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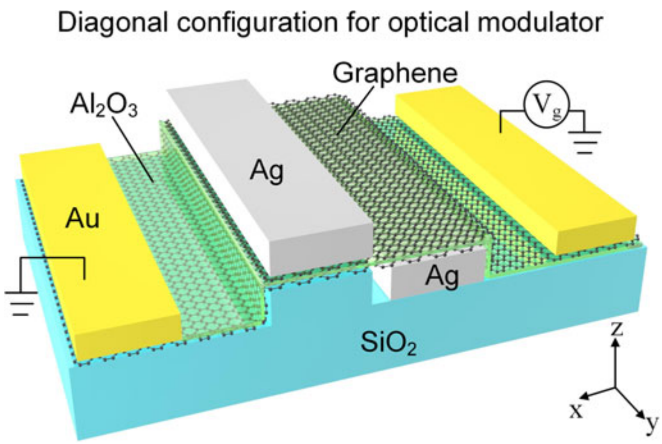

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Highly Efficient Graphene-Based Optical Modulator With Edge Plasmonic Effect

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Abstract: We report a highly efficient graphene-based modulator by using an edge plasmonic effect in this paper. The modulation efficiency of the proposed modulator can be as large as 1.58 dB/μm, which is several times larger than that of previous reported modulators. By enhancing the gap plasmon mode and the edge plasmonic effect in a well-designed diagonal waveguide, a wedge-to-wedge SPP mode is strongly confined in both horizontal and vertical directions in terms of a small mode area ($A_{eff}/A_0 < 1/1000$), which significantly improves the light-graphene interaction. A large modulation efficiency of 4.05 dB/μm has been obtained after geometry optimization, which is the best values reported in our knowledge. The physical reason for the improvement is explored. We find the sharpness of the waveguide edges has strong impact on the field enhancement and modulation efficiency. Geometry optimization is made to further investigate the enhancement mechanisms and modulation capacities. Our results may promote the development of active nanophotonic devices incorporating two-dimensional materials.

Index Terms: Graphene-based optical modulator, edge plasmonic effect, diagonal plasmonic waveguide.

1. Introduction

Electrical-Optical modulator is one of the essential components in optic communications [1], which requires fast-speed, large-bandwidth, and ultra-small footprint. To improve the modulation capacity, graphene has been considered as a potential candidate due to its outstanding electrical and optical properties [2], including extremely broad optical bandwidth from visible to infrared wavelengths, high modulation speed originates from unprecedent carrier mobility, and large active controls from the material properties [3]. So far, various efforts have been made to exploit the advantages of graphene-based optical modulators (GOM). Single layer graphene on top of [4] and inside [5] silicon waveguide are studied with high modulation efficiency around 0.1 dB/μm. Increasing number of graphene layers is a way to improve the modulation capacity, e. g., modulator with dual-graphene layers [6] is proposed to obtain a larger modulation efficiency of 0.16 dB/μm. Besides, graphene

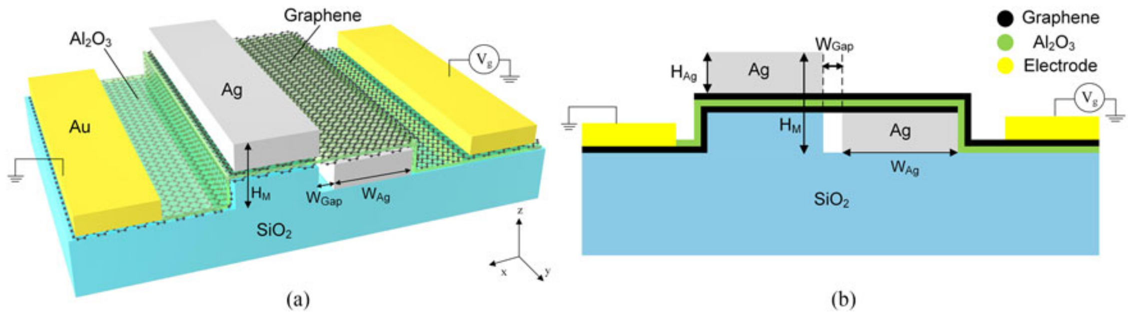

Fig. 1. (a) 3D Schematic illustration of the proposed electro-absorption graphene modulator integrated with a diagonal plasmonic waveguide. (b) 2D cross-sectional view of proposed modulator.

with compound waveguides have been proposed to further improve the modulation performance. For instance, D. Englund *et al.* presented a graphene-based modulator by utilizing a photonic crystal nanocavity with the modulation depth of 3.2 dB [7]. A. Phatak *et al.* designed a silicon slot waveguide with strong transverse electric mode to improve the modulation efficiency [8]. However, in all previous graphene modulators design, there exist a fundamental limitation: the dimension mismatch between graphene's thickness (0.34 nm) and optical mode in silicon waveguide, which seriously limits the effective interaction and modulation capacity. To solve this, surface plasmon polariton (SPP) has been considered as a solution for squeezing the mode size to compensate the mismatch because of its deep subwavelength confinement capability [9]. GOM with plasmonic effects have been studied including flat metallic [10], MIM [11], [12], groove structure [13] showing their potentials to improve the modulation capacities. However, most of plasmonic structures with graphene can only achieve one-dimensional deep subwavelength confinement. As a result, light-graphene interaction is enhanced only along one direction of the graphene surface [12]–[14], which significant limit the further improvement of the modulation capacity.

