Graphene-Based Polarization-Independent Mid-Infrared Electro-Absorption Modulator Integrated in a Chalcogenide Glass Waveguide

Yong Zhou1, Rongguo Lu1*, Guangbiao Wang1, Jiangbo Lyu1, Meng Tan1, Liming Shen1, Rui Lin1, Zhonghua Yang2 and Yong Liu1

Abstract
A polarization-insensitive graphene-based mid-infrared optical modulator is presented that comprised SiO2/Ge23Sb7S70, in which two graphene layers are embedded with a semiellipse layout to support transverse magnetic (TM) and transverse electric (TE) polarizing modes with identical absorption. The key performance index for the polarization independent modulator is polarization-sensitivity loss (PSL). The waveguide of our device just supports basic TE and TM modes, and the PSL between two modes is of < 0.24 dB. The model can offer extinction ratio (ER) more than 16 dB and insertion loss less than 1 dB. The operation spectrum ranges from 2 to 2.4 μm with optical bandwidth of 400 nm. The 3 dB modulation bandwidth is as high as 136 GHz based on theoretical calculation.

Keywords: Chalcogenide glass, Graphene, Mid-infrared, Optical-modulator, Polarization-insensitive

Introduction
Near-infrared wavelength optical fiber communication networks are becoming the core of the whole telecommunication networks. However, the mid-infrared is also an important waveband for the application of electro-optic device in military and civil fields, such as infrared countermeasure, chemical sensing, infrared guidance, environmental monitoring, space communication, etc. In addition, mid-infrared integrated electro-optic devices, such as photodetectors and modulators, also are developed to expand the 1.55 μm communication window.

In recent years, 2D functional electro-optic materials, such as graphene [1–4], chalcogenide [5], and black phosphorus [6], have been discovered, which accelerated the development of integrated electro-optic and broke the traditional performance limitation. Among these materials, graphene is considered as an ideal material for realizing optical modulators due to some attractive advantages [7], such as constant absorption over a wide spectrum [8], ultra-high carrier mobility at room temperature [9], electrically controllable conductivity and compatibility with CMOS processing. Consequently, graphene-based optical modulator has become a hot research topic. However, by far, the operation waveband of most reported graphene-based optical modulators is around 1.31 μm or 1.55 μm [10–13]. The modulation principle of near infrared and mid-infrared is the same, but the operation wavelength of modulator mainly depends on the waveguide transparency windows. The key point for the realization of graphene-based mid-infrared modulators is the integration of graphene and various mid-infrared waveguide materials. In 2017, Lin et al. [14] reported a mid-infrared electro-absorption optical modulator based on Ge23Sb7S70-on-graphene structure, which opened the field of graphene-based mid-infrared modulator.

Graphene as electro-optic material, we also need to consider one of the most important characteristics of anisotropic dielectric [15], which has been experimentally...
proved in this article [16]. The permittivity in plane is tunable, however, the permittivity in vertical is a constant of 2.5. So, the graphene can only strongly interact with the in-plane electric field [16], that is the reason why reported graphene-based modulators before have a strong polarization dependence, in which modulators can only modulate in-plane electric filed mode [10–13]. Generally, the polarization state of light in waveguide or fiber is random. To realize the wide commercial application of graphene-based modulator, the problem of polarization dependent needs to be solved.

In this work, we present a new structure of graphene-based mid-infrared polarization-independent electro-optic modulator, which has the advantages of large modulation bandwidth and wide spectrum of polarization insensitivity. We used the SOI structure and a Ge$_{23}$Sb$_7$S$_{70}$ glass strip which is embedded in SiO$_2$ cladding as waveguide core. In the Ge$_{23}$Sb$_7$S$_{70}$ waveguide, two graphene layers are U (semiellipse)-type distribution and are insulated by Ge$_{23}$Sb$_7$S$_{70}$ glass. Since the graphene layer is U-type distribution, both TE and TM modes can strongly interact with graphene. By proper choosing structure parameters, we can well overcome the polarization dependence. Using the finite element method (FEM), we analyzed the effective mode index (EMI) and absorption coefficient ($\alpha$) of the U-structure device. The result shows that the real parts of EMI for TE ($N_{te}$) and TM ($N_{tm}$) modes have the same fluctuations (with constant difference) in different chemical potential ($\mu_c$), and the imaginary parts of both TE and TM modes have almost identical fluctuations and wavelength independent in a wide spectrum. By proper choosing of switching points for “ON” and “OFF” states, for both TE and TM modes, the modulation depth is more than 16 dB, the operation wavelength spectrum is 2–2.4 μm, the PSL is less than 0.24 dB, and the theoretical 3 dB modulation bandwidth is as high as 136 GHz.

