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Design and analysis of low loss plasmonic waveguide and directional coupler based on pattern-free suspended graphene sheets

Shahram Bahadori-Haghighi , Rahim Ghayour*, Mohammad Hossein Sheikhi

Department of Communication and Electronics Engineering, Shiraz University, Shiraz, Iran

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ABSTRACT

Suspended graphene sheets exhibit promising characteristics such as very high carrier mobility and long relaxation time of carriers. It is highly desirable to realize high performance electronic and optical devices based on suspended graphene layers. For the first time in this paper, a feasible low loss plasmonic waveguide based on a pattern-free *suspended* graphene sheet is proposed. Using an analytical approach, the dispersion relation of surface plasmon polaritons in a suspended graphene-based structure is investigated and derived. The obtained dispersion relation is then used to justify the mode characteristics of the proposed structure. According to our calculations, the propagation length of the proposed suspended graphene plasmonic waveguide at the wavelength of 10 μm is obtained as long as ~9 μm that is 25 times longer than that in its unsuspended counterpart. The structure of a plasmonic coupler which is based on the proposed suspended graphene plasmonic waveguide is also introduced. An ultrashort coupling length of just 496 nm is obtained. The proposed structures are simulated using three-dimensional finite-difference time-domain method. We believe that our proposed suspended graphene-based structures could pave the way for taking the unique advantages of graphene in the future low loss mid-infrared and terahertz integrated circuits.

1. Introduction

Graphene as a two-dimensional (2D) atomic crystal with carbon atoms arranged in a honeycomb lattice possesses unique mechanical, electrical, thermal and optical properties. In recent years, graphene has attracted increasing attention in the field of photonics. The outstanding optical characteristics of graphene have made it as a promising material for photonic applications such as photodetectors [1–3], mode-locked laser [4], polarizers [5,6], optical switches and modulators [7–9].

Graphene plasmonics has been one of the most successful research fields. Plasmonics is generally an exciting approach to overcome the diffraction limit of light so that nanoscale photonic integrated circuits become feasible. Surface plasmon polaritons (SPPs) at the interface between a metal and a dielectric have widely been studied [10,11]. High propagation loss of SPPs is a serious limitation in realization of the plasmonic components. Graphene behaves as a new plasmonic material which its long carrier relaxation time has relatively mitigated that limitation. Strong mode confinement of graphene surface plasmons (GSPs) and tunability of their characteristics are other advantages of SPPs in graphene compared to those of the noble metals. In addition, it is notable that GSPs mainly lie in the terahertz to mid-infrared region of the electromagnetic spectrum. This part of the spectrum has recently received much attention since it is an important range for various promising applications such as sensing, medical diagnostics, thermal imaging and free space communications [12].

One of the most important building blocks in integrated graphene-based components is a graphene plasmonic waveguide (GPWG). As there are some problems associated with the graphene ribbons such as bandgap opening and edge scattering effects [13,14], pattern-free GPWGs are preferred. Various types of pattern-free GPWGs have already been proposed [15–17].

High carrier mobility of graphene results in the long relaxation time of carriers and therefore, the propagation length of GSPs becomes reasonably long. Meanwhile, the propagation loss of the already proposed pattern-free GPWGs is in the order of 4–6 dB μm^{-1} that is still high [15,16]. Such relatively high propagation loss hinders the development of plasmonic integrated circuits.

* Corresponding author.
E-mail addresses: sbahadori@shirazu.ac.ir (S. Bahadori-Haghighi), rghayour@shirazu.ac.ir (R. Ghayour), msheikhi@shirazu.ac.ir (M.H. Sheikhi).

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Suspended graphene layers exhibit high carrier mobility of more than 200,000 $cm^2 V^{-1} s^{-1}$ [18,19]. However, when a graphene layer is deposited on a substrate, its mobility is considerably reduced to 10,000 $cm^2 V^{-1} s^{-1}$, where the relaxation time of carriers is significantly limited. Such a degradation of carrier mobility is mainly because of interactions of graphene with the underlying substrate. Interfacial phonons, surface charge traps, substrate stabilized ripples and fabrication residues under the graphene sheet are all in charge of this limitation [19,20]. Therefore, it would be highly desirable to realize integrated devices based on suspended graphene sheets. It is interesting to say that high performance field effect transistors using suspended graphene layers have already been proposed [21,22] that would play important roles in future electronic circuits. However, apart from a few studies on photodetectors [23,24], suspended graphene-based optoelectronic devices have not been investigated in detail.

In this paper, for the first time, we propose a low loss plasmonic waveguide and directional coupler using pattern-free suspended graphene layers. The proposed suspended graphene-based structures can be implemented using the similar fabrication process as presented in Ref. [19]. In section 2, the proposed suspended GPWG is analyzed in detail. The dispersion relation of SPPs in a suspended graphene-based structure is obtained using an analytical approach. It is illustrated that the results achieved by the analytical formulas are in very good agreement with the simulation results. In order to show the advantage of the proposed structure, it is compared with a conventional unsuspended pattern-free GPWG. Section 3 presents the structure of the plasmonic directional coupler based on a suspended graphene sheet. The mode analysis of the directional coupler is performed and the structure is simulated using three dimensional (3D) finite-difference time-domain (FDTD) method. The low loss operation of the directional coupler over a wide spectral width is illustrated. The proposed structures could potentially be used in future integrated plasmonic devices.

