Optics Communications 370 (2016) 226–230

Contents lists available at ScienceDirect

Optics Communications

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

Edge plasmons and cut-off behavior of graphene nano-ribbon waveguides

Haowen Hou [a,d,*], Jinghua Teng [b], Tomás Palacios [c], Soojin Chua [a,d,*]

[a] Singapore-MIT Alliance for Research and Technology, 1 Create Way, 138602, Singapore
[b] Institute of Materials Research and Engineering, Agency for Science, Technology, and Research (A*STAR), 2 Fusionopolis Way, Innovis, 138634, Singapore
[c] Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States
[d] Department of Electrical and Computer Engineering, National University of Singapore, Block E4, Engineering Drive 3, 117583, Singapore

ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form
28 February 2016
Accepted 7 March 2016

Keywords:
Surface plasmons
Waveguides
Infrared optical materials
Metamaterials

ABSTRACT

Graphene nano-ribbon waveguides with ultra-short plasmon wavelength are a promising candidate for nanoscale photonic applications. Graphene edge plasmons are the fundamental and lowest losses mode. Through finite element method, edge plasmons show large effective refractive index and strong field confinement on nanoscale ribbons. The edge plasmons follow a $k^{1/2}$ dispersion relation. The wavelengths of the edge plasmons and center plasmons differ by a fixed factor. The width of edge plasmon is inversely proportional to wave vector of edge plasmon k_{edge}. Edge defects associate with graphene nano-ribbon induce extra losses and reduce the propagation length. Cut-off width of edge plasmons reduces with increasing frequency. Cut-off width of center plasmon is enlarged by edge component but the enlargement effect diminishing with the increase of k_{edge}. The results are important for the application of graphene plasmon towards ultra-compact photonic devices.

1. Introduction

The emergence of plasmonics enables ultra-compact components for realizing nanoscale photonic devices to surpass the diffraction limit [1]. Noble metals such as gold and silver are widely used as suitable platforms for plasmonic application in the visible and near IR range. They supports surface plasmons originating from the oscillation of the free electrons in the metal. However, metal plasmons are so lossy that obstruct its further development. To address the issue, spoof surface plasmons [2,3] had been developed to get plasmonic like behavior by structuring the metal films because metals are almost perfect conductor at far IR and THz range. Unfortunately, it is not possible to tune the plasmonic response of metals with an external field.

Graphene as a 2D materials has been proposed as an ideal metamaterials to support surface plasmons at THz and infrared frequencies [4–7]. Graphene plasmons can be tuned by electrical, optical and magnetic method, which provides great potential for new applications [8]. Graphene plasmons have high effective refractive index, which leads to ultra-short wavelength, a tightly confined field and a correspondingly record-small mode area [5]. At infrared wavelengths, graphene plasmons wavelengths as short as 200 nm have been observed experimentally [9,10].

Graphene plasmons can be classified into two groups – center plasmons and edge plasmons. Center plasmons with field concentrated within the center area are the waveguide plasmonic mode of a graphene sheet infinite in extent [11]. New exciting nanoscale photonic devices were proposed based on Graphene sheets such as tunable plasmonic couplers [6], resonators [12], modulators [13] and interconnect network [14]. When the graphene sheet is patterned into graphene nano-ribbons, edge plasmons appear. Edge plasmons, where the energy is localized on the edge, are the fundamental and lowest loss plasmon mode in graphene nano-ribbons [15]. Edge plasmons were first observed experimentally by a scattering type SNOM in a tapered graphene nano-ribbon on the Al_2O_3 substrates [16]. Due to their ultra-short wavelength and low loss, edge plasmons are regarded as the best candidate for the graphene plasmonic applications. However, there are still few papers discussing edge plasmons and many properties of edge plasmons need further investigation.

In this work, edge plasmons on the different widths of graphene nano-ribbon are investigated. In addition, we report the dispersion relation, edge defects effect, and cut-off behavior of the edge plasmons on graphene nano-ribbons. The modification on center plasmon cut-off behavior by edge plasmons width is studied in details. These prospects are important for the graphene plasmon based device design and applications.

