Optics Communications 382 (2017) 86–92

Contents lists available at ScienceDirect

Optics Communications

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

Graphene-ribbon-coupled tunable enhanced transmission through metallic grating

Yu-Xiang Peng [a], Meng-Dong He [a,b,*], Ze-Jun Li [a], Kai-Jun Wang [a], Shui Li [a], Jian-Bo Li [a], Jian-Qiang Liu [c], Mengqiu Long [d], Wei-Da Hu [b], Xiaoshuang Chen [b]

[a] *Institute of Mathematics and Physics, Central South University of Forestry and Technology, Changsha 410018, People's Republic of China*
[b] *National Laboratory for Infrared Physics, Chinese Academy of Sciences, Shanghai 200083, People's Republic of China*
[c] *College of Science, Jiujiang University, Jiujiang 332005, People's Republic of China*
[d] *School of Physics and Electronics, Central South University, Changsha 410083, People's Republic of China*

ARTICLE INFO

Article history:
Received 10 April 2016
Received in revised form
14 June 2016
Accepted 29 June 2016

Keywords:
Surface plasmon polariton
Enhanced transmission
Fabry–Perot cavity
Graphene ribbon
Metallic grating

ABSTRACT

We report the tunable enhanced transmission of light through a hybrid metal–graphene structure, in which a graphene ribbon array is situated over a metallic grating. The graphene ribbon is employed to make the graphene–insulator–metal waveguide of finite length as a Fabry–Perot (F–P) cavity. When the slit of metallic grating is opened at the position with a maximal magnetic field in F–P resonant cavity, the transmission of light through metallic grating is greatly enhanced since the strongly localized magnetic field is effectively coupled to the slit. The transmission spectrum and the enhancement factor can be adjusted by changing geometrical parameters including the width and the length of slit, the width of graphene ribbon and the period of metallic grating. The transmission peaks exhibit a broad tuning range with a small change in the Fermi energy level of graphene. Moreover, the enhancement factor of transmission peak can be manipulated by the Fermi energy level and the carrier mobility of graphene, and an enhancement factor of 154 is obtained. The findings expand our understanding of hybrid metal–graphene plasmons and have potential applications in building active plasmonic devices.

1. Introduction

In the past a few centuries, the diffractive property of a hole in a screen has been a research subject since the hole is probably the simplest optical element, and is an object of curiosity and technological application [1]. From Bethe's theoretical description, we know that the transmission through a hole in a perfectly conducting metal screen of zero thickness with a radius $r \ll \lambda$ is very weak since its transmission efficiency scales with $(r/\lambda)^4$ [2]. However, at the end of the 20th century, the phenomenon of extraordinary optical transmission through metallic nanoholes/nanoslits was observed experimentally, the value of transmission peak was orders of magnitude greater than that predicted by the standard aperture theory [3,4]. Such enhanced transmission phenomenon can be attributed to the excitation of the plasmon resonance modes on metal film and the localized plasmon resonance modes in individual holes/slits [5–7]. In order to increase the amount of light passing through a metallic nanohole/nanoslit, researchers have proposed several methods, including corrugating the metal surface with periodic grooves [8], designing bumps on the two sides of a slit [9], filling the hole with a material of high dielectric permittivity [10], utilizing nanofocusing of radiation in tapered slits [11], etc. In these approaches, the transmission is enhanced by a resonant process that leads the effective coupling of light to a small aperture/slit. Besides the above approaches, placing a split-ring resonator in front of a aperture [12] or constructing a cavity resonator at the entrance of a slit [13,14] can also improve aperture's/slit's transmission efficiency due to the highly localized electric or magnetic field at the resonance frequency of resonator.

In recent years, graphene, a two-dimensional atomic crystal consisting of carbon atoms arranged in a honeycomb lattice, has emerged as an alternative and unique plasmonic material that displayed a wide range of extraordinary properties [15,16]. Compared to metal plasmon, graphene plasmon presents two appealing properties: ultrabroad and fast tunability via electrostatic gating or chemical doping [17,18], and extreme field confinement [19,20]. Just because of the properties, graphene enables active control or dynamic tuning of plasmon modes [21–24] and has promising applications in surface enhanced spectroscopies [25],

---

[*] Corresponding author at: Institute of Mathematics and Physics, Central South University of Forestry and Technology, Changsha 410018, People's Republic of China.

