



Hybrid plasmonic optical modulator based on multi-layer graphene

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Abstract

Hybrid plasmonic waveguide provided high confinement of the propagating light and it is compatible with silicon on insulator technology. Graphene with unique optical properties has been used in optical modulator to give a high extinction ratio, broadband operation, and small footprint. In this paper, we used graphene as an absorber layer in a hybrid plasmonic waveguide structure to get sub-wavelength field confinement and better interaction between the graphene and the propagating light to reach maximum absorption of the graphene. We studied the effects of a different number (2–6) of the graphene layers on the extinction ratio, bandwidth, and energy consumption. The modulation extinction ratio is as high as 36 dB/ μm and it has a flat response in a wide range of wavelength. The power consumption is about 14 fJ/bit. This modulator has a good response in all communication bands.

Keywords Graphene · Hexagonal-boron-nitride · Plasmon · Opto-electric · Modulator

1 Introduction

High-speed modulator with the broadband operation and high modulation depth are essential for integrated optoelectronic devices (Miller 2009; Reed et al. 2010). The silicon-based modulator has a weak response (Soref and Bennett 1987) which makes them inefficient in the integrated circuits (Miller 2010). Graphene as 2D material with unique electrical and photonic properties like optical absorption of nearly 2.3% over wide frequency ranges from ultraviolet to infrared (Wu et al. 2007; Novoselov et al. 2005; Falkovsky and Pershoguba 2007; Grigorenko et al. 2012), high carrier mobility (Du et al. 2008), transparency (Nair et al. 2008), and mechanical flexibility (Lee et al. 2008), low contact resistance (Robinson et al. 2011) make it appropriate material in electro-optical devices (Sensale-Rodriguez 2015). The absorption of Graphene can enhance by integrating it into a waveguide structure (Luo et al. 2015). The flexibility of graphene sheets enables it to be used for flexible high-speed communication systems (Lee et al. 2012).

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The First time, Liu and et al. investigated Graphene-based modulator that the modulator had a single sheet of the graphene on the top of the silicon waveguide and maximum profile of the incident light was on top and bottom of the silicon waveguide so that the graphene absorption was maximized. The Extinction ratio of this modulator was $0.1 \text{ dB}/\mu\text{m}$ and it had a 1.2 GHz bandwidth (Liu et al. 2011). In Liu and et al. (2012) introduced the other graphene modulator with two graphene layers and it had a $0.16 \text{ dB}/\mu\text{m}$ Extinction ratio and a 1 GHz bandwidth. Both of these modulators have a weak response because the absorption is limited to field distribution of the propagating light. In the other kind of modulator, graphene embedded in the middle of the slot waveguide and it had a 3 dB modulation depth (Lu and Zhao 2012). In waveguide-coupled graphene-on-graphene, optical modulators could reach modulation depth >0.5 and a 120 GHz bandwidth with the absorption of the evanescent wave by graphene (Koester and Li 2012). In Ref. (Gosciniak and Tan 2013) investigated the new designing of the modulator based on the rib photonic waveguide configuration with a double-layer graphene which placed between a slab and ridge. They obtained a 3 dB extinction ratio and a 12 THz bandwidth. Shin and Kim (2015) proposed a broadband silicon optical modulator using a graphene-integrated hybrid plasmonic waveguide, and calculated a 13.7 dB extinction ratio at a wavelength of $1.55 \mu\text{m}$. A graphene hybrid plasmonic waveguide modulator is studied in Chen et al. (2016). This modulator could have a large extinction rate (up to 39.75 dB) and broadband modulation bandwidth (up to 190.5 GHz). Graphene-based electro-absorption modulator with a hybrid plasmonic waveguide and a double-layer graphene is investigated and it obtained a 13 dB extinction ratio and a 0.4 THz bandwidth (Huang et al. 2016). In Wan and Deng (2017), is studied the modulation and enhancement of optical absorption of graphene-loaded plasmonic hybrid nanostructures and they reached a 27.5% modulation depth in visible and near-infrared. In previous work, we designed an electro-optics modulator with one and two graphene layers with the sub-wavelength thickness. We calculated a 9% modulation depth with two graphene layer which was placed in the position of the maximum optical field that causes the maximum absorption (Vahed and Ahmadi 2017). Recently, A graphene-based long-range hybrid plasmonic slot (LRHPS) waveguide modulator with the waveguide structure consists of a silica substrate, two high-index silicon strips, two low-index slots, two graphene layers, and a metal is studied and they obtained an $8.257 \text{ dB}/\mu\text{m}$ extinction ratio and a 15 THz bandwidth with a center wavelength of 1550 nm (Hu and Wang 2017). A tunable graphene-based hybrid plasmonic modulator is proposed with a $0.6 \text{ dB}/\mu\text{m}$ modulation depth in Qu et al. (2017). Also, the different types of 2D layered material have been studied after the discovery of graphene. Recently, black phosphorous and bismuth have been introduced as novel 2D material and have been used in optical device design (He et al. 2019). Optical modulator and switch based on 2D black phosphorous and bismuth are designed for optical communications (Zheng et al. 2017; Wang et al. 2018; Lu et al. 2017).

