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Modeling of 2D graphene material for plasmonic hybrid waveguide with enhanced near-infrared modulation

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ABSTRACT

Modulating near-infrared signals is critical for high density optical interconnects. In order to achieve enhanced modulation effects, we design a near-infrared modulator in combination with a gold nanostripe waveguide and graphene. Conventional assumption of isotropic permittivities for graphene leads to exaggeration of light absorption at the so-called "epsilon-near-zero" point and extreme overestimation of modulation efficiency, and the anisotropic permittivities assumption faces problems for thickness definition and lower computational efficiency. Therefore, we treat graphene as a 2D conductive surface in the simulation to solve these problems, and investigate the plasmonic effects on modulation enhancement and the trade-off on the modulation efficiency versus the insertion loss. Our method is promising for the design of advanced optical devices based on 2D materials.

1. Background

Electro-optic modulators are significant photonic devices for the link between electrical and optical signals. Compared with conventional electro-optic crystals, graphene is more promising for high-performance electro-optic modulators, which have ultra-high modulation speed, ultra-broad optical operation bandwidth, high density integration, compatibility with semiconductor technology and low costs [1,2]. However, although the optical absorption coefficient of graphene is much higher than conventional electro-optic crystals, the light-graphene interaction for optical communication wavelengths is extremely weak due to the atomic scale of graphene thickness, which limits its further applications in electro-optic modulation [3]. Therefore, many light-trapping nanostructures for graphene have been proposed [4–6]. Recently, graphene/metal hybrid nanostructures based on plasmonic effects of metals have attracted a surge of interest [7–10]. Some plasmonic nanostructures for light trapping in graphene have been demonstrated experimentally [11,12]. Despite this, systematic design and optimization for the plasmonic nanostructures based on reliable optical modeling and compatibility with complementary metal-oxide-semiconductor technology is quite in demand. In fact, graphene has an extremely small thickness and extraordinary physical properties, which bring about some new challenges in device modeling and simulation. Over the past few years, many simulation models of graphene-based electro-optic modulators have been proposed [13–16], but these models generally treat graphene as an isotropic lossy dielectric material with a 3D bulk volume, which might lead to illusive enhancement effects of light-graphene interaction, especially for plasmonic hybrid nanostructures [17]. Recently, some researchers have realized that graphene can be considered as an anisotropic lossy dielectric material with a finite thickness due to its exceptional structural and optoelectronic properties [18], whereas the effective thicknesses of graphene for this assumption in many device models are not universal [19,20]. Therefore, it is necessary to regulate the computational assumption in the design of graphene-based electro-optic modulators. In this paper, we treat graphene as an anisotropic 2D material with a surface conductivity, and design a compact electro-optic modulator for optical intensity modulation in combination of graphene and a plasmonic nanostripe waveguide. Three simulation methods for graphene material properties are compared, and the plasmonic effects for modulation enhancement are systematically investigated.

2. Methods

We design an ultra-compact modulator in combination with a gold nanostripe and a silicon waveguide on top of a buried layer of silicon dioxide, and two graphene layers are integrated on the silicon waveguide, as shown in Fig. 1. Two hexagonal boron nitride (*h*BN) layers are used as insulating layers [8]. For optical simulations, we

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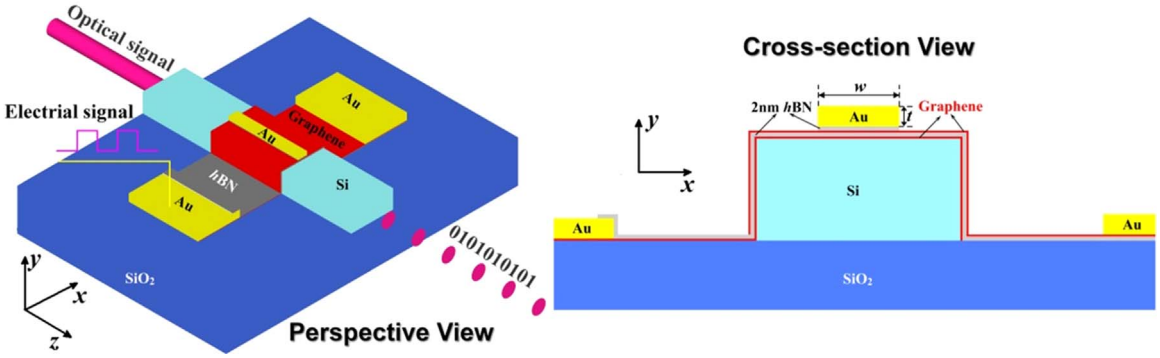

Fig. 1. Design of graphene-based electro-optic modulator. The symbols w and t represent the width and thickness of the gold waveguide.

solve Maxwell's equations on a rectangularly meshed cross section of the modulator based on a finite-difference eigenmode method [21], which calculates the mode field profiles, modal effective index and propagation loss. The use of gold nanostripe makes the modulator sensitive to light polarization. The fundamental quasi-transversal electric (TE) mode is dominant, whereas the quasi-transversal magnetic (TM) mode is rapidly evanescent due to high damping in gold. Therefore, we focus on the study of TE mode.