E-mail address: hemendong@sohu.com (M.-D. He).

http://dx.doi.org/10.1016/j.optcom.2016.06.086
0030-4018/

molecular sensing [26], etc. In this paper we utilize a graphene ribbon array to enhance and tune the transmission of light through a metallic grating. As the plasmon resonance modes in a Fabry–Perot (F–P) cavity, which is composed of graphene ribbon, dielectric layer and metal film, are excited, the strongly localized magnetic field in the cavity can be effectively coupled to the slit of metallic grating, as a result the transmission of light through metallic grating is enhanced. We obtain 154-fold enhancement under a certain condition. Furthermore, the transmission peak can be tuned over a wide wavelength range by a small change in the Fermi energy level of graphene, which is useful for designing active plasmonic devices.

2. Model and numerical method

Fig. 1 depicts the schematic of our proposed structure, where a layer of SiO_2 is embed between a metallic grating on the top of SiC substrate and a graphene ribbon array covered by a electrolyte layer and a metallic pad. A plane wave of TM polarization (its magnetic field is perpendicular to the x–z plane) with a unitary magnetic field impinges normally on the top of electrolyte layer. The geometry is defined by the following parameters. w_s and w_g denote the widths of metallic slit and graphene ribbon, respectively, $t_{C(M,O,E)}$ is the thickness of SiC substrate (metallic grating, SiO_2 and electrolyte layer), P represents the period of metallic grating (graphene ribbon array), and L_x is the lateral displacement between the centers of graphene ribbon and metallic slit along the x-direction. In the mid- and far-infrared frequency ranges, the interband conductivity of graphene is much smaller than its intraband conductivity, so we only consider intraband conductivity in the following calculations, i.e., $\sigma_g = i(e^2E_f/\pi\hbar^2)/(\omega + i\tau^{-1})$ [17], where E_f and τ represent the Fermi energy level and the carrier relaxation time of graphene, respectively. E_f and τ are given by $E_f = \hbar v_f(\pi n)^{1/2}$ and $\tau = \mu E_f/ev_f^2$, respectively, where n, v_f (10^6 m/s), and μ stand for the carrier concentration, the Fermi velocity, and the carrier mobility of graphene, respectively. The relative permittivity of graphene is obtained by $\varepsilon_g = 2.5 + i\sigma_g/(\varepsilon_0\omega t_g)$ [20], where ε_0 and t_g (0.5 nm) are the permittivity of vacuum and the thickness of graphene, respectively. We show the real part and the imaginary part of graphene's relative permittivity as a function of chemical potential (carrier mobility) and frequency in Figs. 2(a) and 2(b) (Figs. 2(c) and 2(d)), respectively. For a certain chemical potential or carrier mobility, the real part and the imaginary part of graphene's permittivity vary with frequency. It is worth noting that, for a certain frequency, the real part of graphene's permittivity is sensitive to the change of chemical potential E_f, while the change of E_f has little influence on the imaginary part of graphene's permittivity. With respect to the carrier mobility, the situation is just the reverse, the carrier mobility mainly affects the imaginary part of graphene's permittivity. The metal in our considered structure is chosen to be gold (Au), and it is modeled as Drude metal with $\Gamma = 3.33 \times 10^{13}$ rad/s, and $\omega_p = 1.36 \times 10^{16}$ rad/s [27]. The electrolyte on the top of graphene ribbon is modeled as a dielectric with refractive index of 1.7 [27], and the permittivities of SiO_2 layer and SiC substrate are taken to be 3.9 [28] and 9 [27], respectively. By applying a voltage between the metallic pad and the electrolyte layer, the carrier concentration and thus the Fermi energy level of graphene can be electrically tuned.