In our structure, we used multi-layer graphene in a hybrid plasmonic waveguide structure to enhance the modulation depth. It consist graphene-hexagonal-boron-nitride-graphene (graphene-hBN-graphene) as absorption layer. The hBN used as a flat substrate for graphene. The effect of the number of graphene layers on the bandwidth has been studied. We study this proposed modulator based on a three-dimensional (3D) Finite Difference Time Domain (FDTD) from 1300 to 1600 nm and reach a $36 \text{ dB}/\mu\text{m}$ extinction ratio. This paper is organized as follows. In section II, we introduced the structure. In section III, the numerical results have been demonstrated for our proposed modulator. In section IV, the paper is concluded.

2 Structure and Analysis

Graphene conductivity can obtain from Kubo formula (Falkovsky 2008a, b):

$$\sigma(\omega) = \frac{2ie^2k_B T}{\pi\hbar^2(\omega + iT^{-1})} \ln \left[2 \cosh \left(\frac{\mu_c}{2k_B T} \right) \right] + \frac{e^2}{4\hbar} \left\{ \frac{1}{2} + \frac{1}{\pi} \tan^{-1} \left(\frac{\hbar\omega - 2\mu_c}{2k_B T} \right) - \frac{i}{2\pi} \ln \left[\frac{(\hbar\omega + 2\mu_c)^2}{(\hbar\omega - 2\mu_c)^2 + (2k_B T)^2} \right] \right\} \tag{1}$$

Both inter-band and the intra-band transition is considered in this formula, Where e is the charge of the electron, T is the temperature, k_B is the Boltzmann constant, ω is the angular frequency, \hbar is the reduced Planck constant, μ_c is chemical potential and τ is the inter-band relaxation time. The chemical potential of the graphene is tunable and varying by the gate voltage (Wang et al. 2008). Therefore the conductivity of graphene is varied by the gate voltage. The permittivity of the graphene is related to conductivity and ω in this formula $\epsilon(\omega) = 1 + i\sigma(\omega)/\epsilon_0\omega d$ (Wang et al. 2012; Yao et al. 2013) which d is the thickness of graphene. Figure 1 shows the permittivity of graphene in 1550 nm. For $\mu_c < 0.52$ the permittivity of graphene is positive and the graphene act as a dielectric. At $\mu_c > 0.52$, the permittivity of graphene is negative and the graphene acts as a metal. By electrical tuning of the graphene permittivity, it switches between dielectric and metal which can change the effective mode index (EMI) of the waveguide and the loss. Also, graphene can work as the saturable absorber under intensive radiation. The optical absorption of graphene decreases with increasing the light intensity, finally, becomes saturated under sufficient intensive light due to Pauli blocking principle. Therefore, graphene can be used as active material in all-optical modulator and as a saturable absorber for passively ultrafast mode-locked lasers (He et al. 2019; Li et al. 2014).

