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Graphene plasmonic waveguide based on a high-index dielectric wedge for compact photonic integration

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ABSTRACT

A novel waveguide consisting of a uniformly biased graphene placed above a high-index dielectric triangular wedge is proposed and analyzed theoretically. The combination of graphene plamonics and slot effect results in both the tight confinement and low loss. Superior to the previous studied graphene ribbon waveguides, the new design is easy to fabricate and supports single mode transmission. Studies on the crosstalk between adjacent waveguides reveal the ability to increase the integration density by ∼2 times compared with the traditional metal–insulator–metal slot waveguide. The proposed waveguide could be an interesting alternative to realize high density photonic circuits at terahertz and far-infrared regime.

1. Introduction

Plasmons, the collective oscillations of conduction electrons, have become an ever-increasing demand for high-density subwavelength photonic circuits [1]. The unique electronic properties of graphene [2,3], a two dimensional form of carbon in which the atoms are packed in honeycomb crystal lattice [4,5], make it a promising platform to build highly integrated plasmonic devices and systems from near-infrared to terahertz regime. Graphene's complex conductivity ($\sigma_g = \sigma_{g,r} + i\sigma_{g,i}$) is governed by the Kubo formula, which relates to the radian frequency ω, charged particle scattering rate Γ, temperature T, and chemical potential μ_c [6]. The graphene sheet with $\sigma_{g,i} > 0$ effectively behaves as an extreme thin metallic layer capable of supporting TM plasmons [7] when the intra-band transitions in the conduction band dominate [8]. Compared to noble metal, graphene supports SPPs with longer propagation length, tighter mode confinement and the controllability using external gates [9].

The concept of graphene ribbon waveguides (GRWs) [9–11] shows the potential to build graphene plasmonic circuits [12] and transformation optical devices [9,13]. Due to the existence and hybridization of edge graphene surface plasmons (EGSPs) at the boundary lines, the favorable single-mode transmission is difficult to achieve in GRWs [14]. The typical lateral dimension of GRWs ranging from hundreds of nanometers [9] to several micrometers [14]. So the GRWs based circuits cannot fully exploit the progress in CMOS process which already shrank down beyond the 22 nm [15]. Moreover, the strong hybridization between ribbon pairs placed at close proximity will further degenerate the performance in compact integrations [16].

In this paper we propose a novel plasmonic waveguide by integrating a uniformly biased graphene sheet with a high-index dielectric nano-wedge. The fabrication is compatible to the CMOS process. The EGSPs and their hybridizations are no longer supported in the new design due to elimination of the boundary lines in GRWs. High order TM modes are suppressed due to the reduced coupling area over the tip of wedge. So the single-mode transmission of TM_{00} mode is achievable in the proposed structure. The crosstalk between adjacent proposed waveguides is investigated through simulations as well, and their packing density doubles the corresponding parameter of the traditional metal–insulator–metal (MIM) waveguide designed for dense integrations. The formed structure provides one of the fundamental building blocks to enable large-scale-integrated photonic circuits in compact footprints at the terahertz and far-infrared range.

2. Geometry and modal properties of the proposed graphene waveguides

The proposed waveguide shown in Fig. 1 consists of a uniformly biased monolayer of graphene separated from the top edge of a high-index GaAs ($n_{sub} = 3.30$) wedge by a nanometer scale

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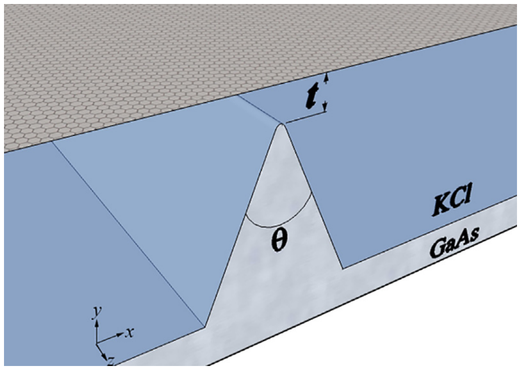

Fig. 1. Schematic of the proposed waveguide.

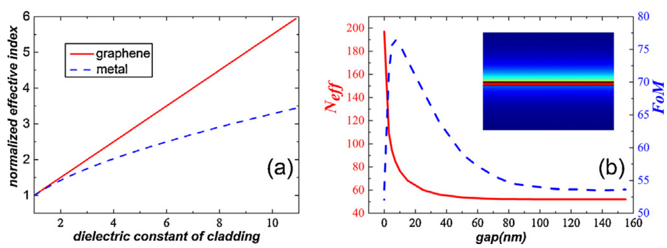

Fig. 2. (a) Dependence of normalized effective index on cladding dielectric constant for graphene (solid line) and metal (dashed line) 1D structure; (b)Dependence of N_{eff} (solid line) and FoM (dashed line) on t for 1D structure. Inset: $|E(x,y)|$ distribution of the 1D SPP TM mode with $t = 7$ nm.

low-index KCl ($n_{buf} = 1.46$) gap of thickness t, with air ($n_{clad} = 1$) covering the rest regions. The GaAs wedge tip has an angle of θ and a small curvature radius of 10 nm to avoid singularities in simulations [17]. To fabricate such waveguide, the focused-ion beam (FIB) technique could be used to form the wedge with high accuracy and graphene can then be transferred after depositing a thin KCl layer on the wedge. Another approach might be using a reverse step by depositing GaAs after milling a V-shape groove in the substrate and then covering the monolayer of graphene, similar as the fabrication process for the WPP waveguide in [13]. The configuration with $\sigma_{g,i} = (2.98e-03 + 1.60e-01i)$ mS, i.e. $\mu_c = 0.27$ eV is used unless noted otherwise. The modal properties are investigated at $\omega = 30$ THz [8,9], $\Gamma = 0.43$ meV [18], $T = 300$ K, by means of the finite element method (FEM) solver.

