Optics Communications 402 (2017) 265–269

Contents lists available at ScienceDirect

Optics Communications

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

Theoretical investigations in active control of plasmon induced nanofocusing based on graphene monolayer on substrate

Buzheng Wei *, Yuguang Yang, Yao Xu, Shen Ye, Shuisheng Jian

Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, Beijing Jiaotong University, Beijing 100044, China
Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Keywords:
Nanofocusing
Slow light effect
Graphene
Surface plasmon polaritons (SPPs)

ABSTRACT

A compact graphene monolayer on substrate nano-structure to realize nanofocusing and slow light effect is analytically and numerically investigated in this letter. By creating a chemical potential well in the desired positions via chemical doping or external gating, the normalized electric field enhancement factor here reaches over 300 where the mid-infrared (MIR) light is slowed down to over as high as 1/7000 times the speed in vacuum at the same time. The spot size is in 1 nm magnitude. Furthermore, when the chemical potential along the graphene sheet is properly designed, multi-focusing can be successfully controlled. The incident wave can also be trapped at the corresponding positions if it contains multiple frequency components. This structure may find applications for energy focusing on nano chips or lenses in the MIR regime beyond the diffraction limit.

1. Introduction

Thanks to the unique optical and electric properties [1–3] of graphene, many graphene based metamaterial devices are intensively investigated in the concern of this ability and have been applied to a wide range of application areas in the recent decades. Y. Korniyenko et al. identified the time-dependent electron transport in a ballistic graphene field-effect transistor with an ac-driven gate, which provided two regimes that can be useful for applications to detect THz radiation or as a frequency multiplier [4]. Assisted by the integrated graphene transistor, Liu et al. proposed a charge-density-wave oscillator suitable for a variety of practical applications [5]. Using first-principles calculations, Deya Das et al. reported a large band-gap opening with linear dispersion in the graphene/graphane heterostructure which constitutes promising features for room-temperature electronic and optical devices [6]. Among these pioneering works, a branch of controlling the chemical potential of graphene to alter its optoelectric properties becomes a relatively simple way to design graphene based structures and to put it into practical applications.

One of the applications here is the graphene based structures to realize nanofocusing and slow light effect. Liu et al. investigated nanofocusing of THz waves in tapered graphene multilayers, which the device performed the field amplitude enhancement by 620 and to slow light to a group velocity 1/2815 of the light speed in vacuum [7]. The device they proposed was considerable and practical but the enhancement and the slow down factor remained to be challenged. Qiu et al. proposed an extremely simple way of an isolating freestanding graphene sheet to realize nanofocusing and slow light [8] but the desired gradient chemical potential distributions of a suspended graphene sheet was relatively unpractical to obtain. Zhu et al. also put forward a graphene-hexagonal boron nitride heterostructure with a maximum enhancement of the amplitude of normalized electric field ($|E| = \sqrt{E_x^2 + E_y^2 + E_z^2}$ V/m) over 60 [9].

In this letter, we propose a concise structure composed of a single layer graphene on SiO_2 substrate to realize nanofocusing and slow light effect. To appropriately design the chemical potential distributions along the graphene sheet, we can create a relatively small area where the real part of propagation constant far exceeds the imaginary part. In this way, the energy accumulation speed dominates the competition with the loss rate. Thus nanofocusing is observable. By designing multiple such areas, multi-focusing can be successfully achieved. If the incident wave is composed of several frequency components, each component will be trapped at the corresponding position where chemical potential meets the critical value. A relatively high group index is acquired compared to Ref. [7].

---

* Corresponding author at: Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, Beijing Jiaotong University, Beijing 100044, China.
E-mail address: 14111010@bjtu.edu.cn (B. Wei).

http://dx.doi.org/10.1016/j.optcom.2017.06.042
Received 20 December 2016; Received in revised form 11 April 2017; Accepted 12 June 2017
Available online 20 June 2017
0030-4018/© 2017 Elsevier B.V. All rights reserved.

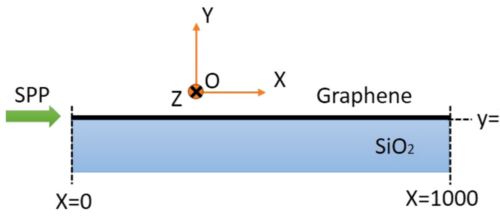

Fig. 1. The device is composed of $d = 0.5$ nm thick monolayer graphene on 100 nm thick SiO_2 substrate. Incident transverse magnetic (TM) wave is launched at the left port $x = 0$ nm and propagates along positive x direction.

