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Graphene surface plasmon waveguides incorporating high-index dielectric ridges for single mode transmission

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ABSTRACT

We report a novel plasmonic waveguide by incorporating a uniformly-biased graphene sheet over a high-index ridge. The fundamental mode in the proposed waveguide concentrates in the low-index low-loss gap, which is easier to excite and leads to longer propagation length than that of graphene ribbon waveguides', where the field is mostly confined at the high-loss graphene edges. The single mode transmission can be achieved at far-infrared regime without the hard-to-fabricate, ultra-narrow ribbon that results in extra material loss. Instead of the reflection mechanism at the ribbon edges, the optical field is laterally confined by the effective index difference of graphene plasmons due to the ridge. The results based on the effective index method (EIM) have been validated by finite-element simulations at each stage. Rapid design and optimization is carried out by EIM without requiring further extensive numerical computations. The presented waveguide might be employed in integrated wafer-scale photonic systems to enable high performance graphene-based devices.

1. Introduction

Graphene surface plasmons (GSPs), bound electromagnetic modes supported by doped graphene, demonstrate remarkable properties including unique tunability, long plasmon lifetime and deep sub-wavelength confinement [1]. As a fundamental building block for GSP applications, graphene waveguide has been the subject of intense study [2–4]. Various ribbon-based waveguides have been theoretically conceived and/or experimentally demonstrated. Such ribbons can be either physical graphene strips [5–7] or virtually created by biasing inhomogeneous conductivity across a single sheet of graphene [8–10].

In the previous schemes, only the middle section of waveguide is engineered with positive imaginary part of surface conductivity to support GSPs. The optical field is confined by the near complete reflection at the ribbon edges [10], analogous to the conventional metal-insulator-metal (MIM) waveguide [11]. The graphene ribbon waveguide (GRW) inherits all the advantages of GSPs [4]. However, only extremely narrow (width <50 nm) ribbon can operate at the single-mode region [2,3] which is preferable in conventional surface plasmon polaritons (SPPs) waveguide design [12]. Such narrow ribbon leads to three major problems. Firstly, it is challenging to fabricate, integrate and excite such a narrow GRW. Secondly, the tight mode confinement in single mode region of GRW leads to a large propagation loss [3]. Moreover, edge scattering and nano-scale effects rises extra material loss in ultra-narrow graphene ribbon [5,13].

To circumvent the above problems, here we present an novel configuration to create a GSP propagation channel without ribbon edges. The proposed waveguide consists of a uniformly biased graphene sheet suspended over a high-index dielectric nano-ridge. In contrast to the GRWs requiring sophisticated transferring the nano-scale graphene strip [14], precise electron-beam lithography [5] or spatially biasing the graphene sheet using complicated gates [10], the simple transfer of a whole piece of uniformly biased graphene sheet without the need of precise positioning and complicated bias gates could enable low-cost wafer-scale integration. The fabrication of our proposed substrate structure incorporating high-index ridges is also CMOS compatible and relatively easy to fabricate. Theoretical analysis shows that the effective index mismatch caused by the high-index ridge results in strong lateral optical confinement, with a large portion of the power stored in the nano-scale gap. Single mode transmission is achievable with a lower loss than that of the GRW's at the far-infrared regime. The role of geometry and graphene on forming the desired waveguide is investigated in detail by both rigorous electromagnetic simulator and the lightweight effective index method (EIM). The determination of single mode width and optimization of key parameters are implemented using the EIM without requiring extensive numerical computations.

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2. Schematic and modal properties of the proposed waveguide

A schematic of the proposed waveguide shown in Fig. 1 consists of a uniformly biased graphene sheet separated from a high-index GaAs ridge (permittivity: $\varepsilon_3=10.86$, width: w, height: h) by a low-index cladding. The permittivities of the upper-cladding and lower-cladding are ε_1 and ε_2 respectively. The graphene can be either air coated ($\varepsilon_1=1$, $\varepsilon_2=2.12$) or sandwiched in KCl ($\varepsilon_1=\varepsilon_2=2.12$). To look into the typical modal properties of the new structure, here we focus on the symmetric configuration ($\varepsilon_1=\varepsilon_2$) to simplify the following theoretical analysis. The thickness of the nano-scale gap between graphene and ridge is t. Graphene's complex conductivity is governed by the Kubo Formula [15], which relates to the radian frequency ω, relaxation time τ, temperature T, and chemical potential μ_c. In this work, the commercial finite element method (FEM) solver COMSOL^{TM} is used to simulate the proposed waveguide with $\omega=30$ THz [10], $\tau=1.0$ ps [16], $\mu_c=0.27$ eV and $T=300$ K.

The $|E|$ profiles for the guided TM modes with different geometric configurations are shown in Fig. 2(a)–(f). The high order mode shown in Fig. 2(f) can be avoided when the width of the ridge is narrower than the cutoff width of the TM_{01} mode. Although the field distribution looks like that of hybrid SPP modes supported by noble metal [17,18], the new mode is not hybridized due to the absence of photonic mode in the ridge at 30 THz. The fundamental mode in GRWs, i.e. the even hybridization of EGSP mode, concentrates at the high-loss graphene edges [2,3], which is hard to excite and leads to high loss. The fundamental mode in the proposed structure, on the other hand, concentrates in the low-index, low-loss gap. The fundamental mode with a field profile similar to the Gaussian beams could also be readily excited by gratings etched on the ridge. In addition, enhanced light-matter interaction, such as enhanced nonlinear effect [19], can be achieved with modal field in the dielectric materials. The proposed structure also avoids the additional material loss resulted from the ultra-narrow width of the graphene ribbon.

