original 2D shape of graphene layer or pattern it, thus circumventing the problems of using graphene as the plasmonic materials mentioned above. The modal properties of the proposed waveguide, including mode effective index $Re(n_{eff})$, normalized

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attenuation constant Im(n_{eff}) and the coupling length, are numerically calculated.

2. Calculation methods

The unique property of graphene lies in its complex conductivity, which consists of both interband and intraband contributions. With random-phase approximation [22], the conductivity of graphene is calculated and investigated as [6]:

$$\sigma_g(\omega, \mu_c, \tau, T) = \frac{ie^2(\omega + i/\tau)}{\pi\hbar^2}\left[\frac{1}{(\omega + i/\tau)^2}\right]\int_0^\infty \varepsilon\left(\frac{\partial f_d(\varepsilon)}{\partial\varepsilon} - \frac{\partial f_d(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon - \int_0^\infty \varepsilon\left(\frac{\partial f_d(-\varepsilon)}{(\omega + i/\tau)^2} - \frac{\partial f_d(\varepsilon)}{4(\varepsilon/\hbar)^2}\right)d\varepsilon \quad (1)$$

If the condition $K_BT \ll \mu_c$ is satisfied, the above equation can be simplified as:

$$\sigma_{\text{inter}} \approx \frac{ie^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - (\omega + i/\tau)\hbar}{2|\mu_c| + (\omega + i/\tau)\hbar}\right] \quad (2)$$

$$\sigma_{\text{intra}} \approx \frac{ie^2K_BT}{\pi\hbar^2(\omega + i/\tau)}\left[\frac{\mu_c}{K_BT} + 2\ln\left(e^{-\mu_c/K_BT} + 1\right)\right] \quad (3)$$

In our calculations, the temperature T in the above equations is set as 300 K. The τ is the relaxation time of the electrons, which equals to 0.6 ps [23] through $\tau = 1/2\Gamma$ (Γ is scattering rate). μ_c is chemical potential, which is equal to Fermi level E_f for $K_BT \ll \mu_c$. The dielectric constant of the graphene [24] is derived by:

$$\varepsilon(\omega) = 1 + i\sigma_g/(\varepsilon_0\omega h) \quad (4)$$

where h is the thickness of graphene and $\mathcal{E}_0$ is the permittivity of free space.

With the above equations one can calculate that in visible frequencies, graphene serves as a lossy dielectric, which does not support spp. However, from mid-infrared to THz regime, the intraband contribution dominates the over conductivity, and the real part of graphene permittivity becomes negative. As a result, the graphene behaves like an ultrathin metal film in the optical frequencies, which can support SPs. Using the above conductivity model for graphene and the finite element method (FEM) based mode solver, the eigen mode properties of the MLGSPP waveguides working in the THz regime are calculated and presented in the following sections of the paper.

3. Schematic and modal properties of MLGSPP

A schematic of the proposed waveguide is shown in Fig. 1, where a single layer of graphene (thickness of graphene is assumed to be 0.5 nm) is placed on the SiO_2 ($\mathcal{E} = 3.9\mathcal{E}_0$) substrate. Similar to DLSPPW [21], a metal (Cu with a conductivity $\sigma = 4 \times 10^7$ S/m is used in this paper) stripe with width w and height d is laid on the top of the spacer material, which is assumed to be SiO_2 in this paper with a thickness t. Besides the fact that the bulk property of graphene is not affected in this waveguide, another advantage of using a full unpatterned graphene layer lies in the ease of fabrication. After the transfer of graphene flake onto the SiO_2 substrate and the deposition of the spacer layer, only one step of photolithography and metal evaporation are required to realize the structure after lift-off process. The main purpose of this paper is to comprehensively look into the modal properties of the waveguide, with the emphasis on the investigation of the dependence of the waveguide's property on the geometrical parameters as well as the chemical potential of graphene. To have a tight confinement, the thickness of the spacer layer is chosen to be quite small throughout this paper.

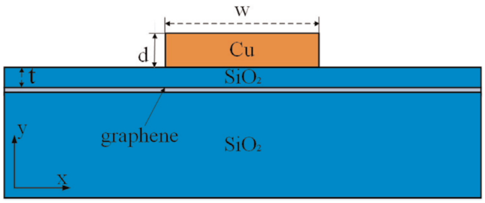

Fig. 1. Schematic of the proposed waveguide, and surface plasmons propagates along the z direction.

A typical distribution of the electric field amplitude |E| for the fundamental TM mode at the frequency of 7 THz is shown in Fig. 2(a). As can be seen, the electric field is tightly confined in the region of spacer material between the metal stripe and graphene layer. Fig. 2(b) and (c) gives the normalized |E| distribution along x and y direction respectively. One can see that the mode in the y direction is like the metal–insulator–metal (MIM) mode in optical plasmonics while in x direction it has a Gaussian profile. Note that in the THz region, the amplitude of the metal's dielectric constant is extremely large, leading to a near-zero penetration depth of electromagnetic wave into the metal. In this case the metal is similar to perfect electric conductor (PEC) [23]. However, the amplitude of graphene dielectric constant is relatively smaller compared to that of metals in THz regime, making graphene a good plasmonic material in this frequency band. In this context, the mode in the y direction should be referred to as PEC-insulator-plasmonic mode, not MIM mode, as there is only one plasmonic mode at the interface between the central insulator and the surround material. The Gaussian distribution of the mode in the x direction is due to the index-guiding mechanism of the mode confinement in this direction, quite similar to the mode confinement of DLSPPWs. The mode width is defined as the full width where the electrical density decays to 1/e of its peak value. The mode width in the x direction and y direction is 2.4 μm and 0.05 μm respectively, which corresponds to the phenomenon of the effective mode area. These two dimensions correspond to 1/125 and 1/6000 of the operation wavelength respectively, demonstrating the high capacity of the waveguide for extreme mode confinement.

We numerically investigate the modal properties of MLGSPP waveguide including the mode effective index defined by $Re(n_{eff}) = \beta/K_0$ and the propagation loss is connected with Im(n_{eff}) [25,26] where β is the complex propagation constant of the waveguide mode and $K_0 = 2\pi/\lambda_0$ is the free space wave vector. Dependence of $Re(n_{eff})$ and Im(n_{eff}) on width w of Cu stripe is shown in Fig. 3(a) as w increases from 0.5 μm to 4 μm when t is fixed as 200 nm. One can see that $Re(n_{eff})$ is quite high in this waveguide, between 8 and 18 in the investigated w range, much larger than the refractive index of any dielectric material involved in the waveguide. This is due to an ultra-small value of the spacer material thickness (200 nm) compared to the wavelength (~42.8 μm), resulting in an extremely high effective index of the central region of the waveguide [21]. Actually from the effective index method point of view, the cross section of the MLGSPP waveguide can be divided into three regions from the left to the right. The central region composed of Cu/SiO_2/graphene supporting the aforementioned PEC-insulator-plasmonic mode is found to have an effective index denoted as n_{eff1} up to a few tens depending on the thickness of the SiO_2 layer [23]. The left or right region consisting of air/SiO_2/graphene configuration supports the regular SPP mode at the graphene/SiO_2 interface, thus has an effective index of n_{eff2}. The mode confinement in the x direction is due to the contrast