2. Material and discussion

The XOY plane is parallel to the paper sheet while z axis points perpendicularly into the XOY plane. The XOY plane schematic diagram of the proposed concise nanostructure is shown in Fig. 1. The structure is infinite in z direction. A 0.5 nm thick monolayer graphene is on 100 nm thick $\mathrm{SiO_2}$ substrate. Incident transverse magnetic (TM) wave with z component magnetic field (H_z) and x, y components electric field (E_x, E_y) is launched at the left port $x = 0$ nm and propagates along positive x direction. The only material dependency on incident frequency is the conductivity of graphene film. Since the working frequency covers mid-infrared range, taking 50 Thz for example, $\hbar\omega/2$ and the chemical potential $\mu_c = 0.14$ eV are in the same order of magnitude. So the effect from interband electron transition cannot be neglected. Besides, we only consider TM surface waves, so the surface conductivity of graphene is expressed as $\sigma_s = \sigma_{inter} + \sigma_{intra}$. σ_{inter} and σ_{intra} can be derived by the well known Kubo formula [10]

$$\sigma_{inter} = i\frac{e^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - \hbar(\omega + i\tau^{-1})}{2|\mu_c| + \hbar(\omega + i\tau^{-1})}\right], \qquad (1)$$

and

$$\sigma_{intra} = i\frac{e^2 k_B T}{\pi\hbar^2(\omega + i\tau^{-1})}\ln\left[\frac{\mu_c}{k_B T} + 2\ln\left(exp\left(-\frac{\mu_c}{k_B T}\right) + 1\right)\right], \qquad (2)$$

where e is the electron charge, $\hbar$ is the reduced Planck constant, ω is the incident angular frequency and k_B is the Boltzmann constant. $\tau = 0.5$ ps is the momentum relaxation time as a conservative value throughout this letter and $T = 300$ K. Here, μ_c stands for chemical potential of graphene and has a significant influence on the performances of our device. Even for the case of proper dielectric substrate, gating a graphene sheet in a supported area will lead to a locally varying doping and corresponding local μ_c of graphene rather than a uniform sheet-doping [11]. Hence, in the practical realization of building such a non-uniform chemical potential distribution environment in a continuous graphene monolayer, the prior method is to set a metal electrode at the desired controlling region on graphene and to make it to be brought outside into contact with a bias voltage. The chemical potential has a dependency on the external gate voltages and is experimentally demonstrated in Ref. [12]. Besides, in Ref. [13], it is assumed that it takes about 1 V change to alter the chemical potential from 0.54 to 0.64 eV, which means the changing of chemical potential results in an acceptable change in bias voltage. This unique optical property provides possibilities to confine localized electromagnetic (EM) waves to certain positions where μ_c satisfies critical value. Other than the tunable gating method by changing the external voltages, by varying the doping or the height of substrate [14], the chemical potential of the corresponding upper attached graphene area can also be modified. The surface relative permittivity of graphene is denoted by $\varepsilon_{xx} = \varepsilon_{zz} = 2.5 + i\sigma_s/\varepsilon_0\omega d$ and the surface normal component is $\varepsilon_{yy} = 2.5$ based on the dielectric constant of graphite [13]. Here, $d = 0.5$ nm is the modeled graphene film thickness which is acceptable in simulations compared with the practical one atom thick condition as long as the mesh is fine enough [15]. The dispersion relationship of TM polarized plasmonic waves in graphene is given by [13]

$$\varepsilon_{up}(\beta^2 - \varepsilon_{up}k_0^2)^{-1/2} + \varepsilon_{below}(\beta^2 - \varepsilon_{below}k_0^2)^{-1/2} = -i\sigma_s/\omega\varepsilon_0, \qquad (3)$$

where $k_0 = 2\pi/\lambda$ is the vacuum wavevector, $\varepsilon_{up} = 1$ and $\varepsilon_{below} = 3.9$ are the relative permittivity of air up and $\mathrm{SiO_2}$ below the graphene sheet, respectively. Since $\beta \gg k_0$ [13], Eq. (3) is thus reduced to