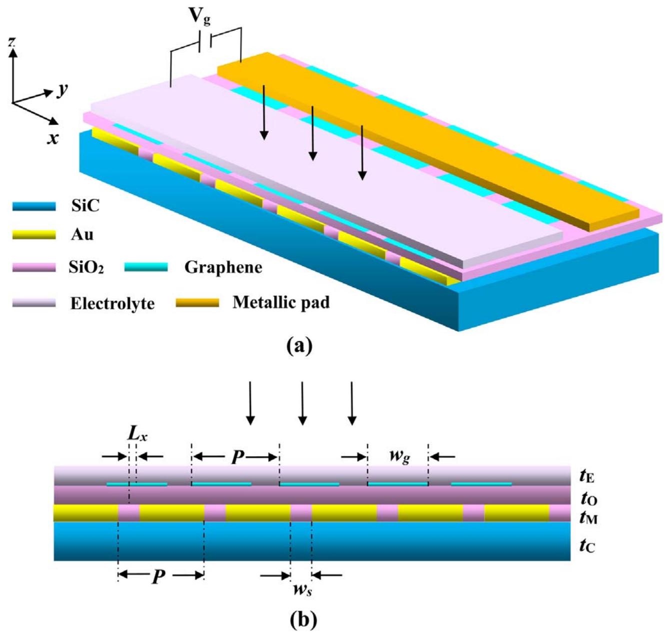

Fig. 1. (a) Stereogram and (b) side view of our proposed structure, which is composed of a thin gold (Au) film with a nanoscale slit array, a graphene ribbon array, SiO_2 layer, electrolyte layer, metallic pad and SiC substrate. The meanings of symbols are explained in the text.

In this paper, the numerical calculations for transmission spectra and field distributions are performed by using Lumerical FDTD solutions based on the finite-difference time-domain method. Owing to a large dimensional difference between the thicknesses of graphene and metallic film, we use nonuniform mesh in stimulations. The mesh size inside graphene ribbon along the z-axis is set to 0.05 nm, and the mesh size gradually increases outside the graphene ribbon. The mesh sizes inside metallic slit along the x- and z-axes are taken as 5 and 10 nm, respectively. The periodic boundary condition is imposed in the x-direction, while in the z-direction the perfectly matched absorbing boundary condition is applied at the two ends of computational space.

3. Results and discussion

Now, we compare the transmission property of bare metallic grating with that of metallic grating with graphene ribbon array. The transmission spectra of metallic grating with and without graphene ribbon array are shown in Fig. 3(a), where the transmission of bare metallic grating is enlarged 10-fold. Both the periods (P) of metallic grating and graphene ribbon array are $8\mu m$. The widths of metallic slit (w_s) and graphene ribbon (w_g) are taken as 40 and 720 nm, respectively. t_E, t_O, t_M and t_C are 300, 20, 80 and 600 nm, respectively. The Fermi energy level (E_f) and carrier mobility (μ) of graphene are set to 0.6 eV and 20,000 $cm^2\,V^{-1}\,s^{-1}$, respectively. As expected, for a metallic grating with very narrow slits, its transmission is very weak in the frequency region of interest (blue curve in Fig. 3(a)). When a graphene ribbon array is placed on top of the metallic grating, the spectral line shape has a significant change (red curve in Fig. 3(a)). There are two remarkable transmission peaks in the spectrum. The two transmission peaks are located at 6.3 and 13.3 THz, respectively, and their values are 0.28 and 0.08, respectively. Here, we define the enhancement factor (η) as the ratio of the light transmission through the metallic grating with graphene ribbon array to that through bare metallic grating. η as a function of frequency is shown in Fig. 3(b). Similarly, there are two peaks in the spectrum. The frequencies of the two peaks are the same as those of the two transmission peaks in Fig. 3(a), and the enhancement factors of the two peaks at 6.3 and 13.3 THz are 42.2 and 45.0, respectively. It means that the transmission of light through the metallic grating is greatly enhanced by the graphene ribbon array.

Intuitively, each nanoslit of metallic grating is blocked by a