Available online at www.sciencedirect.com

ScienceDirect

Photonics and Nanostructures – Fundamentals and Applications 20 (2016) 59–67

PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications

www.elsevier.com/locate/photonics

Comparative analysis of graphene-integrated slab waveguides for terahertz plasmonics

S.E. Hosseininejad *, N. Komjani

Department of Electrical Engineering, Iran University of Science and Technology, Narmak, Tehran 16846-13114, Iran

Received 23 November 2015; received in revised form 12 April 2016; accepted 18 April 2016
Available online 30 April 2016

Abstract

This paper presents a comparative study of hybrid and non-hybrid plasmonic slab waveguides based on one and two isolated graphene layers and also hybrid graphene–metal structure. Analysis is performed by analytical approach based on transfer matrix theory and numerical approach based on finite element method. Propagation properties of the structures are exploited at terahertz frequencies. Comparison of the waveguides is done by four characteristical parameters including complex effective refractive index, propagation length, spatial length, and field distribution according to the layer thicknesses and graphene Fermi level (chemical potential). Based on the results, it is easy to choose an appropriate waveguide as the building block for the guided-wave and radiated-wave applications based on graphene.

Keywords: Graphene; Hybrid structures; Noble metals; Plasmonic waveguides; Terahertz regime

1. Introduction

Graphene, a two-dimensional material with only one atom thickness, consists of carbon atoms bonded in a hexagonal lattice [1,2]. The unique electronic and optical properties of graphene make it a new platform for terahertz (THz) and nanophotonic applications such as nanometric integrated circuits, spectroscopy, imaging, transformation optical devices, lenses, modulators, absorbers, directional couplers, reconfigurable antennas, metamaterials with extraordinary electromagnetic properties, etc. [3–9].

Many applications can be devised on the foundation of basic guided-wave structures. Surface plasmon-polaritons (SPPs) are surface waves which can propagate in the interface between two media whose real parts of permittivity have different signs (e.g. a metal–dielectric interface) [10]. A suitable plasmonic material has a permittivity with large negative real part and small imaginary part in the desired frequency region. While noble metals outperform all other plasmonic materials for SPP waveguides in visible and near-infrared regions, graphene is introduced for far-infrared (THz) and mid-infrared plasmonics due to its low losses, high carrier mobility, tunability, and suitability for ultra-compact devices [11–13].

* Corresponding author. Tel.: +98 9127323281.
E-mail address: Ehsan_hosseininejad@elec.iust.ac.ir (S.E. Hosseininejad).

http://dx.doi.org/10.1016/j.photonics.2016.04.002
1569-4410/

Getting ideas from the plasmonic structures based on the noble metals [14–18], different graphene waveguides have already been investigated such as the structures based on single graphene layer [19] and two isolated graphene layers (double-layer graphene) [20,21], ribbon-like structure [22–25], wedge and groove waveguides [26], graphene–metal structure [27], multilayer graphene structure [28], and tapered graphene waveguide [29]. In addition, the effects of having one-dimensional photonic crystal [30] and nonlinear media [31–33] on the surface plasmons characteristics have been investigated. On the other hand, in our previous work [11], the hybrid plasmonic waveguide using a single-layer graphene has been surveyed for achieving higher propagation length than the pure plasmonic waveguide and also the comparison between graphene and noble metals has been performed in mid-infrared regime (at 30 THz). Recently, this structure has been applied for a broadband modulator [37].

The present paper surveys two novel structures, including a hybrid structure based on two isolated graphene layers and a hybrid graphene–metal structure. Furthermore, a comprehensive comparison among the pure and hybrid plasmonic structures is performed. Analytical and numerical methods are applied for extracting propagation properties of graphene-based waveguides. Some of the results are: (1) the pure plasmonic structure based on two isolated graphene layers supports shorter spatial length and larger propagation length compared with the structure based on single graphene layer, (2) the hybrid structure based on two isolated graphene layers supports a mode with enhanced reconfiguration capability compared with the hybrid form of single graphene layer, and (3) the hybrid graphene–metal structure supports the best compromise between spatial length and propagation length among the structures.