* Corresponding authors at: Department of Electrical and Computer Engineering, National University of Singapore, Engineering Drive 3, 117583, Singapore.
E-mail addresses: a0103393@u.nus.edu (H. Hou), elecsj@nus.edu.sg (S. Chua).

http://dx.doi.org/10.1016/j.optcom.2016.03.023
0030-4018/

2. Edge plasmons and cut-off behavior

The goal of this section is to describe the modeling of graphene parameters. For terahertz and far-infrared wavelength, the graphene intraband conductivity term usually dominates over the interband term. So, we can neglect the interband conductivity and approximate the intraband conductivity with high doping level (E_F »$k_B T$) by a Drude-like expression [7,17]:

$$\sigma_g = \frac{ie^2 k_B T}{\pi\hbar^2(\omega + i\tau^{-1})}\left(\frac{E_F}{k_B T} + 2\text{In}(e^{-E_F/k_B T} + 1) \approx \frac{ie^2 E_F}{\pi\hbar^2(\omega + i\tau^{-1})}\right) \tag{1}$$

where i is the imaginary unit, e is the charge of electron, E_F is the Fermi level, $\hbar$ is the reduced Plank's constant, ω is the angular frequency, τ is electron scattering time and taken to be 0.5 ps. For graphene, the intrinsic scattering by the acoustic phonon of graphene is extraordinarily weak, and limits the room temperature mobility to 2×10^5 cm^2/Vs [18]. The dominant scattering mechanisms are substrate optical phonons [18] and defects in grapheme [19]. By proper substrate engineering, τ=0.5 ps is able to achieve [19]. Considering that $\tau >$ 1.5 ps and τ=0.9 ps have been experimentally achieved in freestanding grapheme [20] and graphene on boron nitride [21]. The choice of τ=0.5 ps is rather conservative to feature the actual loss of graphene.

There are two type of approaches to model the graphene. The graphene can be modeled as a surface boundary condition (2D approach), which has no physical thickness [22]. But the full wave 3D approach is also valid by treating the graphene as 1 nm or 0.335 nm thickness volume material according to the reference [6,23]. Here the 3D approach was adopted. The surface conductivity was converted to a bulk conductivity value that can be used in the simulation program. The graphene layer has a very small thickness Δ compared to inferred wavelength. The permittivity of graphene can be modeled as $\varepsilon_{\parallel}=\varepsilon_r+(i\sigma_g)/(\omega\varepsilon_0\Delta)$ for In-plane component and $\varepsilon_{\perp}$ for out-plane component, where ε_r=2.5. Note that $\varepsilon_{\parallel}$ has a thickness dependent parameter. Therefore the choice of Graphene thickness will have a huge influence on the simulation result. In the simulation, Δ is not the real thickness of the Graphene ribbon which is around 0.34 nm. In order to save time and computer memory, Δ is set to be 1 nm and the deviation from the analytical value for center plasmons n_{eff} [11] is less than 0.5%. After different parameters of graphene established, the simulation was carried by COMSOL multiphysics for both modal analysis and frequency domain analysis. We assume graphene nano-ribbon has a zigzag edge structures and are always metallic, independent on their width.

2.1. Edge plasmon properties

Consider a graphene ribbon (σ_g) with width W placed on the surface of substrate (ε_2) with the surrounding medium air (ε_1). The edge plasmon has an electrical field profile concentrated on the edge of the graphene nano-ribbon. The edge plasmons (wave vector k_{edge}) are propagating along the z-direction. Edge plasmons can be divided into symmetric edge plasmon and asymmetric edge plasmon as shown in the Fig. 1(a) and (b), depending on whether the maximum of the electrical field at the edges are symmetric or asymmetric along the center line of the ribbon.

