Optics Communications ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Analysis of a tunable band-pass plasmonic filter based on graphene nanodisk resonator

Q1 Shiwei Sheng [a], Kang Li [a,*], Fanmin Kong [a], Huawei Zhuang [a,b]

[a] School of Information Science and Engineering, Shan Dong University, Jinan 250100, China
[b] School of Information and Electrical Engineering, Shan Dong Jianzhu University, Jinan 250101, China

A R T I C L E I N F O

Article history:
Received 16 July 2014
Received in revised form
15 September 2014
Accepted 3 October 2014

Keywords:
Surface plasmon polariton
Graphene
Filter
Resonator

A B S T R A C T

A plasmonic filter based on graphene ribbons coupled with a graphene nanodisk resonator was proposed. According to the theory of disk cavity, the resonance frequencies can be manipulated by changing the radius of the disk, which is in agreement with the results obtained by our study. Electrical tunability of this filter by tiny change of the chemical potential of the graphene was confirmed. In addition, the bandwidths of resonance spectra are tunable by changing the coupling distance between the graphene nanodisk and nanoribbon. This work provides an effective method for designing graphene based ultra-compact devices for optical communication.

1. Introduction

Recently, graphene has generated great interest due to its remarkable mechanical, thermal, electronic and optical properties [1]. Because of its many unique properties, graphene has the promise to revolutionize many applications, including optical modulators, light-emitting devices, photodetectors, transistors, and ultrafast lasers [2,3]. In recent years, much effort has been devoted to developing surface plasmonic (SP) devices based on graphene [4,5]. Surface plasmon polaritons (SPPs) are electromagnetic waves that propagate along the surface of a noble metal [6,7]. Recent theoretical analysis and experiments have shown that highly confined SPPs can also propagate along the graphene surface [8–10]. Moreover, compared with noble metal SPPs, graphene SPPs have many advantages. First, graphene can support SPPs from mid-infrared frequency to terahertz [11]. Second, the optical property of graphene can be flexibly tuned via electrical gating or chemical doping [12,13], which means that the property of graphene SPPs can be modulated in real time. Actually, previous SPP devices have to be tuned to different working wavelengths by carefully reconstructing the geometries or modifying the supporting substrates, which are difficult to achieve once the devices are fabricated. To address this issue, many approaches to achieve dynamic tuning of the plasmonic devices have emerged by integrating them with materials with tuneable permittivity, such as liquid metals [14] and liquid crystals [15]. Finally, the confinement of graphene SPPs is much stronger and the loss is lower than noble metals. Graphene SPPs can be confined down to volumes that are several orders of magnitude smaller than SPPs in noble metals [13,16]. All these merits make graphene the most promising material for manufacturing highly tunable, extremely high speed, very energy saving, and ultra-compact plasmonic devices.

Currently, many studies about graphene SPPs are focusing on a single layer graphene with finite width, which is often called graphene nanoribbon. Graphene nanoribbon can support two kinds of guided SPP modes [9], which are called edge mode and waveguide mode. When the width of a graphene ribbon shrinks to a few tens of nanometers, the waveguide mode will disappear and only the edge mode will be left [9,16]. Edge mode and waveguide mode coupling between double layers of graphene has also been investigated, both in top–bottom configuration and side–side configuration [16–18]. Many kinds of two-dimensional waveguide devices based on graphene nanoribbons have been studied, such as optical splitters [13,19], optical switches [20] and Mach–Zenhnder interferometers [21]. Some kinds of planar plasmonic filters based on graphene nanoribbons have been proposed [22–24]. Plasmonic filter is one of the most important devices in communication, and have been studied widely in recent years [25–27]. By using graphene, the property of plasmonic filters can be tuned flexibly and size of which can be shrunk into within half micrometers.

In this paper, we proposed a nanoscale band-pass plasmonic filter based on two graphene nanoribbons coupled with a

* Corresponding author. Tel: +86 531 88361608.
E-mail address: kangli@sdu.edu.cn (K. Li).

http://dx.doi.org/10.1016/j.optcom.2014.10.009
0030-4018/© 2014 Published by Elsevier B.V.

graphene nanodisk. Comparing this structure with the band-pass plasmonic filter based on graphene ring resonators [22], both the propagation loss and the bend loss of the disk resonator are very small. The dispersion relationship of SPPs modes that exist in a monolayer graphene nanoribbon deposited on a SiO_2/Si substrate was studied using finite element method (FEM) analysis. The SPPs field distribution and propagation in the filter were characterized by the finite-difference time-domain (FDTD) method. Numerical results showed that this structure acts as a highly tunable optical filter that can be tuned with a tiny change of the chemical potential of the graphene. With different radiuses of the disk, the working frequency range and the transmission peak frequency can be changed. By changing different coupling distances between the disk and the waveguide, the band width of the filter can be tuned. This structure can also serve as a tunable optical modulator and optical switch working in the infrared wavelength.