The proposed modulator has a hybrid plasmonic structure. The field confinement is enhanced in the hybrid plasmonic waveguide and it causes the low loss and so a relatively

Fig. 1 The permittivity of graphene as a function of the chemical potential at $\lambda = 1550$ nm and the temperature $T = 300$ K

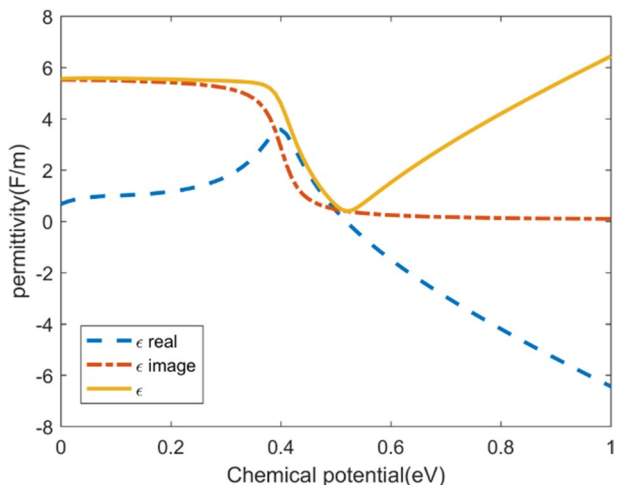
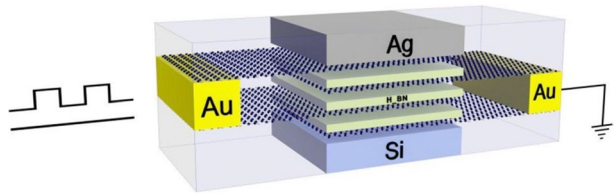


Fig. 2 The proposed structure of multi-layer graphene-based modulator



long propagation distance (Dai and He 2009, 2010; Oulton et al. 2008). This structure consists of Si waveguide and graphene-hBN-graphene embedded in the middle of SiO₂ and on the top of the device (Fig. 2). Ag is located to make the hybrid plasmonic structure and confine the incident light. HBN is a clean surface for graphene and it causes less disorder (Woessner et al. 2015; Giovannetti et al. 2007; Geick et al. 1966). Graphene thickness is assumed to be a 1 nm. The gold is used as the electrode. The width of the main waveguide is 200 nm to have good mode confinement and the device footprint became small. The height of modulator is 20 nm for two-layer graphene. The space between the silicon and Ag and width of the hybrid plasmonic waveguide (HPW) is effective on the mode confinement and effective index (Alam et al. 2010; Dai et al. 2011). Generally, the hybrid mode is a supermode resulting of the coupling between the SP mode and the Si waveguide mode. But, the SP mode supported by plasmonic waveguide is TM mode (He and Li 2013; Gosciniaik et al. 2015). Therefore, the supported hybrid modes of our proposed structure can be only TM mode and we investigate only the TM modes in this paper.

In fabrication, the Si waveguide can be created using a conventional silicon-oxide-insulator (SOI) platform. The waveguide structure has a high compatibility with Complementary metal-oxide-semiconductor (CMOS) fabrication technologies (Shin and Kim 2015). Plasma-assisted chemical vapor deposition can be used to grow a single layer graphene on hBN (Yang et al. 2013). Then, film transfer method can be used to form multi-layer stacking of graphene and hBN on the Si waveguide (Kim et al. 2011). The unwanted region of

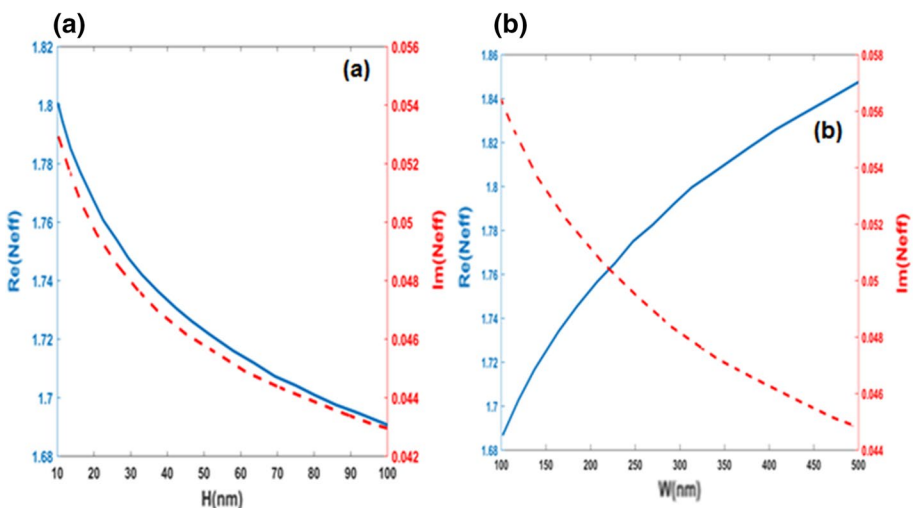


Fig. 3 **a** Variation of the effective mode index (EMI) with the height and **b** with the width of HWP

graphene can be removed by e-beam lithography and oxygen plasma. A thin layer of Au is deposited as electrode. Finally, a silver layer is deposited on top graphene.

