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# A Tunable THz Wave Modulator Based on Graphene

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## Abstract

A novel terahertz modulator based on graphene is proposed and designed. The device consists of a silicon ridge covered by a graphene sheet. The transmission properties of the proposed structure demonstrate that the introduction of graphene can improve the switching and filtering performance of modulators, and enhance its field confinement capability. In the case of the number of layers, a blue shift can be observed in the center wavelength with increase of graphene layers. Meanwhile, the relationship between the number of layers and the peak of reflection spectra is an inverse proportion function. In addition, we find that the center wavelength is almost unchanged with respect to the different chemical potential, thus the effective refractive indices of the cross section of light propagation direction can be well preserved. These findings will contribute to the research and development of graphene based THz waveguide modulators.

## 1. Introduction

Inrecent decades, terahertz (THz) technology has attracted wide attention in many different applications, such as spectroscopy, high-speed communication, bioscience, bioscience and medical science [1]. The progressively developed research progress in the THz field [2], [3] has promoted the demand of devices that can manipulate THz waves including modulators, filters and switches. Much effort has been put on the design of diverse devices in THz system. Yang et al. proposed a structure consisting of an array of terahertz resonators which can reconfigure the resonance frequency by changing the size of metal rings [4]. Sensale-Rodriguez et al. generated a THz modulator consisting of a single-layer graphene-based structure which achieved the modulation depth of 15% [5]. And a modulator can both control amplitude and phase of the THz transmitted wave was designed by He et al [6]. However, the THz modulator owning good performance is still not fully developed.

In this letter, we strictly investigate a graphene based THz modulator able to control the amplitude and resonance frequency of the modulated THz wave. The results distinctly indicate the modulator exhibit excellent switching and filtering performance and the strong confinement capability for modulators. The maxima modulation depth of 79% and low insertion loss of 1.02 dB is achieved. Moreover, the devices can be easily fabricated and integrated by semiconductor manufacturing process because of the current semiconductor devices are based on C, Si, and Ge.

## 2. Geometry and basic theory

The three-dimensional (3D) structure and 2D cross section geometries of the proposed modulator are shown in Fig. 1. The silicon core is placed on the silicon dioxide substrate and is covered with graphene. For convenience description, the height and width of the silicon layer are denoted as h and w, respectively. Besides, the depth and width of the grooves and the length of Bragg grating period are assumed as a, c and Λ, respectively. In order to facilitate the manufacturing, we assume that c is equal to half of Λ. Due to the presence of grooves, the effective refractive index change along the incident direction of light are named neff1 and neff2, respectively. The grating period Λ can be defined as [7]:

$$\Lambda = \frac{m\lambda_c}{2n_{\mathrm{eff}}} = \frac{m\lambda_c}{n_{\mathrm{eff1}} + n_{\mathrm{eff2}}} \tag{1}$$

where λc is the center wavelength of the resonant wavelength and m is an integer that stands for the grating order. According to Eq (1), the effective refractive index and center resonant wavelength determine the period of the Bragg grating. To design proper structure for special center resonant wavelength, the effective refractive index (neff1, neff2) should be accurately computed. The effective refractive index is calculated by using MODE solutions.

The graphene layer upon the grating can be formed by chemical vapor deposition (CVD) [8]. In this proposed structure, the graphene layer serves as a waveguide switch due to its extraordinary electro-optic properties that can be regulated by controlling the gate voltage. Generally, the surface conductivity model is better than the volume dielectric model when the graphene layer is constructed because of its unique 2D planar structure. Therefore, the surface conductivity model is employed to characterize graphene properties. The dynamical conductivity can be summarized as following equation [9], [10]:

$$\sigma(\omega,\Gamma,\mu_c,\mathrm{T}) = \sigma_{\mathrm{intra}}(\omega,\Gamma,\mu_c,\mathrm{T}) + \sigma_{\mathrm{inter}}(\omega,\Gamma,\mu_c,\mathrm{T}) \tag{2}$$

where ω is the angular frequency, Γ is the scattering rate, σ is the chemical potential, and T represent

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temperature. Among the many variables that appear in Eq (2), chemical potential is directly related to the optical absorption properties of graphene layer [5]. The optical properties of graphene can be determined by scattering rate and chemical potential. The scattering rate is numerically chosen in Ref.[11],the relationship of voltage and chemical potential [12] can be demonstrated by Lumerical DEVICE. In combination with references [12], [13] and some simulations, the width and height of the silicon core are set to w = 210 μm and h = 90 μm, respectively. Additionally, the Bragg grating period length is taken as Λ = 125μm, and the number of grating cells is 60.