The modal properties include the effective index ($N_{eff}=Re(\beta/k_0)$) and the propagation length ($L_p=1/Im(\beta)$) expressed in the plasmon wavelength, which is also known as figure of merit ($FoM=Re(\beta)/Im(\beta)$) [10], where is k_0 the free space wavenumber, β is the complex wavenumber obtained from the FEM or EIM. The dependence of N_{eff} and FoM on gap thickness t is shown in Fig. 3 as ridge width w varies from 40 nm to 80 nm. Fig. 3 illustrates that increasing t from 3 nm to 50 nm results in an evolution of modes from strong to weaker confinement. The larger value of w is preferred in term of FoM, while high order modes might be supported with increasing w. It is noted that the modal effective index of this structure shown in Fig. 3 is quite large, and to excite the GSP, either the near-field techniques using nano-antennas [20,21] or far-field coupling incorporating diffraction gratings [5,6,22–24] could be used.

Superior to metal-based SPP waveguides, graphene-based structure can be tuned by adjusting chemical potential μ_c. The N_{eff} and FoM of the TM_{00} mode of proposed structure with $[t, w]=[9,80]$ nm and different μ_c are illustrated in Fig. 4. For comparison, the modal properties of the ribbon waveguide embedded in KCl with identical graphene parameters are also simulated and plotted in Fig. 4. The width of the ribbon is 45 nm, which enables single mode transmission. As shown in Fig. 4, N_{eff} decreases while L_p increases monotonically with the increased μ_c, indicating lower propagation loss achieved at the price of weaker confinement at a larger chemical potential. Due to the difference in lateral confinement mechanism, the fundamental modes of our proposed waveguide and GRW concentrate in the low-loss gap and the high-loss graphene edges, respectively. The proposed waveguide is capable of extending the L_p by $\sim$16% more than the conventional single mode ribbon waveguide as shown in Fig. 4 (the L_p increases from 0.58 μm to 0.67 μm with $\mu_c=0.27$ eV). A comparison of lateral

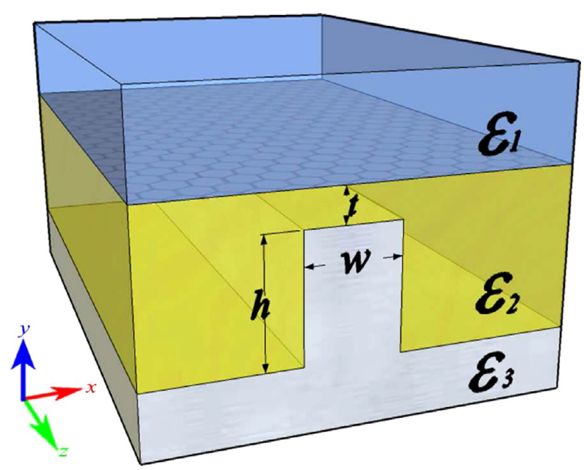

Fig. 1. Schematic of the proposed waveguide, where the graphene is represented by a honeycomb lattice for illustration.

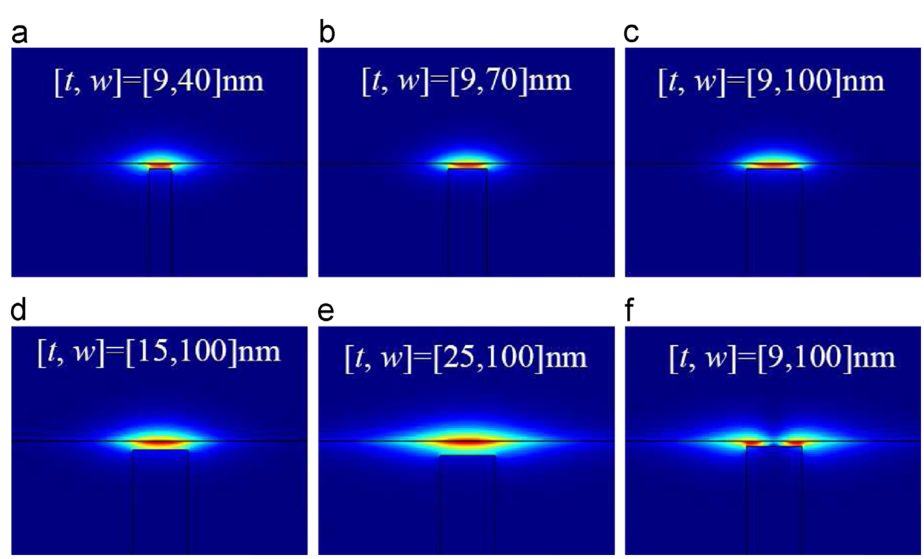

Fig. 2. $|E|$ profiles of (a)–(e) the fundamental TM_{00} modes and (f) TM_{01} mode with different geometric configurations.