**Methods**

The transparency window of Ge$_{23}$Sb$_7$S$_{70}$ glass ranges from 2 to 10 μm [17] that is a great material for mid-infrared photonics. Previous study led by Lin et al. [14] has proved its feasibility to realize Ge$_{23}$Sb$_7$S$_{70}$-graphene mid-infrared modulator. In this work, we also take Ge$_{23}$Sb$_7$S$_{70}$ glass as waveguide material. The geometrical structure of our proposed modulator is depicted in Fig. 1, which was fabricated using a thermal nanoimprint process. Details of the process steps are schematically illustrated in Fig. 1. You can also reference paper [18] to get details for the preparation of PDMS composite stamps and Ge$_{23}$Sb$_7$S$_{70}$ glass solution. Details for geometrical size and materials are presented in Fig. 2b.

A SiO$_2$ layer with thickness $h=0.8$ μm was grown on Si substrate, and then a groove with width $w=0.96$ μm and height $h=0.8$ μm was made in SiO$_2$ layer by using photolithography method. After filling Ge$_{23}$Sb$_7$S$_{70}$ solution and patterning by thermal nanoimprint, a U-type Ge$_{23}$Sb$_7$S$_{70}$ groove was made. A 10-nm-thickness hexagonal boron nitride (hBN) layer was paved at flat area. Then, first graphene layer, 50-nm-thickness (spin-coating) Ge$_{23}$Sb$_7$S$_{70}$ insulator and second graphene layer were paved to the U-type Ge$_{23}$Sb$_7$S$_{70}$ groove in order. Finally, we filled the U-type Ge$_{23}$Sb$_7$S$_{70}$ groove with Ge$_{23}$Sb$_7$S$_{70}$ solution and transferred hBN cladding and added electrode. The electrode structure is Au–Pd–graphene since the contact resistance between graphene and Pd is less than 100(Ω/μm) [19]. Graphene sheet width between electrode and waveguide is 0.8 μm. Figure 2c, d presents the electric field distribution for both TE (in-plane) and TM (vertical-plane) modes.

When voltage is applied onto the graphene, graphene’s chemical potential $\mu_c$ is dynamically tuned. In our model, graphene is treated as an anisotropic material. The perpendicular permittivity $\varepsilon_\perp$ of the graphene does not vary with the $\mu_c$ and always stays as a constant of 2.5, whereas the in-plane permittivity of the graphene $\varepsilon_\parallel$ can be tuned as [12].

\[
\varepsilon_\parallel(\omega) = 1 + \frac{i\delta}{\omega\varepsilon_0 h_g}
\]

The $\delta$ stands for the conductivity of graphene and relates to chemical potential $\mu_c$, which can be deduced from Kubo formula [20]. The $\omega$ represents the radian frequency, and $h_g=0.7$ nm is the effective thickness of graphene.

We made a Ge$_{23}$Sb$_7$S$_{70}$ strip waveguide, in which two flat graphene layers were embedded (Fig. 3 insert). Figure 3 plots the real and imaginary part of EMI for both TE and TM mode at the wavelength of 2.2 μm. The
EMI of TE mode changed obviously for both real and imaginary parts. On contrary, no significant fluctuations occurred to the EMI of TM mode for both real and imaginary parts. The main reason is that TM mode polarization is perpendicular to the graphene plane and $\varepsilon_{\parallel}$ is nontunable in chemical potential. In this work, we bend the graphene layer as U-type layout to impose equal influence on both TE and TM modes.

**Results and Discussion**

Although the polarization-independent electro-optic modulator based on graphene has been reported [15–21], the polarization independence of these devices is closely related to wavelength [22]. Therefore, in our model, the U-structure is used, in which we find that the sensitivity of the waveguide polarization is weak correlation with wavelength. The imaginary part of the EMI is known as electro-absorption. As shown in Fig. 3, the imaginary part of the EMI reaches peak at low chemical potential around $\mu_c = 0.1 \text{ eV}$. Thus, the $\mu_c = 0.1 \text{ eV}$ point can be chosen as “OFF” state point. At the same time, the discrepancy of imaginary part of the EMI between TE and TM modes is highest at “OFF” state point. To get lower discrepancy of absorption, we just need to minimize the discrepancy of absorption at “OFF” state point. At wavelength $= 2.2 \text{ μm}$ and $Ra = 0.35 \text{ μm}$ (size of minor radius of the ellipse...
that is the horizontal axis), by sweeping the \( \mu_c \) from 0.1 to 0.8 eV, under different \( R_b \) (size of major radius of the ellipse that is the vertical axis), the influence of varied \( \mu_c \) on EMI for both TE and TM modes is analyzed, as shown in Fig. 4a. It is obvious that the discrepancy values between the TE and TM modes decrease rapidly as \( R_b \) is tuned from 0.35 to 0.55 \( \mu m \). It indicates that it is possible to reach lower PSL around \( R_b = 0.55 \mu m \). Therefore, sweeping the parameter \( R_b \) around 0.55 \( \mu m \), we find that the discrepancy of absorption between TE and TM modes decreases firstly and then increases with the increase in \( R_b \). At the point \( R_b = 0.565 \mu m \), a minimum value can be obtained.