Firstly, we investigated the EMI for the HPW without the graphene-hBN-graphene layers by using FDTD. The height and the width of the waveguide are important parameters in studying of the EMI. Figure 3a and b show the effect of height (H) and width (W) of the waveguide on the EMI. In Fig. 3a, we fixed W at 200 nm and increase H from 10 to 100 nm. The real and imaginary components of the EMI decrease for a larger value of H. This behavior can be explained from weaker mode confinement. Because the increase of H grows up the distance between Si and Ag layer in HPW and decrease the mode confinement. It's clear from Fig. 3b that the real component of the EMI increase and the imaginary component of EMI decrease for a larger value of W. The HPW structure of this modulator improves the interaction between the incident light and graphene as an absorber layer. Graphene layer is a wider sheet to reach Au contacts for voltage tuning and make away the electric field from the main path of modulation. The whole device is embedded in the SiO_2 .

3 Result and discussion

In this paper, the number of graphene layers and its effect on the extinction ratio and the bandwidth is studied. Increasing the number of the graphene-hBN-graphene layer increased the variation of the EMI and the loss of HPW. The hBN layer between the graphene layers is worked as a dielectric and made the graphene layer to have single sheet properties. The EMI of the modulator is changed by tuning of the graphene chemical potential, too. Figure 4 shows the EMI of the structure as function of the chemical potential for different number of the graphene layers in 1550 nm. Increasing the graphene layers increases the effectiveness of the EMI of the structure from the variation of the chemical potential. This effect is used to improve the performance of this modulator. In structure with two layers of graphene, the Si and Ag layer refractive indexes and losses is affected the EMI more.

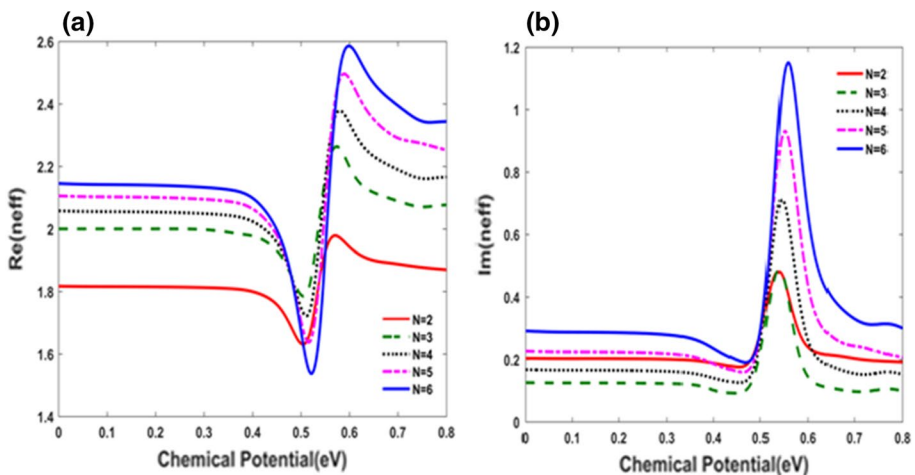
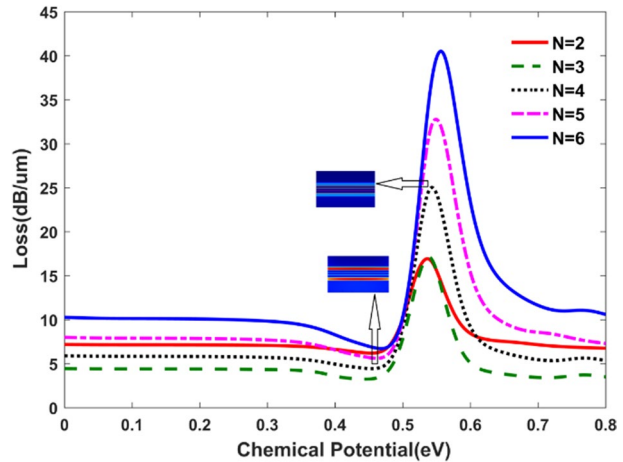