As we demonstrated in previous work [22], Kubo formulas are used to calculate graphene's complex conductivity $\sigma(\omega, \mu_c, \Gamma, T)$, which is a function of angular frequency ω, chemical potential μ_c, scattering rate Γ and Kelvin temperature T. Γ and T are taken as 16.67 ps^{-1} and 300 K, respectively. In the near-infrared regime, graphene can be assumed as a lossy dielectric material due to interband transition. Because the light-graphene interaction originates from the transport of carriers on the 2D surface, one can assume that graphene is an anisotropic dispersive material with an effective permittivity tensor, as defined in Ref. [22]. In this work, we simulate the same device by setting graphene as a 2D conductive surface, a volumetric isotropic dielectric material (ε=1-$\sigma/i\omega\Delta$, where Δ is the effective thickness of graphene), and a volumetric anisotropic dielectric material [22], respectively. Compared with the volumetric assumption for graphene, the 2D surface configuration treats graphene as a conductive plane with a zero thickness in numerical simulation, which requires much less discrete meshes surrounding graphene.

3. Results and discussion

Initially, we reveal the influences of various graphene material configurations without a gold nanostripe, as shown in Fig. 2(a). It

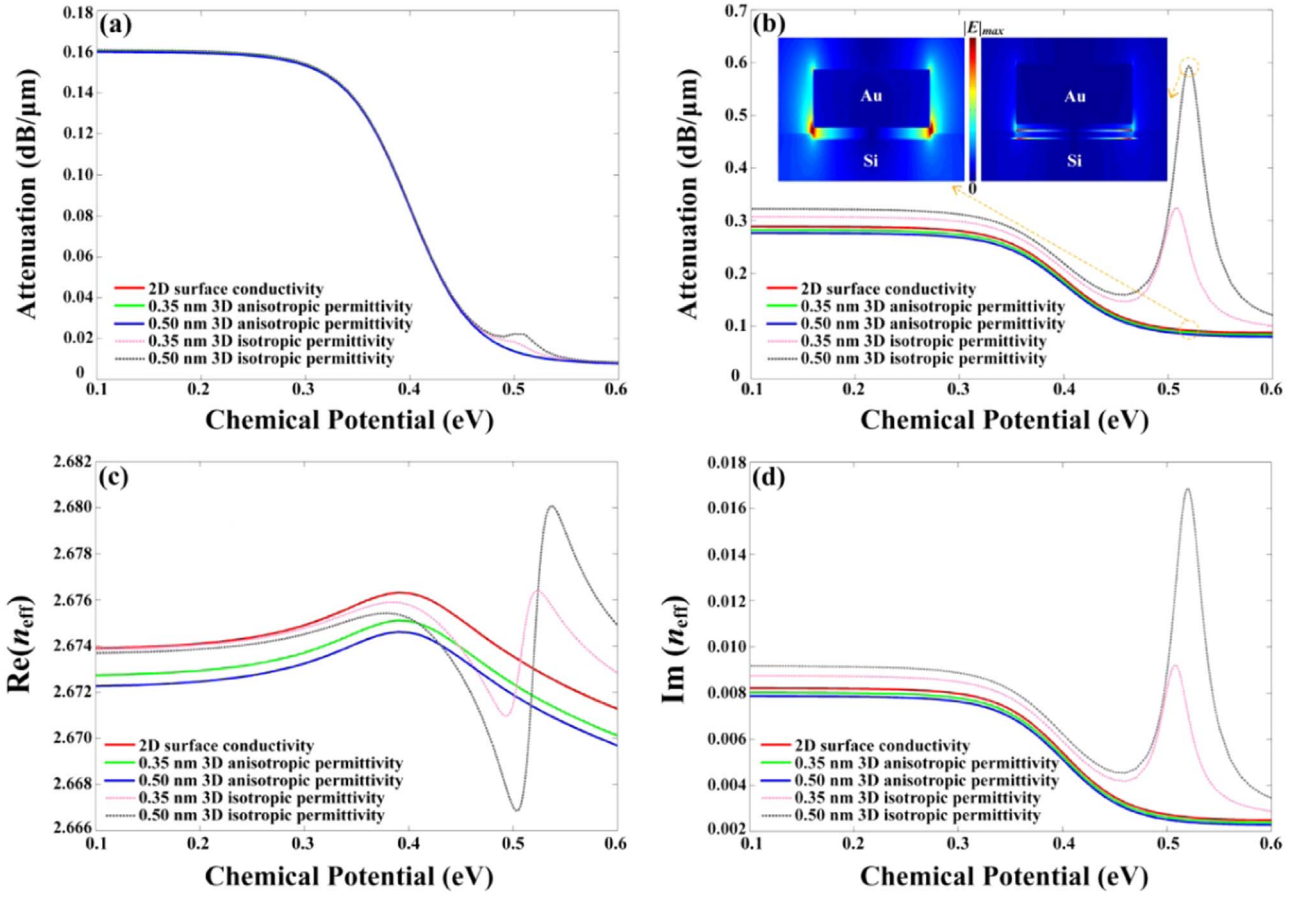

Fig. 2. Attenuation as a function of μ_c for various material configurations of graphene: (a) without a gold nanostripe, (b) with a gold nanostripe. The inset in (b) denotes the filed distributions at μ_c=0.55 eV for 2D and isotropy configurations. Modal effective indexes for various material configurations: (c) real part, (d) imaginary part.

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