$$\beta(\omega, \mu_c) = -\frac{\omega\varepsilon_0(\varepsilon_{up} + \varepsilon_{below})}{i\sigma_s} \qquad (4)$$

the in-plane wavevector $\beta(\omega, \mu_c)$ can be written as $\beta(\omega, \mu_c) = Re(\beta(\omega, \mu_c)) + iIm(\beta(\omega, \mu_c))$, where $Re(\beta(\omega, \mu_c))$ denotes the wavenumber, while $Im(\beta(\omega, \mu_c))$ describes the propagation loss property of SPP waves. The larger $Re(\beta(\omega, \mu_c))$ is, the shorter wavelength and stronger localization of EM waves are.

Next, we discuss the influence of chemical potential and incident frequency on the performance of nanofocusing. For simplicity, we first assume the incident frequency $f = 50$ THz. $Re(\beta(\omega, \mu_c))$ and $Im(\beta(\omega, \mu_c))$ are depicted in Fig. 2(a) (b) as a function of μ_c and incident frequency. As μ_c decreases, $Re(\beta(\omega, \mu_c))$ drastically increases around 0.1 eV. It means that the localization of EM waves becomes increasingly strong. Although the loss rate is increasing at the same time, the energy accumulation rate far exceeds the loss rate. Hence, nanofocusing effect becomes obvious around this area. When the chemical potential decreases to the critical value where $Re(\beta(\omega, \mu_c)) = Im(\beta(\omega, \mu_c))$, the SPP wave is fully damped which means the energy acquired loses immediately with the same quantity. In other words, nanofocusing effect actually depends on the competition between energy accumulation and loss during propagation [8]. Once the chemical potential is smaller than the critical value, $Re(\beta(\omega, \mu_c)) < Im(\beta(\omega, \mu_c))$, the SPP waves are not supported anymore. In Fig. 2(c), the value of $Re(\beta(\omega, \mu_c)) - Im(\beta(\omega, \mu_c))$ is plotted to help understand the critical chemical potential position.

3. Numerical simulation

To numerically investigate nanofocusing effect, we use the finite element method (FEM) in COMSOL Multiphysics Ver 5.2 to calculate electric field distributions and magnetic field distributions of the propagating SPP waves. The graphene sheet is located in XOZ plane at $y = 0$ nm. The length of the structure is designed to be $x = 1000$ nm. The TM wave is excited on the left port of the structure and scattering boundary condition is applied. According to the discussion above, by locally doping or applying bias voltage, we set a chemical potential well in the center $x = 500$ nm where we choose a moderate μ_c to satisfy $Re(\beta(\omega, \mu_c)) \gg Im(\beta(\omega, \mu_c))$. While $x < 500$ nm and $x > 500$ nm, μ_c virtually increases and decreases drastically, respectively.

As shown in Fig. 3(a) and (b), the normalized electric field and z component magnetic field distributions of incident frequency $f = 50$ THz are illustrated while the values of normalized electric field divided by the normalized electric field at launching point $|E|/|E_0|$ along the graphene sheet are in Fig. 3(c). From the simulation results we can conclude that the chemical potential is the key controlling factor where nanofocusing points are determined. When μ_c is far above the critical value, $Im(\beta(\omega, \mu_c))$ is extremely small and almost no loss is induced when SPP wave is traveling along the graphene sheet. When the wave comes around the focal point, μ_c drops down to the critical value drastically which brings the effect of sharp increasing in both $Re(\beta(\omega, \mu_c))$ and $Im(\beta(\omega, \mu_c))$. But still the energy accumulating rate far exceeds the loss rate. With a relatively large wavenumber, nanofocusing is numerically observable. Hence, we assume if $Re(\beta(\omega, \mu_c))$ were infinite, loss would be zero compared to $Re(\beta(\omega, \mu_c))$, which creates a singularity point at $x = 500$ nm where energy here is forever trapped. But this is not achievable practically because no such conditions can be made and the loss cannot be neglected. However, when the wave propagates beyond $x = 500$ nm, loss rate begins to dominate and the SPP wave vanishes here. The enhancement factor (EF) is defined as $|E|^2_{peak}/|E_0|^2$. For the