Ring resonator modulators based on double-layer graphene and Chalcogenide glasses waveguide in mid-infrared light

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Abstract. A ring resonator modulator based on double-layer graphene and Chalcogenide glasses waveguide is presented and investigated. Wide bandwidth mid-infrared light operation can be achieved. A strong interaction between mid-infrared light and graphene is obtained, which change the effective mode index in the waveguide significantly while the change of applied voltage. Besides, the modulator we proposed owns a large extinction ratio of 33.57 dB.

1. Introduction

In the visible and near-infrared spectral range, photonics has been widely developed and applied. More and more attention is paid to the mid-infrared spectrum bands because there are many potential applications including free space communication, chemical sensing, and military technology [1]. For example, there have been many research on chemical sensing, many of the pollutants, toxic gases or liquids that we want to detect or monitor, have a lot of absorption peaks in the mid-infrared spectral region. Therefore, the sensitive optical sensor based on the mid-infrared band is very attractive. In the infrared band of surgical and medical treatment on the high precision of the burning tissue have great advantages, because the water has a strong absorption in the infrared band, the depth of penetration is very small, especially in the micron, the penetration depth in the clinical application of only a few microns, so it is possible for infrared optoelectronic devices for the development of minimally invasive effective and safe diagnosis technology. Others, the rapid progress of mid-infrared sources and detector, have made mid-infrared modulator an attractive device.

In recent years, Chalcogenide glasses (ChGs) have become a research hotspot and one of best material candidates for integrated photonics [2-8] since they have lots of merits such as low attenuation in near and mid-infrared region, easy fabrication and so on. Most traditional materials for integrated photonics undergo high loss in transmission due to the intrinsic material absorption in mid-infrared region (3to20μm) while ChGs have a wide mid-infrared transparency with a wavelength up to 20 μm, so ChGs is suitable for spectroscopic chemical sensing and thermal imaging [9].

2D functional electro-optic materials graphene is also considered as an ideal material, such as a wide spectrum, ultra-high carrier mobility at room temperature, electrically controllable conductivity and compatibility with CMOS processing [10-12].

2. Structure and principle of ring resonator

Ring resonator modulators (RRMS) based on the dispersion effect of free carrier plasma have attracted
more and more attention due to their low loss, easy integration and low energy consumption\textsuperscript{[13]}. The ring resonator is essentially an infinite impulse response filter. The structure is composed of a straight waveguide and an annular cavity. The feedback of the waveguide is used to form the feedback, and the response of the light at different wavelengths is different. The structure is simple, easy to manufacture, and is compatible with the plane process. Due to the micro ring is a resonant device, a lot of field energy can better the external material interaction. Here, we use this advantage to combine it with graphene, can be used to control the working wavelength of the micro ring, realize high speed modulation.

As shown in Fig.1, it illustrates the how the structure and principle of ring resonator\textsuperscript{[14-15]}. $a_1$ is input light coming from straight waveguide’s left side which can be coupled to the ring resonator, $b_1$ is output light which obtained through straight waveguide’s right side. The matrix equation of the whole coupler can be written as following:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} t & k_2 \\ -k_1 & t \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \text{and } a_2 = ab_2e^{i\phi} \tag{1}$$

In which $t$ is self-coupling coefficient, $k$ is cross-coupling coefficient of the ring resonator, they satisfy the formula $k^2 + t^2 = 1$. $\alpha = e^{-\pi/\lambda lm(n_{eff})}$ is the racetrack waveguide attenuation factor, $l$ is the perimeter of the ring waveguide, $\lambda$ is the input wavelength, $\phi$ is the phase shift induced. The output amplitude can be calculated from the matrix in Eq. (2):

$$b_1 = \frac{t - \alpha e^{-i\phi}}{1 - \alpha e^{-i\phi}} a_1 \tag{2}$$

Fig.1 Operation principles of the coupling region between the straight waveguide and the racetrack micro resonator

It can be seen that the output port becomes zero when $\alpha = t(\phi = 2\pi m)$. If $m\lambda = 2n_{eff}r$, the resonator will be at resonance state. The output port of the ring resonator modulator can change fast by tuning the resonant wavelength through the applied voltage, which can be used in a series of resonator devices based on active graphene.

3. Ring resonator modulators structure and analysis

The structure of ring resonator modulators is illustrated in Fig.2. The diagrammatic sketch of the ring with $10\mu m$ radius, and the waveguide width is $600nm$, the two graphene flakes are separated by a $10nm$ thick hBN isolation layer to form the desired capacitor structure. Both the upper and the lower graphene flakes are isolated from the ChGs waveguide by a $5nm$ thick hBN isolation layer to form the desired capacitor structure. Since Pd/graphene contact resistance can be very low at room temperature\textsuperscript{[16]}, the metal palladium is deposited on the graphene flakes and then Au is deposited on palladium to act as electrodes. The external voltage is applied through the electrodes added on the partial ring structure.