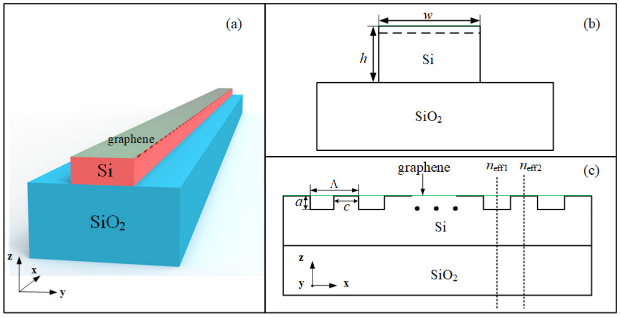

**Figure 1.** (a) 3D and (b) - (c) 2D cross-section geometries of the proposed Bragg grating modulator.

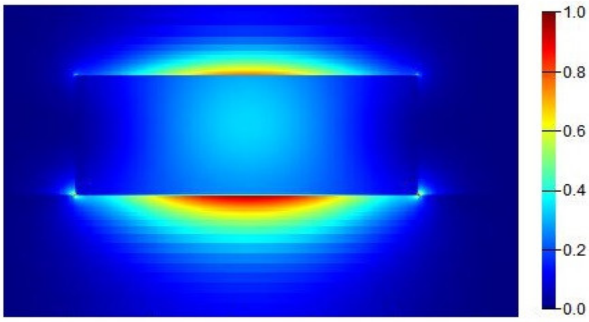

**Figure 2.** The normalized electric field distribution of the proposed Bragg grating modulator when w =210 μm, h = 90 μm at the wavelength of 525 μm.

## 3. Results and discussion

In the present work, we focus on the wavelength range from 500 μm to 550 μm, the corresponding frequency is 0.5151 THz - 0.6000 THz. In order to better understanding properties of the proposed modulator, the investigation is started by studying the electric field distribution of the proposed structure. To obtain accurately results, the perfect match layer (PML) boundary condition is employed [14]. In the case of one layer of graphene, the normalized electric field distribution of the light propagation direction at the incident wavelength of 525 μm is shown in Fig. 2. It is clearly that the electric field is strongly confined at up and down surface of silicon layer. It also indicated that the structure has rather strong field confinement capability. In order to get further insight into the characteristics of the Bragg grating modulator, the transmission spectrum of the proposed device when a=10 μm is shown in Fig. 3. As shown in Fig. 3, there is a high pass-band and the center wavelength is 520 μm. The peak of reflection spectrum is 65% when the Bragg grating cells is 60. It indicates the device has good filter properties. The number of graphene layers also has a great influence on the performance of the proposed structure. Therefore, the reflection spectra of the proposed configuration with different number graphene layers are investigated. Fig. 4 shows the reflection spectra with different layers of graphene at 1, 2, 3 and 4 respectively. The center wavelength shows blue-shifted with increase of the number of graphene layers. It indicates that the effective refractive indices are decrescent with increase of graphene layers. Besides, the peak of reflection spectra is also reduced gradually, which implies the filter properties of the proposed structure is degenerated and the absorption losses is enlarged with increase of graphene layers. This result is consistent with previous studies [15].