We note that the extreme case of $\theta = 180$ deg corresponds to the graphene sheet positioned on a high-index substrate with a low-index buffer layer. The effective index ($N_{eff} = \beta/k_0$) of graphene plasmonics and metal surface plasmonics normalized to its value when $n_{clad} = 1$ is shown in Fig. 2(a). Due to the different dispersion relationships [7,19], the graphene plasmonics are more sensitive to the cladding material than SPPs at metal–dielectric interface. The $|E|$ distributions, effective index, propagation length ($L_p = 2\pi/\alpha$) expressed in terms of the plasmonic wavelength ($\lambda_{spp} = \lambda_0/N_{eff}$) which is also known as figure of merit (FoM = β/α) [9] of one-dimensional structure are shown in Fig. 2(b). The field enhancement in the buffer layer rendered in the inset of Fig. 2(b) arises from the continuity of the displacement field at the material interfaces [20]. It is expected that, for very thin buffer layer, the fundamental mode becomes close to the graphene plasmonics at air–GaAs interface, i.e. $N_{eff} \rightarrow 197.6$. Correspondingly, the N_{eff} should approach progressively the effective index of graphene plasmonics at air–KCl interface with increasing t, i.e. $N_{eff} \rightarrow 51.9$. Due to the tight confinement of graphene plasmonics, the modal properties varies less than 5% ($t = 50$ nm) and 1% ($t = 100$ nm) from gap thickness $t \rightarrow \infty$. So the wedge with height of 100 nm is high enough to eliminate the effect of substrate.

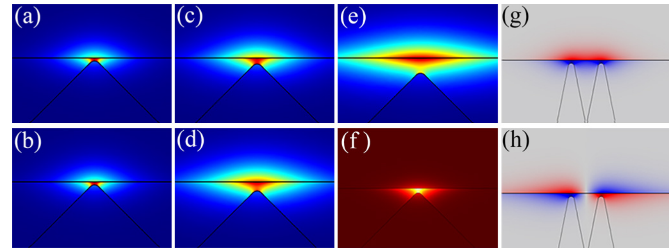

Fig. 3. (a–e) $|E(x,y)|$,(f) intensity distributions with $\theta = 90$ deg and different gap thickness: (a) $t = 3$ nm, (b) $t = 5$ nm (c, f) $t = 10$ nm (d) $t = 15$ nm (e) $t = 25$ nm; $E(y)$ distributions of (f) the symmetric and (f) the anti-symmetric modes with $\theta = 45$ deg, $t = 10$ nm.

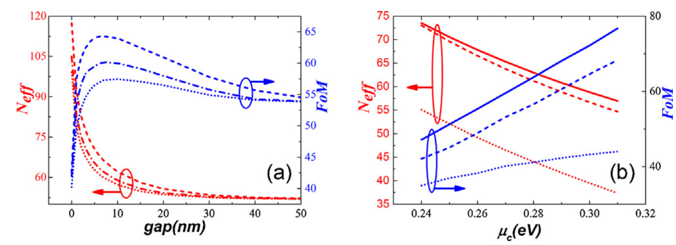

Fig. 4. (a) Dependence of N_{eff} and FoM on t and for the proposed structure with different θ. Dashed line: $\theta = 135$ deg, dash-dotted line: $\theta = 90$ deg, dotted line: $\theta = 45$ deg; (b) Dependence of N_{eff} and FoM on μ_c. Solid line: guided mode in proposed waveguide, dash-dotted line: EGSPs in 300 nm wide ribbon, dotted line: fundamental WGSPs in 300 nm wide ribbon.

2D light confinement can be obtained by reducing the tip angle. Light is laterally confined over the tip of wedge due to the effective index mismatch between the modes propagating at graphene with different gap width. The situation is similar to what happens in shallow ridge waveguides and Bloch surface wave (BSW) ridge waveguides [21], where lateral confinement is obtained by perturbing the 1D mode of slab waveguide and BSW in photonic crystal, respectively.

Single-mode guiding avoids various mode dispersion and interference effects (usually unwanted) and is favorable or required in most practical photonic circuits [22]. While the EGSPs are eliminated in the new design due to the absence of the boundary lines. The high order TM modes are suppressed because of the reduced coupling area over tip of wedge, only the fundamental TM_{00} mode is supported. The $|E(x,y)|$ distributions for the guided TM mode with different gap thicknesses are depicted in Fig. 3(a)–(e), where the wedge tip-angle is fixed at 90 deg. As shown in Fig. 4(f), the low-index nano-gap between the graphene sheet and the high-index wedge could effectively confine a large portion of the intensity due to the slot effect [23].

The modal effective index (N_{eff}), figure of merit (FoM) of the SPP mode of proposed structures with different gap are shown in Fig. 4(a) as tip-angles various from 45 deg to 135 deg. 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 guided SPP mode of proposed structure with different μ_c are illustrated in Fig. 4(b). So the fabrication-error can be compensated by tuning the chemical potential. For comparison, modal properties of EGSPs and fundamental waveguide graphene surface plasmons (WGSPs) in GRWs on KCl substrate are also plotted in Fig. 4(b). The width of the ribbon is 300 nm, which enables the fundamental WGSPs far from cutoff. Fig. 4(a) illustrates that increasing the gap from 0 nm to 50 nm results in an evolution of the mode from more confined than EGSPs to less confined and FoM reaches its maximum at $t = \sim 7$ nm, which suggests that bigger θ and gap thickness between 5 nm and 10 nm are preferred. As seen from Fig. 4(b), N_{eff} decreases while FoM increases monotonically with the