The conductivity of graphene can be tuned by external applied voltage\textsuperscript{[17]}, which can be deduced from Kubo formalisms as shown in Eq. (3)\textsuperscript{[18-19]}

$$\delta(\omega) = \delta_{intra} + \delta_{inter} \tag{3}$$
In which \( \delta_{\text{intra}} \) and \( \delta_{\text{inter}} \) are conductivity of intraband and interband respectively, 

\[
\delta_{\text{intra}} = \delta_0 \frac{4\mu}{\pi} \frac{1}{\hbar \Gamma_1 - i\omega}
\]

\[
\delta_{\text{inter}} = \delta_0 \left[ 1 + \frac{i}{\pi} \arctan \frac{\hbar \omega - 2\mu}{\hbar \Gamma_2} - \frac{1}{\pi} \arctan \frac{\hbar \omega + 2\mu}{\hbar \Gamma_2} + \frac{i}{\pi} \ln \left( \frac{(\hbar \omega + 2\mu)^2 + (\hbar \Gamma_2)^2}{(\hbar \omega - 2\mu)^2 + (\hbar \Gamma_2)^2} \right) \right]
\]

Where \( \hbar \) is the reduced Planck constant, and \( \omega \) is the angular frequency. \( \mu \) can be tuned by applied voltage, chemical potential \( |\mu| = \hbar v_F (\pi a_0 |V_g - V_{\text{Dirac}}|)^{1/2} \) [17,20,21], the Fermi velocity \( v_F \approx 1.1 \times 10^6 \text{m/s} \), \( a_0 = \varepsilon_\varepsilon_0/\omega \) is yield from the simple capacitor model, \( |V_g - V_{\text{Dirac}}| \) would be the applied voltage. \( \Gamma_1 = 1/\tau_1, \Gamma_2 = 1/\tau_2 \), where \( \tau_1, \tau_2 \) are intraband relaxation time and interband relaxation time respectively. And \( \delta_0 = e^2/(4\hbar) = 60.8 \mu\Omega \) is the optical conductivity of undoped graphene. The incident light is \( \lambda = 2500 \text{nm} \), \( \tau_1 = 1.2 \text{ps} \) and \( \tau_2 = 10 \text{fs} \). The permittivity of graphene can be calculated by using \( \varepsilon = 1 + i\delta/(\omega\varepsilon_\varepsilon_0\hbar) \) and \( \hbar = 0.7 \text{nm} \) is the thickness of single graphene layer, permittivity of graphene is shown in Fig.3(a), where it is varied in a large range according to \( \mu \) variation. Around \( \mu = 0.25 \text{eV} \), the real part and imaginary of permittivity sudden change. The \( \mu \) can be dynamically tuned by the applied voltage. This means the effective mode index of the waveguide with graphene layer can be dynamically tuned by voltage.

The effective mode index of TE mode \( n_{\text{eff}} \) variation (red line for the real part \( \text{Re}(n_{\text{eff}}) \) and blue line for the imaginary part \( \text{Im}(n_{\text{eff}}) \)) for the designed waveguide is shown in Fig.3. We can draw from this figure, the maximum value at \( \mu = 0.54 \text{eV} \) and the minimum value at \( \mu = 0.48 \text{eV} \) of \( \text{Re}(n_{\text{eff}}) \) experience a change of 0.05.

Fig.3 (a) The permittivity of graphene changed with chemical potential. (b) The effective mode index of the hybrid waveguide as a function of chemical potential if compared with \( \Delta n_{\text{eff}} \) of the conventional optical modulators (at the order of \( 10^{-4} \)) [15], the value has been significantly enlarged.
For a ring resonator, the phase of the propagating light is related to the $Re(n_{eff})$ and wavelength through [15]:

$$\varphi = \left(\frac{2\pi}{\lambda}\right) \cdot Re(n_{eff}) \cdot l$$  \hspace{1cm} (6)

In which, the phase can be tuned by the applied voltage. And according to Eq. (2), the transmittance of Ring resonator with graphene built-in waveguide. Modulators based on single-layer graphene have been proposed [22]. The more graphene layers in the waveguide, the greater the influence on the propagation mode. In this paper, we studied ring resonator modulators based on double-layer graphene, and graphene layers are placed at the center of the ChGs waveguide with maximum light intensity [23]. And the relationship between the chemical potential of the graphene layer and the applied voltage have been proposed [22]. The results are illustrated in Fig.4.

Fig.4 (a) Transmission of the ring resonator at chemical potential from 0 to 0.8eV; (b)-(d) The resonance wavelength at 0.47eV, 0.56eV, 0.62eV

As shown in Fig.4(a), it is the results for transmittance at chemical potential from 0 to 0.8eV, it is obvious that the transmittance changes rapidly with the change of chemical potential. At 0.42eV and 0.51eV the transmittance fell to a minimum of 0.004, which can be seen as signal ‘0’. If the chemical potential is tuned to be 0.8eV, the transmittance up to a maximum value of 0.91, and it can be seen as signal ‘1’. By shifting the chemical potential between 0.51eV and 0.7eV, the ring resonator modulator with extinction ratio of 33.57 dB is achieved. Fig.4(b)-(d) shows the resonant wavelength of micro ring under different chemical potentials. The resonant wavelength has changed obviously while chemical potential from 0.47eV to 0.62eV. This means that the ring resonator modulators can achieve wide bandwidth mid-infrared operation.

4. Conclusion

In summary, we investigated influence of double layers on ChGs waveguide ring resonator modulator. Results indicate that the ring resonator modulators can achieve wide bandwidth mid-infrared light operation. A ring resonator modulator based on graphene and Chalcogenide glasses waveguide is presented. The effective refractive index of graphene waveguide can be changed because of the change of applied voltage. The resonance wavelength can be tuned by applying bias voltage, providing an easy
way to achieve mid-infrared light modulation. Besides, the modulator we proposed owns a large extinction ratio of 33.57dB. Furthermore, compared to the conventional single-layer graphene ring resonators modulator with low interaction between graphene and waveguide, this proposed device could overcome this shortcoming due to the double-layer.

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