Briefly, Section 2 presents the approach of graphene modeling and also the analysis methods of the structures. Study of the graphene-based waveguides and the comparison among them are performed in Section 3. Finally, we conclude the paper in Section 4.

2. Approach of modeling and analysis

Two approaches can be considered to solve Maxwell's equations in the presence of graphene. In the first method, a graphene layer is modeled as a boundary condition that includes the complex surface conductivity as $\sigma_g = \sigma_{real} + j\sigma_{imag}$ [34]. In the second method, graphene is represented as a layer of bulk material with small thickness ($d_g = 0.34$ nm) [2]. Therefore, an equivalent permittivity is defined as:

$$\tilde{\varepsilon}_g = \varepsilon_{real} + j\varepsilon_{imag} = \begin{cases} \left(-\frac{\sigma_{imag}}{\omega d_g} + \varepsilon_0\right) + j\left(+\frac{\sigma_{real}}{\omega d_g}\right) & \text{with assumption } e^{-j\omega t} \\ \left(+\frac{\sigma_{imag}}{\omega d_g} + \varepsilon_0\right) + j\left(-\frac{\sigma_{real}}{\omega d_g}\right) & \text{with assumption } e^{+j\omega t} \end{cases} \quad (1)$$

We apply the second approach with assumption of harmonic time dependence exp(+$j\omega t$) in the analysis of plasmonic slab waveguides based on graphene. The graphene conductivity can be calculated by the well-known Kubo formula [35] with assumption of no magnetostatic bias field as:

$$\sigma_g(\omega, \mu_c, \tau, T) = \sigma_{intra} + \sigma_{inter} = \frac{-j}{\omega - j\tau^{-1}} \frac{e^2 k_B T}{\pi\hbar^2} \left(\frac{\mu_c}{K_B T} + 2\ln\left(e^{-\mu_c/K_B T} + 1\right)\right) + \frac{-j(\omega - j\tau^{-1})e^2}{\pi\hbar^2} \int_0^\infty \frac{f(-\varepsilon) - f(+\varepsilon)}{(\omega - j\tau^{-1})^2 - 4(\varepsilon/\hbar)^2} d\varepsilon \quad (2)$$

where ω is the radian frequency, e is the electron charge, $\hbar$ is the reduced Plank constant, k_B is the Boltzman constant, T is the temperature, and $f(\varepsilon) = 1/\{1 + \exp[(\varepsilon - \mu_c)/(k_B T)]\}$ is the Fermi–Dirac distribution function. μ_c, the chemical potential which is related to density of charged carriers, can be tuned by applying DC bias electric field. τ is the electron relaxation time of graphene, corresponding to the phenomenological scattering rate Γ as $\tau^{-1} = 2\Gamma$. The first term in Eq. (2) implies the contribution of the intraband transition of an electron to the conductivity of graphene while the second term accounts for the interband transition.

Permittivity of metals is described by the Drude model dielectric function, with exp(+$j\omega t$) time harmonic dependence as:

$$\varepsilon_M = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 - j\omega_\tau \omega} \quad (3)$$

where ω_p is the plasma frequency, ω_τ is the damping frequency, and ε_∞ is a constant. Results of fitting Drude model to the dielectric function of silver (Ag) in the terahertz and infrared frequencies are presented in [36] as: $\omega_p = 1.37 \times 10^{16}$ rad/s, $\omega_\tau = 2.733 \times 10^{13}$ rad/s, and $\varepsilon_\infty = 1$.

There are three criteria for choosing a good plasmonic material, including negative Re[ε], low Im[ε] (or low loss), and high Re[ε]/Im[ε]. It is known that the loss of graphene is lower than that of metals in the terahertz and