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Ultrafast suspended self-biasing graphene modulator with ultrahigh figure of merit

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ABSTRACT

A theoretical investigation of a suspended self-biasing graphene waveguide for electro-optical modulators is presented. The light–matter interaction can be enhanced by suspending the waveguide. For electro-absorptive modulation, the normalized modulation depth can be 0.54 dB/μm with a 3-dB footprint of only 1.5 μm^2. The insertion loss is extremely low ~ 0.002 dB, with the figure of merit of ~ 2700. For the electro-refractive modulation, a 100% modulation can be achieved with much smaller π-phase shift length of only 18.0 μm. The modulators also show great potential for high-speed (~ 559.2 GHz) modulation. The compromise between modulation speed and modulation efficiency is reduced significantly and the design is near-optimal to its fundamental limits. Moreover, a verification simulation by COMSOL is also given. This suspended graphene modulator can pave the way to practical high-speed, compact-footprint, and high-efficiency devices.

1. Introduction

Optical modulator [1–3] is a device used for modulating the optical waves by low-frequency information signal waves. According to the different types of the information signal, it can be divided into electro-optical [1–3], all-optical [4,5], acoustic-optical, and magneto-optical types. The amplitude, frequency, or phase of the carrier waves will be modified by the low-frequency signal. For electro-optical modulators, they can also be divided into electro-absorptive [1,3] and electro-refractive [2] types, by the loss mechanism and mode index mechanism, respectively.

The modulation speed is a key parameter for a modulator. However, it is always low for the slow response of the traditional devices. Moreover, the compromise between modulation speed and modulation efficiency is always a problem to realize a good modulator. Silicon-based modulators [1,2] have been nearing the limits of performance improvements for modulation speed, footprint, and efficiency. Since graphene was first fabricated [6] in 2004, it has shown great potential for optical modulator applications. The first graphene-based modulator was reported in 2011 [3]. Since then many papers [7–19] have reported about graphene-based modulators, for both electro-absorptive [7–17] and electro-refractive [18,19] types. The graphene-based modulators can be designed to have a higher modulation speed (30 GHz [7], 35 GHz [8]), larger modulation depth (~ 90% [7,9–11,18], 100% [12]), broader operation bandwidth (15 THz [9,11]), and smaller footprint ($0.18 \cdot 0.3$ μm^2 [11]) than traditional modulators because of the much broader and higher tunable absorption and ultrahigh carrier mobility of graphene. However, high channel mobility reduction [3,13] due to dielectric interfaces has become a major barrier limiting the modulation speed and bandwidth. And low light–matter interaction [14], large energy consumption [15], and large insertion loss [16,17] also limits the modulation efficiency.

Suspended graphene device was first fabricated and demonstrated in 2007 [20,21]. And it was found that a suspended single-layer graphene can achieve a higher carrier mobility, which is more than 200 000 $cm^2/V \cdot s$ [22,23]. Moreover, suspending the graphene can lower the contact resistance (between graphene and metal) and the graphene sheet resistance because of its higher mobility, and achieve high-quality device.

To the best of our knowledge, the suspended self-biasing graphene waveguide has not been used as a modulator yet. By suspending the double self-biasing graphene layers, it has at least four distinctive advantages: (i) We can design the modulator to realize the highest light–graphene interaction (in the cases of references [3,13], the modulators are not optimized when they just used the silicon waveguide to confine the fields). Then the modulation efficiency can be enhanced and the footprint can be smaller; (ii) Since the self-biasing graphene waveguide is suspended in the air, the channel mobility reduction caused

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by graphene–dielectric interaction will be lower, the total resistance, including the graphene–metal contact resistance and graphene sheet resistance, of the modulator, can be even lower. Moreover, the capacitance will be lower with a thicker insulator. Therefore the modulation speed and bandwidth can be enhanced. The compromise between modulation speed and modulation efficiency can be reduced; (iii) The insertion loss will be extremely low, and the figure of merit (FOM) (defined as the ratio of modulation depth to insertion loss [11]) can be even better; (iv) Since the two graphene layers are under the same ambient, the modulation curves [3,13] will be totally symmetrical.