Fig. 4 **a** The real component and **b** the imaginary component of the EMI as a function of the chemical potential in 1550 nm with the $N=2-6$ graphene layers

Fig. 5 Losses of the modulator as a function of the chemical potential in 1550 nm with $N=2-6$ graphene layers. The inset shows the electric field of the cross section in the modulator (ON and OFF state mode profile)



Increasing of the graphene layers increase the height of the structure. Therefore, the variation of the chemical potential affects the EMI of the structure more.

Figure 5 shows the losses of the structure in 1550 nm with a different number of the graphene layer with variable chemical potential. Due to the relation between the loss and the imaginary part of the EMI, we see the same behavior in these two figures. In two layers of structure, most of the structure's losses are due to the presence of Ag. The presence of Ag causes a high loss in all values of chemical potentials in structure with two-layer graphene. By increasing the number of graphene layers, the effect of the Ag layer decreases, and the graphene layers are affected the structural losses more. The graphene layer at any chemical potential affects the structure's loss. Therefore, the loss of structure increases with increasing of the graphene layers. The insert at Fig. 5 represents the mode profile in the ON state (at the chemical potential with the lowest loss) and the OFF state (at the chemical potential with the highest loss). In OFF state mode, the metallic properties of graphene increase and the profile of light is limited to graphene layers, and in the ON state mode, the mode profile is as the plasmonic hybrid waveguide and it is bounded between the Si and Ag layers.

The broadband operation capability of modulator is investigated in Figs. 6, 7, 9 and 10. We evaluated the wavelength dependent characteristics of the proposed modulator. The results show that the device operates on the optical fiber communication bandwidth from 1300 to 1600 nm with changing only the applied bias voltage. We change the wavelength (λ) from 1300 to 1600 nm and change the chemical potential of graphene and then we study the effects of them on HPW as a modulator. The mode confinement in the short wavelength increases the real part of the EMI. The increase of graphene layers causes the EMI change by tuning of the chemical potential more. The increase of the graphene layers improves the difference between the maximum and minimum of the loss and it causes the high extinction ratio (ER) and modulation depth. Losses in the HPW with two graphene layers are more than the HPW with three and four layers in $\mu_c < 0.5$. Figure 6 shows the loss of HPW for a variable number of graphene layers in this proposed modulator from 1300 to 1600 nm. These figures show that the modulator can operate as a broadband device and it possesses the good mode confinement from 1300 to 1600 nm.

Figure 7 shows the extinction ratio (ER) of this modulator for 1300–1600 nm with a different number of the graphene layers. It shows that the ER increase with a constant coefficient at short wavelengths. The modulator has a good response for all communication