To determine the width of edge plasmon, we first consider the general dispersion of edge plasmons $k_0^2=k_x^2+k_y^2+k_z^2$. In the infinite extended graphene layer, k_0 can be expanded into k_y and k_z , where $k_z=k_{edge}$. Therefore, $k_0^2=k_y^2+k_{edge}^2$, which leads to $k_y^2=k_0^2-k_{edge}^2$. For the case where edge plasmons propagate in the z-direction, the plasmon cut-off happens when k_z=0. The asymmetric edge plasmon has an asymmetric profile across the nano-ribbon, which can be approximated as two edge plasmons occupy the nano-ribbon, where $k_x=\pi/2a$. Therefore, taking $k_x=\pi/2a$, $k_y^2=k_0^2-k_{edge}^2$ and k_z=0 into the general dispersion $k_0^2=k_x^2+k_y^2+k_z^2$, we can get width of edge plasmon as:

$$a = \frac{\pi}{2k_{edge}} \tag{2}$$

Eq. (2) shows that the electric field associated with the edge plasmons penetrates a distance of the order of k_{edge}^{-1} into the nano-ribbon. This equation can help us to gain insights of the edge plasmons. The width of edge plasmon a is correlated to $\lambda_0/4n_{eff}$, which implies shorter free space wavelength and higher refractive index lead to stronger edge plasmon localization.

When the nano-ribbon width is very large compared to a, the edge plasmon is localized at either right or left edge and does not significantly affect the edge plasmon on the other edge. As shown in Fig. 2(a), effective refractive index of edge plasmon is almost constant when graphene nano-ribbon is wider than 1000 nm. As the graphene ribbon width shrinks, left edge plasmon and right edge plasmon start to couple and originate symmetric edge plasmon and asymmetric edge plasmon at both left and right edge of the graphene ribbon [21]. The E_y component of the symmetric edge plasmons is symmetric about the y-axis, while E_y component of asymmetric edge plasmons is asymmetric about the y-axis as shown in Fig. 2(b). Symmetric edge plasmons have an increasing effective refractive index n_{eff}^{SEP} with the shrinking graphene nano-ribbon width and have a single mode region (purple region in Fig. 2), which mean it is the most fundamental mode and it does not have cut-off behavior [15]. The effective refractive index n_{eff}^{ASEP} in asymmetric edge plasmons decreases and will be cut-off at certain value of the nano-ribbon width. In addition, with different order of harmonics supported in the graphene nano-ribbon, the center plasmons (labeled as TM_0, TM_1, TM_2 …TM_5) have a cut-off behavior as shown in Fig. 2.

The effective index n_{eff}^{SEP} mapping of symmetric edge plasmons with different graphene nano-ribbon width and frequency in the single mode region is shown in the Fig. 3(a). Edge plasmons on nanoscale ribbons show large effective refractive index n_{eff}^{SEP} (up to 61), which implies tight mode confinement. Notice that effective index increases with increasing frequency and reducing graphene nano-ribbon width, which implies edge plasmons have a shorter wavelength and more tightly confinement. Short wavelength and highly confined plasmons are preferred for nano-scale

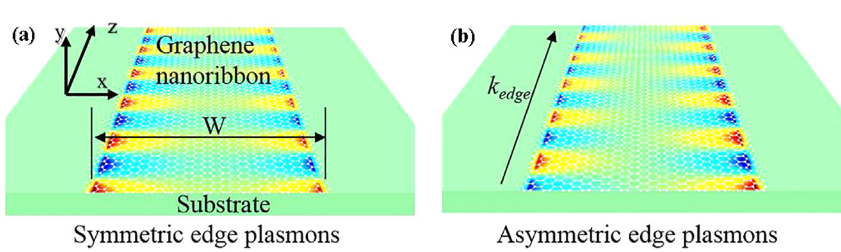

Fig. 1. Two types of edge plasmons supported by a Graphene nanoribbon. (a) Symmetric edge plasmon. (b) Asymmetric edge plasmon. W is width of the nano-ribbon. The color plot presents an example of the E_z spatial distribution.