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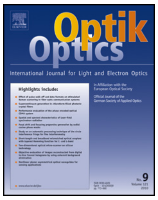

Multi-structural optical devices modeling using graphene tri-layer sheets

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ABSTRACT

In this paper, multi-structural optical devices are designed based on graphene tri-layer sheets using finite deference time domain (FDTD) method with surface boundary condition (SBC). The perfectly matched layer (PML) absorbing boundary condition is also used with FDTD SBC to terminate the computational space. Numerical demonstration of plasmon polaritons (SPPs) wave propagating along variety shaped tri-layer graphene sheets is presented of the proposed method by means of utilizing the gate voltage dependent property of graphene. Finally, the theoretical fabrication of a straight line interferometer, L-shaped optical waveguide and T-shaped optical splitter based on the proposed model is presented. The paper provides an effective technique in modeling multi-layer graphene based high-speed and ultra-compact optical devices.

1. Introduction

Throughout the decades, modeling of optical devices in compact size based on graphene has taken a key interest in research [1,2], because of its high-speed electronics and optical-frequency applications [3,4]. Graphene is a two-dimensional material of graphite [3], hexagonal structure of carbon lattice of only one atom in thickness [5]. It shows many properties in optics and electronics [1,3] including high optical transparency, low reluctance, high carrier mobility [6], tunability, extreme confinement and low electrical losses [7], that make it an appealing applicant to fabricate richly integrated active plasmonic devices and systems for a wideband ranging from near-infrared to the THz region [5]. These properties of graphene can be tuned through changing the charge carriers (biasing voltage) or chemical doping [3]. Today's graphene based multi-functional optical and communication devices are theoretically fabricated, for example, graphene is now used to construct broadband optical polarizers [8], optical splitter, nano-patch antenna [3], interferometer [5] and high-speed optical modulators [9] etc.

Recently, S-shaped waveguide, spiral waveguide and curved waveguide [10] using single graphene layer have been reported as reliable confinement. Then, Y shaped optical splitter, optical spatial switch, Y-Y shaped optical splitter, optical waveguide, and Mach–Zehnder interferometer [5] consisting of two-layer graphene sheets have also been proposed and studied numerically. The optical devices, modeled in Refs. [5,10], show small bending radiation losses that can be reduced using graphene multi-layer parallel sheets that support strong confinement SPPs wave. At present, researchers have concentrated on the optical devices modeling of surface plasmons using graphene multi-layer parallel sheets. The SPPs supporting graphene multi-layer can easily modulated in real time by tuning its biasing voltage dependent optical properties. It is an

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attractive characteristics than conventional noble metals [10,14], especially for ranging of infrared region. Therefore, the researchers are investing their attention to model optical devices based on graphene three sheets, owing to their advantages over not only noble metals but also double and monolayer graphene.

Various numerical methods have been employed by the researchers to model those optical devices. One of the most popular numerical techniques is the finite difference time domain (FDTD) method [15,17] which is an explicit discretization of Maxwell's equations in space and time. Because FDTD solves Maxwell's equations in the time domain, incorporating dispersive materials requires special handling. Recent work has modeled an infinite graphene sheet using FDTD [18]; however, only the intraband (Drude) conductivity was used. While neglecting the interband term may provide good results for long wavelengths, it must be included when considering optical behavior with optical energies near the chemical potential. Recently, the conductivity of graphene with both intraband and interband contributions was modeled in the standard FDTD method [19,20]. However, in the past, standard FDTD with special handing of conductivity has been used for modeling of two layered graphene based optical devices [18–20]. In this works, however, the surface conductivity of graphene was first converted to volumetric conductivity (permittivity), then, partial fractional models were used to approximate the conductivity. The implementation of the volumetric conductivity given by a partial fractional model in the standard FDTD follows in a straightforward fashion. However, as mentioned above, using the standard FDTD method incurs heavy computational burden and long simulation time.

In this paper, for the first time, we theoretically investigate the confinement and propagation properties of SPPs wave propagating along parallel three layer straight lines and 90° sharp bending graphene structures. We use surface boundary condition (SBC) in FDTD method with PML absorbing boundary conditions for modeling optical devices. Numerical results show a better confinement and relatively low bending loss. Numerically, as applications, we illustrate various optical devices including straight line interferometers, L-shaped splitters and switches, and T-shaped multi-output optical waveguides and switches. To tune the flow of energy from input to output through these devices, the gate voltage dependent property of graphene is used and to get higher confinement and lower radiation loss SPPs for nano-photonic networks. The proposed structures would play substantial roles in ultra-compact opto-electronic devices for optical processing and switching.

2. Graphene conductivity modeling

The graphene is modeled as an infinitesimally thin, local two-sided surface characterized by a surface conductivity $\sigma(\omega,P_c,\delta,T)$, resulting from Kubo formula [3,4,11], it as follows:

$$\sigma(\omega, P_c, \delta, T) = \frac{je^2\left(\omega - j2\delta\right)}{\pi\hbar^2}\left[\frac{1}{\left(\omega - j2\delta\right)^2}\left\{\int_0^\infty \varepsilon\left(\frac{\partial g_t(\varepsilon)}{\partial\varepsilon} - \frac{\partial g_t(-\varepsilon)}{\partial\varepsilon}\right)\mathrm{d}\varepsilon\right\} - \int_0^\infty\left(\frac{\partial g_t(-\varepsilon) - \partial g_t(\varepsilon)}{\left(\omega - j2\delta\right)^2 - 4\left(\varepsilon/\hbar\right)^2}\right)\mathrm{d}\varepsilon\right] \quad (1)$$

where ω is radian frequency, P_c is chemical potential, δ is a phenomenological scattering rate that is assumed to be independent of energy and T is Kelvin temperature, $g_t = [\exp\{(\varepsilon - |p_c|)/K_B T\} + 1]^{-1}$ is the Fermi-dirac distribution, and K_B, h are the Boltzmann constant, reduce Plank constant respectively. Kubo equation consists of two parts, the first integral part is intraband contribution and the second is interband contribution. Intraband conductivity is evaluated in the following drude equation [4,11,12].

$$\sigma_{\mathrm{intra[s]}} = \frac{\sigma_0}{1 + j\omega\tau} \quad (2)$$

where $\tau = 1/2\delta$, is the relaxation time and σ_0 is the frequency independent (dc) conductivity can be defined as:

$$\sigma_0 = \frac{e^2 K_B \tau T}{\pi\hbar^2}\left[\frac{p_c}{K_B T} + 2\ln\left(e^{-\frac{p_c}{K_B T}} + 1\right)\right]$$

It is shown for $\omega \ll 2|P_c|/\hbar$, interband would be neglected [12] but for $\omega \geq 2|P_c|/\hbar$, the interband term cannot be neglected [12]. In this paper, highly doped ($P_c = 0.5$ eV) graphene is considered to satisfy the requirement ($\omega \geq 2|P_c|/\hbar$) at room temperature $T = 300$ K. In this case, the graphene will be behaved as thinnest material with low loss supporting TM SPP wave [12,13].

3. 2-D FDTD SBC modeling

Two dimensional transverse magnetic (TM) polarized plane wave incident normally on a graphene sheet is used to implement the SBC of Eq. (2) in the FDTD method. Computational domain is demonstrated by positioning a graphene sheet in xy plane at $y = k_g$ is shown in Fig. 1. The relation between the fields component is expressed by the following equations as:

$$\varepsilon_0\frac{\partial E_z}{\partial t} + \sigma E_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \quad (3a)$$