In this article, we present a theoretical study of practical modulators based on this suspended self-biasing graphene waveguide for both electro-absorptive and -refractive types. In Section 2, we analyze the model and derive the dispersion equation. In Section 3.1, the modulators are designed and its effect on light–graphene interaction is discussed and analyzed in detail. The performance of the modulators has been shown in Section 3.2. For electro-absorptive type, the insertion loss is extremely low ~ 0.002 dB, with the figure of merit of ~ 2700. For electro-refractive type, a 100% modulation can be achieved with much smaller π-phase shift length of 18.0 μm. The modulators also show great potential for high-speed modulation with a predicted 3 dB modulation bandwidth of 559.2 GHz and a speed limit of 4.29 THz. The compromise between modulation speed and modulation efficiency is reduced significantly. The design of this modulator is also near-optimal to its fundamental limits. Moreover, the applied voltage can be lower than 5 V, and the energy consumption can be as low as 1.23 fJ/bit. In Section 3.3, the verification simulation by COMSOL is given, which shows perfect agreements with our calculation results. With all these advantages, the suspended modulator has great potentials for realizing practical high-speed, compact-footprint, and high-efficiency devices.

2. Models and theoretical method

The side-view for the modulator structure and the coordinate system are shown in Fig. 1(a). Here the two graphene sheets sandwiched by the insulator are biased simultaneously by each other to form a p–n junction: one is p-doped and the other n-doped with the same carrier density. That is why the modulator is called as a self-biasing graphene modulator. Here the insulator slab between the two graphene sheets has two functions: first it is used for generating electrons and holes to realize self-biasing; second it is used for confining the mode to enhance the light–graphene interaction. Thus the chemical potentials of these two layers have the same absolute values, and these two graphene layers share the same permittivity.

Fig. 1(b) shows the 3D schematic of the modulator. The active region of the modulator is suspended in the air on the semiconductor wafer. The air interval between the active region and the Si substrate is large enough, so the optical modes remain undisturbed from the substrate. The thickness of the graphene in the calculation is $\delta = 0.33$ nm, and the thickness of the insulator slab is w.

Fig. 1(c)–(f) illustrate a possible way to fabricate the suspended self-biasing graphene modulator. First a trench is made in the semiconductor wafer by etching (c); then an annealed graphene is transferred [24] on the trench (d); after that a thick insulator slab should be deposited on the suspended first layer graphene (e); at last another annealed graphene is transferred on the top of the insulator slab (f).

The equivalent permittivity of graphene can be written as $\varepsilon_g = i\sigma_g/\omega\varepsilon_0\delta$ [25], where δ is the thickness of monolayer graphene, ω is the angular frequency of carrier wave, and ε_0 is the permittivity of vacuum. In the optical range, the surface conductivity σ_g of graphene can be predicted by the Kubo formula [26] which includes the intraband contribution:

$$\sigma_{\text{intra}}(\omega,\mu_c,\tau,T) = \frac{ie^2k_BT}{\pi\hbar^2(\omega+i\tau^{-1})}\{\frac{\mu_c}{k_BT} + 2\text{In}[\text{Exp}[-\frac{\mu_c}{k_BT}]+1]\} \quad (1)$$

and the interband contribution (principal value):

$$\sigma_{\text{inter}}(\omega,\mu_c,\tau,T) = \frac{ie^2}{4\pi\hbar}\text{In}[\frac{2|\mu_c| - \hbar(\omega+i\tau^{-1})}{2|\mu_c| + \hbar(\omega+i\tau^{-1})}] \quad (2)$$

The conductivity of graphene can be written as:

$$\sigma_g(\omega,\mu_c,\tau,T) = \sigma_{\text{intra}}(\omega,\mu_c,\tau,T) + \sigma_{\text{inter}}(\omega,\mu_c,\tau,T) \quad (3)$$

In Eqs. (1)–(3), μ_c is the chemical potential of graphene, τ is the momentum relaxation time representing loss mechanism, in the following research we take $\tau = 3.3$ ps [27], and temperature is $T = 300$ K. $e = 1.6\times10^{-19}$ C is the charge of an electron, the Boltzmann's constant is $k_B = 1.38\times10^{-23}$ J/K, and the reduced Plank's constant is $\hbar = 1.055\times10^{-34}$ J · s.