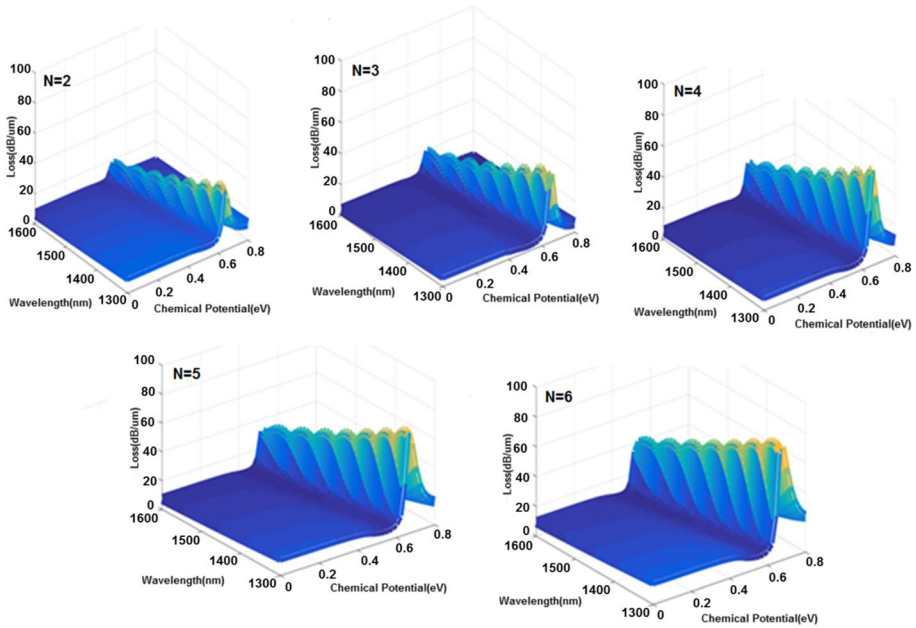
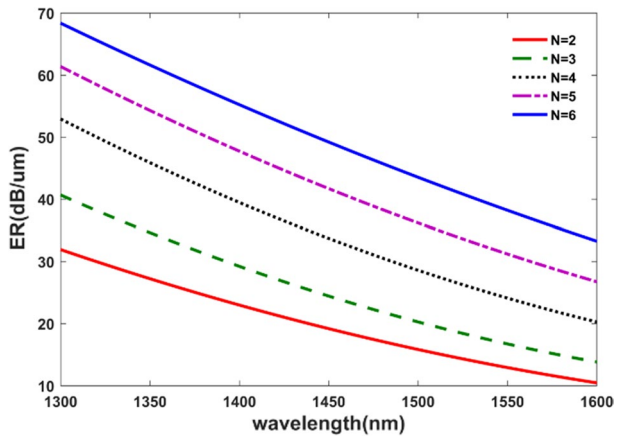


Fig. 6 Loss of the HPW in 1300–1600 nm with $N=2-4$ graphene layers as a function of the chemical potential

Fig. 7 The extinction ratio of modulator in the 1300–1600 nm for $N=2-6$ graphene layers



bands. The variation of ER for 1300–1600 nm wavelength is caused by the mode confinement and the dispersion effects of materials. The mode confinement at short wavelength is more and this causes the intensive interaction between the incident light and the graphene layers. Therefore, the ER is increased.

More graphene layers can increase the interaction between the propagating mode and the graphene layers. This intensive interaction can increase the optical absorption and lead to further modulation depth. Also, the use of multi-layer graphene can improve the

bandwidth of proposed modulator because the parasitic resistance and capacitance are two main factors to increase the operating bandwidth of the optical modulator based on graphene. The high carrier mobility of graphene causes that the bandwidth of this modulator is limited by parallel capacitance. The contact resistance between these Au electrodes and the graphenes limit the current speed of the device due to the resulting RC time. We used an electrical model of the system to calculation of the bandwidth. Therefore, the graphene layers are the capacitance parallel plates and the hBN layer is a dielectric. The capacitance has been calculated by $C = \epsilon(S/d)$ which, S is an area of plates (for 1 μm length of the system, $S = 1 \mu\text{m} \times 0.2 \mu\text{m}$) and the d is the thickness of the hBN layer. The 3-dB bandwidth is $F_{3\text{-dB}} = 1/2\pi RC$ (Ye et al. 2017) for modulator with two layers of the graphene which R is the resistance of the system and it includes graphene-contact resistance and graphene sheet resistance. As we know the graphene sheet resistance is low so the total resistance approximately is equal with the graphene-contact resistance. The graphene and Au contact resistance is about $R = 400 \Omega\text{-}\mu\text{m}$ (Koester and Li 2012). Also, the performance of modulator is investigated based on the figure of merit (FOM) defined as the ratio between ER and bandwidth at wavelength 1550 nm in Fig. 8. The modulator with a number of the graphene layers less than five has the high bandwidth and the low ER. For modulator with a number of the graphene layers more than five, the FOM has a flat response because the height of the structure is increased and the interaction between the incident light and the graphene layers is less than before (the Lower ER). Also, in this state, the bandwidth is decreased by the parallel capacitance in the modulator.