When \( Ra = 0.35 \mu m \), \( Rb = 0.565 \mu m \), wavelength = 2.2 \( \mu m \), the variation of EMI for both TE and TM modes with chemical potential was analyzed. As shown in Fig. 5, the real part of EMI has same variation trend for TE and TM modes with constant difference. Since the modulator is based on electro-absorption principle, we just need to care about the imaginary part of EMI. What is more, under all the \( \mu_c \) values, the \( \alpha \) of both TE and TM are almost identical. It is the property that we need for designing polarization independent electro-absorption modulator. A highest and lowest value of \( \alpha \) (proportional to the imaginary part of EMI) can be obtained at \( \mu_c = 0.1 \) eV and \( \mu_c = 0.8 \) eV, respectively (Fig. 5). Thus, the point of \( \mu_c = 0.1 \) eV and \( \mu_c = 0.8 \) eV can be chosen as “OFF” and “ON” state point.

The variation of \( \alpha \) as a function of wavelength is presented in Fig. 6a, b. It can be seen from Fig. 6 that the \( \alpha \) of the two modes is very identical with the wavelength change in the strong absorption state (“OFF” state), and the differences between the two modes have been kept relatively small. At the “ON” state, the discrepancy of \( \alpha \) between TE and TM modes is at the order of \( 10^{-4} \). To measure the discrepancy further and accurately between two modes, PSL is defined as \( PSL = ER(TE) - ER(TM) \), where \( ER \) is the extinction ratio. We measured the modulation depth of the modulator in two modes as a function of wavelength under the condition of 200 \( \mu m \) long waveguide. As shown in Fig. 7, it can be seen from the diagram that in a wide spectrum range of 2–2.4 \( \mu m \), the modulation depth of the two modes is more than 16 \( \text{dB} \), and PSL is less than 0.24 \( \text{dB} \).

For an optical modulator, the 3 dB modulation bandwidth \( f_{3dB} \) is always one of the important parameters to...
be concerned about. Since graphene has ultrahigh carrier mobility at room temperature, the graphene-based modulator’s operation speed is no longer limited by minority carrier lifetime like traditional semiconductor modulators are. The \( f_{3\text{dB}} \) of a graphene-based modulator is mainly impeded by RC delay, which can be expressed as

\[
    f_{3\text{dB}} = \frac{1}{2\pi RC}
\]  

The \( R \) is the device’s total resistance, including graphene sheet resistance \( R_s \) and metal–graphene contact resistance \( R_c \), which has been carefully discussed in previous works [23]-[25]. The \( C \) is the capacitance of modulator, which mainly consists of the capacitor that is formed by the two graphene flakes. Although this capacitor is not an ideal parallel-plate capacitor model, to preliminarily estimate the \( f_{3\text{dB}} \), we still use the parallel-plate capacitor model to calculate the \( C \). In our calculations, \( R_c = 100 \Omega/\mu\text{m} \) [19] and \( R_s = 200 \Omega/\mu\text{m} \) [26] were used, and the overlap width of two graphene flakes is about 1.53 \( \mu\text{m} \). The estimated \( f_{3\text{dB}} \) is as high as 136 GHz. Moreover, lower values of both \( R_s \) and \( R_c \) are possible in the future, which means higher \( f_{3\text{dB}} \) can be obtained.

The above simulations are based on the semiellipse layout with \( R_a = 0.35 \mu\text{m} \) and \( R_b = 0.565 \mu\text{m} \). However, in fabrication, this exact radius size cannot always be guaranteed. Therefore, we have also investigated the fabrication tolerance (Fig. 8). When \( R_a \) varies from 0.345 to 0.355 \( \mu\text{m} \) (Fig. 8a), or \( R_b \) varies from 0.56 to 0.57 \( \mu\text{m} \) (Fig. 8b), the PSL between two modes is still lower than 0.6 dB. So, our device has large fabrication tolerance.

**Conclusions**

In conclusion, we presented a concept of a broadband polarization-independent graphene-based mid-infrared electro-absorption optical modulator. In our structure, a U-structure double-layer graphene is placed in chalcogenide glass waveguide. Under different graphene chemical potentials, different wavelengths and different short radius lengths, the graphene-induced EMI variations for both TE and TM modes are investigated. The results show that TE and TM modes have almost identical absorption coefficient variation in the mid-infrared 2–2.4 \( \mu\text{m} \), which fulfills the requirement of
polarization-independent modulation. Based on this structure, the modulator with a length of 200 μm has a modulation depth more than 16 dB. The modulation depth difference between the two modes is 0.24 dB, and the theoretical modulation bandwidth of the device is as high as 136 GHz. We believe that this mid-infrared polarization-independent graphene-based electro-optic modulator will further promote the study of the graphene-based modulator in the middle-infrared bands.
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