2. Materials and methods

The complex surface conductivity of graphene can be calculated from the Kubo formula, which depends on the radian frequency ω, charged particle scattering rate Γ, temperature T, and chemical potential (or Fermi Energy Level) μ_c. At mid-infrared wavelength, surface conductivity from interband transition can be suppressed when the graphene is properly doped. So, in this study we only considered the intraband of the surface conductivity, which can be expressed as [8,28]

$$\sigma_{intra}(\omega, \mu_c, \Gamma, T) = \frac{-je^2 k_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln(e^{-\mu_c/k_B T} + 1)\right) \quad (1)$$

where e is the charge of an electron, k_B is Boltzmann's constant, and $\hbar = h/2\pi$ is the reduced Planck's constant. Chemical potential μ_c are currently attainable involving charge-carrier densities $n = \mu_c^2/(\pi\hbar^2\nu_F^2)$, where ν_F is the Fermi velocity [9,29]. The charge-carrier densities n can be changed by chemical doping or an electrostatic gate, resulting in changes in the chemical potential and the surface conductivity. So, dramatic changes of the optical property of the graphene can be achieved through the electrostatic gate tuning method, which is one of the most fascinating properties of graphene. The three-dimensional schematic view and top view of this structure are plotted in Fig. 1(a) and (b) respectively. As shown in the figures, the graphene layer is deposited on the SiO_2/Si substrate. The SiO_2 has a permittivity of $\varepsilon_{SiO2} = 2.09$ and the Si of $\varepsilon_{Si} = 11.9$ [16]. Some structures for electrically controlling the carrier density of graphene have been verified experimentally; we propose to use back-gate structure in this work. The profile of the back-gate structure is plotted in Fig. 1(c). It shows that a bias voltage is applied between the metal under the substrate and above the graphene layer. The effectiveness of this tuning structure has been experimentally confirmed in works of Refs. [29–31]. This device can be realized by chemical vapor deposition, electron-beam lithography and etching method. Firstly, the high-quality large-area graphene films can be grown using an optimized liquid precursor chemical vapor deposition, then it will be transferred onto an SiO_2/Si substrate. In order to manufacture graphene nanodisk and nanoribbons, electron-beam lithography and oxygen plasma etching can be used. Finally, the gold contact for gating can be located on the graphene layer and the Si substrate. Owing to the extremely short wavelengths of graphene SPP, the efficient coupling of light into propagating graphene SPP is challenging. Work of Ref. [32] have demonstrated coupling between infrared photons and graphene plasmons by the compression of surface polaritons on tapered bulk slabs of both polar and doped semiconductor materials. Their proposed coupling device allows for a 25% conversion of the incident energy into graphene plasmons. To test the proposed device, optical response of the system can be measured using a near-field scanning optical microscope. A near field optical probe should be used to scan over the filter, collecting the near-field intensity of the evanescent wave at the surface of the graphene nanoribbons and disk. By comparing the intensities before the coupling position of ribbon and disk and after the position, the transmission property can be calculated.

The equivalent permittivity of monolayer graphene can be calculated by the following equation [13,23]:

$$\varepsilon_{eq} = \varepsilon_0 - \frac{\sigma_i}{\omega\Delta} + i\frac{\sigma_r}{\omega\Delta} = \varepsilon_{eq,r} + i\varepsilon_{eq,i} \quad (2)$$

where Δ is the thickness of monolayer graphene, and ε_0 is the vacuum permittivity. In all our simulations, Δ was assumed to be 0.34 nm, which is a value close to the interlayer separation of graphite. To ensure accuracy, the minimum FDTD mesh size in the z direction was set as $\Delta/10$= 0.034 nm [21,23] and at the parallel direction (x and y directions) of the graphene, the mesh size is set as 1 nm $\times$ 1 nm. The perfectly matched layer (PML) is used in both directions of the model.

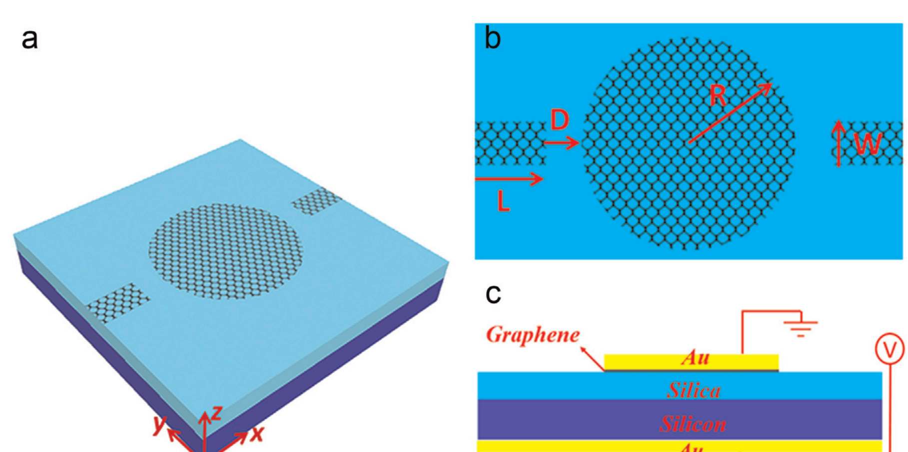

Fig. 1. (a) Schematic view of the proposed plasmonic filter. The monolayer graphene is deposited on the SiO_2/Si substrate. (b) Top view of the proposed plasmonic filter, the length of the graphene ribbon is L, the width of which is W, the radius of the graphene disk is R, and the distance between the ribbon and disk is D. (c) Scheme of proposed back-gate carrier density tuning structure.

Please cite this article as: S. Sheng, et al., Optics Communications (2014), http://dx.doi.org/10.1016/j.optcom.2014.10.009