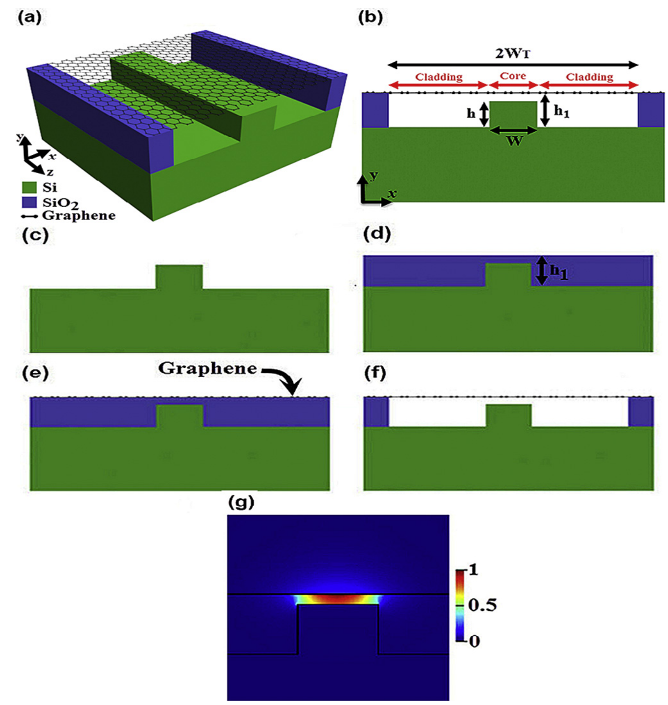

Fig. 1. (a) The perspective and (b) the cross section view of the proposed suspended GPWG. (c)–(f) The possible steps of the fabrication process of the GPWG in brief: (c) patterning of the silicon substrate using e-beam lithography and RIE, (d) deposition of the SiO_2 layer using the steps of PECVD, (e) transfer of the CVD graphene grown on copper onto the SiO_2 layer and (f) selective etching of the middle part of the SiO_2 layer. (g) Electric field profile of the fundamental TM mode around the core region. $2W_T$ is set at 1.2 μm to make sure that the SiO_2 ridges are far away from the active region so that they do not affect the plasmonic mode.

2. Suspended graphene plasmonic waveguide

The 3D schematic of the proposed pattern-free suspended GPWG is shown in Fig. 1a. The cross section view of the structure is also shown in Fig. 1b. As it is shown, a silicon ridge with a width of W and height of h is located at the middle of the structure. The suspended graphene sheet is held by the sided silicon dioxide (SiO_2) ridges a little above the silicon ridge (in the middle). The possible few steps of the fabrication process for the proposed suspended GPWG are briefly shown in Fig. 1c–f. First of all, a silicon substrate is patterned using electron beam (e-beam) lithography followed by reactive ion etching (RIE) [25,26]. As a result, a silicon ridge with the aforementioned geometrical parameters is formed at the middle of the structure (Fig. 1c). Next, the SiO_2 layer is grown by the steps of standard plasma-enhanced chemical vapor deposition (PECVD) method. The SiO_2 layer is polished in such a way that there is a flat surface over the entire sample and the thickness of the SiO_2 layer in the cladding regions is h_1 (Fig. 1d). Afterwards, CVD graphene grown on copper is transferred on the SiO_2 layer by employing the wet transfer method [27]. This step can also be accomplished by locating a single-layer mechanically exfoliated graphene flake on top of the sample (Fig. 1e) [19]. Finally, using the process of lithography followed by selective etching of SiO_2, the middle part of the SiO_2 layer above the silicon ridge is removed while the sides of SiO_2 are not etched (Fig. 1f).

In order to have a more insight into the physical concept of the device, we analyze the structure analytically. First, we start with the complex dielectric constant of the graphene that can be calculated as follows [28]:

$$\varepsilon_g(\omega) = 1 + \frac{i\sigma(\omega)}{\omega\varepsilon_0 \Delta} \tag{1}$$

where Δ is the effective thickness of graphene and is taken as 0.34 nm, ε_0 is the permittivity of free space and σ is the complex conductivity. The contributions of the intraband and interband transitions to the complex conductivity of graphene can be obtained from the Kubo formalism as [6]:

$$\sigma_{\mathrm{intra}}(\omega) = \frac{ie^2\mu_c}{\pi\hbar^2(\omega + i\tau^{-1})} \tag{2}$$

$$\sigma_{\mathrm{inter}}(\omega) = \frac{ie^2}{4\pi\hbar}\ln\left(\frac{2|\mu_c| - \hbar(\omega + i\tau^{-1})}{2|\mu_c| + \hbar(\omega + i\tau^{-1})}\right) \tag{3}$$

where $\hbar$ is the reduced plank constant, e is the electron charge, μ_c is the chemical potential and τ is the relaxation time that is related to the graphene mobility (μ) by the following equation in the mid-infrared and terahertz regime [28–30]:

$$\tau = \frac{\mu\mu_c}{ev_F^2} \tag{4}$$

where v_F is the Fermi velocity that is 10^6 m s^{-1}.

The mobility of graphene is usually taken as 10,000 $cm^2 V^{-1} s^{-1}$. The graphene mobility of 100,000 $cm^2 V^{-1} s^{-1}$ is even assumed in the recently studied graphene plasmonic structures [29,30] but it is not a realistic assumption for a graphene sheet deposited on a substrate. However, the carrier mobility as large as