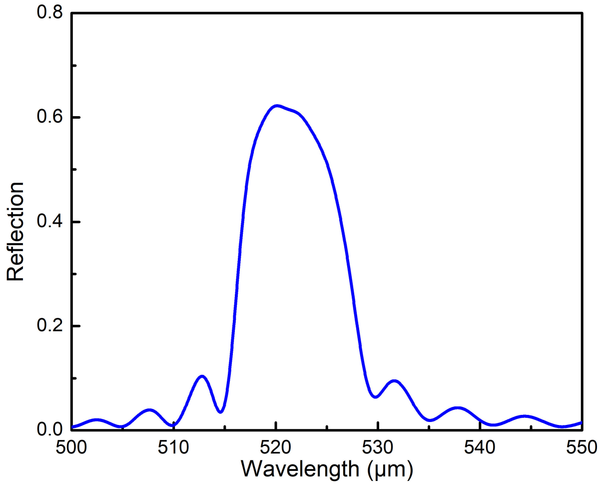

**Figure 3.** Reflection spectrum when Bragg grating's depth a=10μm.

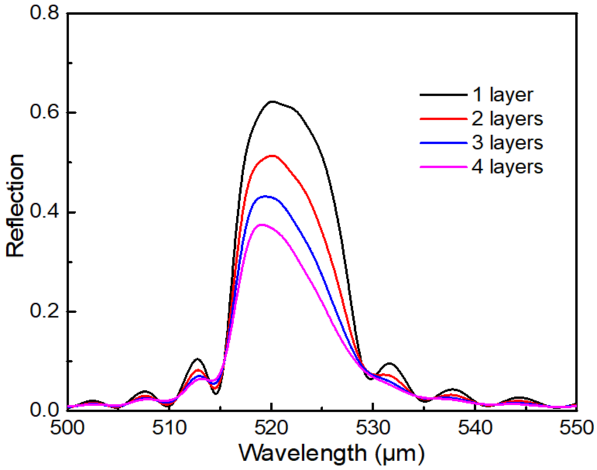

**Figure 4.** Reflectance spectra of the proposed structure with different number of graphene layers at 1, 2, 3, and 4, respectively.

As mentioned above, the chemical potential can directly influence on the properties of graphene. Accordingly, the reflection spectra are investigated with different chemical potential. Fig.5 shows the reflection spectra of the proposed device with different chemical potential at 0.1 eV, 0.3 eV, 0.5 eV, 0.7 eV, 0.9 eV and pure, respectively. Overall, the peak of reflection spectra is gradually reduced with increase of chemical potential of graphene, which mean the reflection capability of the proposed structure is weaken. However, the center wavelength is almost unchanged, which implies the effective refractive indices of the cross section of light propagation direction have no change. In detail, the peak of reflection spectrum can achieve 80% with the pure waveguide, but it only has 23% when the chemical potential at 0.9 eV. In both these cases the reflection power of light is dramatically different. Therefore, these two states can be defined as on-states and off-state, respectively. Additionally, the chemical potential can be change by applied to the voltage of graphene layer [17]. Thus, with a suitable applied voltage, the chemical potential can increase to 0.9 eV. Namely, the status of the device can be controlled by changing applied voltage.

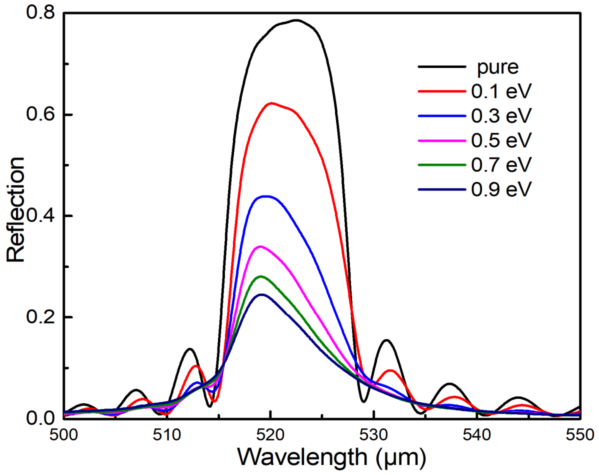

**Figure 5.** Reflectance spectra with different chemical potentials at 0.1 eV, 0.3 eV, 0.5 eV, 0.7 eV, 0.9 eV and pure, respectively.

## 4. Conclusion

In summary, we propose a graphene based THz modulator. The transmission properties of the proposed structure are investigated by using finite different element time-domain method. The result shows that graphene can improve the switching and filtering performance of modulators, and enhance its field confinement capability. With the increase of the number of layers or the chemical potential, the amplitude of reflection spectra in the center wavelength is gradually descending. Therefore, for the number of layers, this means that the degeneration of the filter properties and the absorption loss, whereas this implies that the reflection capability of the proposed structure is weaken in the case of the chemical potential. Therefore, this modulator's performance presents the enormous potential for developing sophisticated THz communication system.

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