The energy consumption of the modulator is calculated by $E_{bit} = \frac{1}{2} C \left(\frac{\sqrt{2}}{2} \Delta V \right)^2$ that C is the capacitance of the modulator and ΔV is the difference between ON and OFF state (Fig. 9) and it has been calculated from $\mu_c = \hbar v_f (\pi n_0)^{1/2} = \hbar v_f \left(\frac{\pi \epsilon_0 \epsilon_r |v_g - v_{offset}|}{\Delta e} \right)^{1/2}$ that v_f is Fermi velocity, n_0 is the carrier concentration in graphene, v_g is the gate voltage, v_{offset} is the offset voltage is caused by the natural doping, ϵ_r is the dielectric constant of hBN and Δ is the thickness of hBN (Wang et al. 2008). The consumption energy of the modulator for a different number of the graphene layers as a function of the wavelength has been plotted in Fig. 10. The consumption energy of the modulator is less than 14 fJ/bit for ER more than 36 dB/ μm and it is less than 2 fJ/bit for ER 10 dB/ μm .

Fig. 8 Figure of merit as a function of the bandwidth and the ER for different number of the graphene layers

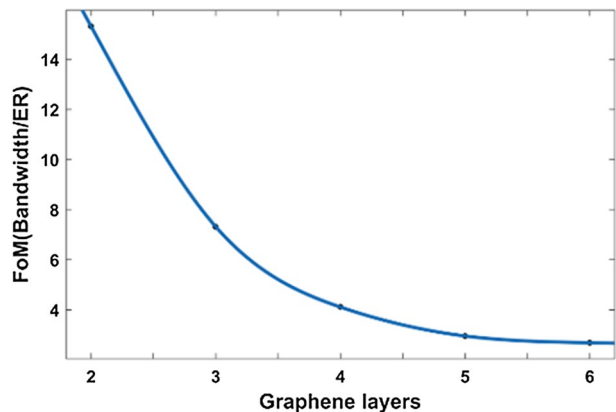


Fig. 9 The Voltage difference between ON and OFF states of the modulator as a function of the wavelength

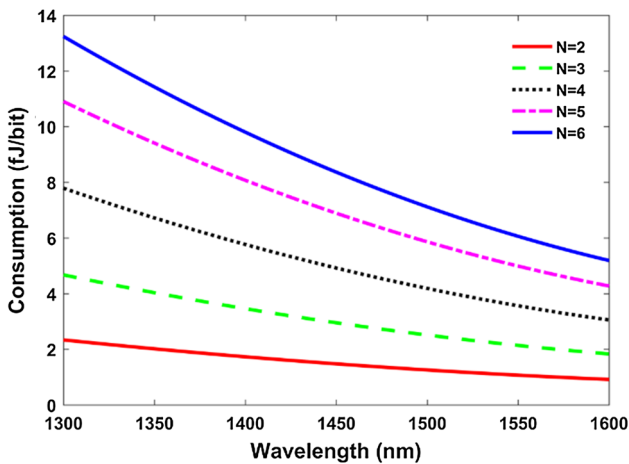
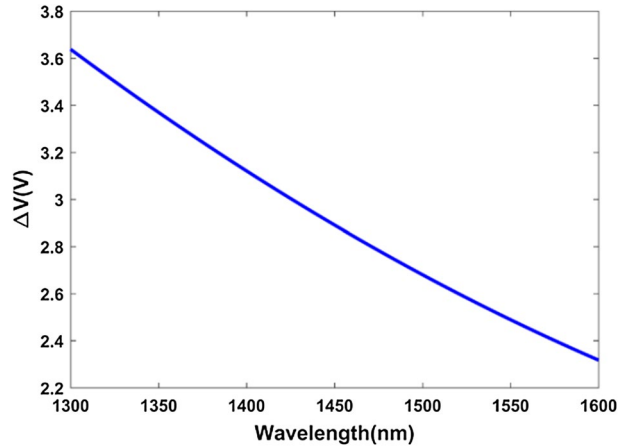


Fig. 10 The consumption energy of the modulator for a different number of the graphene layers as a function of the wavelength

4 Conclusion

In this paper, we studied the hybrid plasmonic structure with a different number of the graphene layers. The hybrid plasmonic modulator has the better interaction of the graphene layers with the propagating light and it causes the high ER in a small footprint, which makes this modulator, could be integrated into the electro-optic circuits. This modulator can achieve a 36 dB/μm ER with 6 graphene layers and a 190.5 GHz the 3-dB modulator bandwidth with two graphene layers. The maximum consumption energy of the modulator is about 14 fJ/bit. Also, the proposed modulator has a good response in all communication bands.

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