The suspended self-biasing graphene waveguide may support transverse magnetic (TM) and transverse electric (TE) modes simultaneously. For TM mode, the light–graphene interaction is much more complex than that of TE mode, because it has two components of the electric field (E_x and E_z). The one-atom-layer thick graphene's periodicity is in the two-dimensional lattice plane, and it reveals anisotropic material properties: the in-plane permittivity ($\varepsilon_g = i\sigma_g/\omega\varepsilon_0\delta$) can be actively tuned by the chemical potentials (the Fermi level), whereas the out-of-plane permittivity ($\varepsilon_\perp$, in the direction perpendicular to the graphene sheet) does not vary with the external parameters. Only the electric field can interact with graphene, so the dispersion relation of TM mode cannot be derived directly. However, for TE mode, it only has an in-plane component E_y which interacts with the graphene [18]. We discuss the symmetric TE mode here. The mode propagates along the z-direction, and the TE mode field distribution in each area can be assumed as the following form [28]:

$$E_y(x) = \begin{cases} A_6\exp[-h_3(x-w/2-\delta)] & x \ge w/2+\delta \\ A_2\cos h_2(x-w/2) + A_3\sin h_2(x-w/2) & w/2 \le x \le w/2+\delta \\ A_1\cos(h_1x) & -w/2 \le x \le w/2 \\ A_4\cos h_2(x+w/2) + A_5\sin h_2(x+w/2) - (w/2+\delta) & \le x \le -w/2 \\ A_6\exp[h_3(x+w/2+\delta)] & x \le -(w/2+\delta) \end{cases}, \quad (4)$$

where $A_1 \sim A_6$ are unsolved mode coefficients in different regions. The permittivity is $\varepsilon_n = \varepsilon_1, \varepsilon_n = \varepsilon_g$ or $\varepsilon_n = \varepsilon_2 = 1$ of the dielectric insulator slab, graphene, or outside air, respectively. The complex propagation constant is $\beta = \beta_1 + i\beta_2$ where β_1 is related to the effective refractive index ($N_{\text{eff}} = \beta_1/k_0$, k_0 is the wave vector in vacuum), and β_2 is related to the mode power attenuation (MPA) $\alpha = 20\beta_2^*\log_{10}(e)$. $h_1 = \sqrt{\varepsilon_1k_0^2 - \beta^2}$, $h_2 = \sqrt{i\sigma_g\omega\mu_0/\delta - \beta^2}$, $h_3 = \sqrt{\beta^2 - \varepsilon_2k_0^2}$. As the tangential electro-magnetic fields are continuous on the interfaces, we have derived the dispersion equations of TE mode as follows [28]:

$$\tan(h_1w/2) = (1 - i\sigma_gk_0^2/h_3\omega\varepsilon_0 + \beta^2\delta/h_3)/(h_1\delta + h_1/h_3) \quad (5)$$

3. Results and discussions

3.1. Mode characteristics

When $w = 100$ nm, we use the material of Aluminum Oxide ($\varepsilon_1 = 3.06$ at $\lambda = 1.55$ μm [19]) to calculate Eq. (5), and obtain the MPA α and effective refractive index (N_{eff}) of TE mode as a function of μ_c at wavelengths of 1.55 μm, as shown in Fig. 2.

The MPA have an abrupt change at the threshold of interband transition, and similar results have been found in [18,19]. When the chemical potential is between $-\pi\hbar c/\lambda$ and $\pi\hbar c/\lambda$, the interband transition takes place. The loss will be more than 2000 times lower when the chemical potential is beyond this scale: The loss is 0.258 dB/μm at $\mu_c = 0.40$ eV, however, the loss is only 0.00097 dB/μm at $\mu_c = 0.41$ eV, 266 times lower; 0.0001 dB/μm at 0.8 eV, 2580 times lower, which makes a normalized modulation depth of 0.257 dB/μm [11]. It is worthy to point out that if the cladding layer is not air, namely the waveguide is not suspended, the modulation depth will be extreme low, such as it is only 0.0052 dB/μm for $\varepsilon_2 = 3.0$, and no mode will be supported when ε_2 is equal or higher than 3.06 (according to our calculation data not shown here). Beyond this absorption threshold, $\mu_c > \pi\hbar c/\lambda$, the