In this paper, a diagonal configuration of GOM (DGOM) is proposed with strongly suppressed mode size (normalized mode area $A_{eff}/A_0 < 1/1000$) by edge plasmonic effect. And modulation efficiency over 1.58 dB/μm with low plasmonic inserting loss of 0.2 dB/μm has been achieved.

2. Structure Design & Properties of Graphene

The proposed DGOM is shown in Fig. 1(a) and (b). It includes a graphene stacks of graphene-Al_2O_3-graphene and a plasmonic waveguide of Ag-air-Ag. The plasmonic waveguide ($H_M = 220$ nm) consists of two Ag waveguides ($W_{Ag} = 300$ nm, $H_{Ag} = 105$ nm) arranged diagonally on silica substrate ($n_{SiO_2} = 1.45$) with a small tip-to-tip gap ($W_{Gap} = 30$ nm), where the intrinsic wedge-to-wedge SPP can be squeezed by face-to-face corners of two Ag waveguides ($n_{Ag} = 0.1453 + 11.3587i$) in the tip-to-tip gap. Besides, graphene stacks are horizontally embedded in the middle of plasmonic waveguide to maximize light-graphene interaction. Here, graphene also plays a role of electrical gating, thus the top and bottom graphene layers isolated by a 10 nm alumina layer ($n_{Al_2O_3} = 1.746$) are connected to different electrodes. By applying a voltage V_g, the permittivity of double-layer graphene can be tuned. It is worth emphasizing that the quantum tunneling effect is negligible for our design because the thickness of Al_2O_3 layer and the tip-to-tip distance of the Ag waveguides are both larger than 10 nm in this work.

In addition, the proposed DGOM can be fabricated as follows. (a) Etching silicon of commercial SOI (silicon on insulator) wafer by inductively coupled plasma (ICP) and SiO_2 waveguide can be fabricated by thermal evaporation and e-beam lithography (EBL). (b) The bottom Ag waveguide can be fabricated by e-beam evaporation and EBL; (c) Graphene grown on copper can be transferred onto the device by wet transfer method, removing undesired region by oxygen plasma and EBL, then depositing a metal electrode by e-beam evaporation; (d) Depositing Al_2O_3 layer by atomic layer deposition (ALD); (e) Another graphene is transferred onto the device, removing undesired

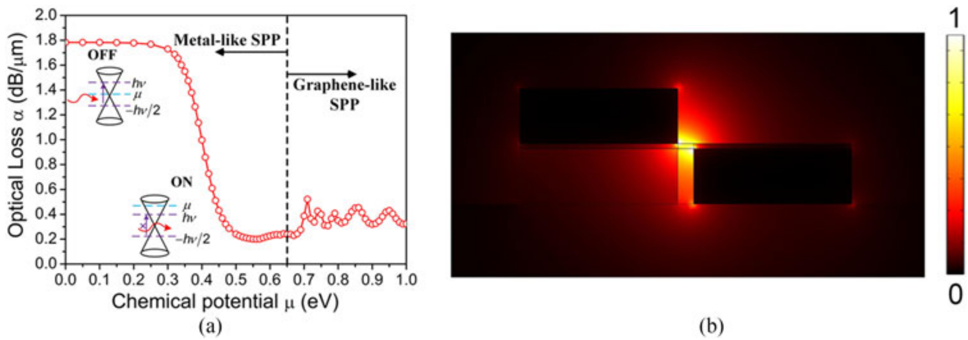

Fig. 2. (a) Optical loss of hybrid plasmonic waveguide as a function of the chemical potential of graphene. (b) Normalized electric field distribution for the diagonal SPP mode of proposed modulator.

region by oxygen plasma and EBL, then depositing a metal electrode by e-beam evaporation; (f) The top Ag waveguide can be fabricated by EBL and e-beam evaporation. All patterns in above steps can be defined by e-beam lithography (EBL).

Graphene is an anisotropic material, where the out-of-plane relative permittivity $\varepsilon_{\perp}$ is a constant 2.5 [15] and the in-plane relative permittivity is [16]

$$\varepsilon_{||} = 1 + i\sigma/\left(\omega\varepsilon_0\Delta\right) \tag{1}$$

here $\Delta = 0.34$ nm is the thickness of graphene, ω is the angular frequency of light and σ is the conductivity of graphene. According to the Kubo formula [17], σ can be calculated as

$$\sigma(\omega, \mu, \Gamma, T) = \frac{-ie^2}{\pi\hbar(\omega + i2\Gamma)}\left[\int_0^\infty \xi\left(\frac{\partial f_d(\xi)}{\partial\xi} - \frac{\partial f_d(-\xi)}{\partial\xi}\right)d\xi\right] - \frac{-ie^2(\omega + i2\Gamma)}{\pi\hbar}\left[\int_0^\infty \frac{\partial f_d(-\xi) - \partial f_d(\xi)}{(\omega + i2\Gamma)^2 - 4(\xi/\hbar)^2}d\xi\right] \tag{2}$$

where $f_d(\xi)$ is the Fermi-Dirac distribution function, $T = 300$ K is the room temperature, Γ represents scattering rate assumed to be 5 meV [11]. μ is the chemical potential of graphene which can be tuned by the applied voltage V_g.

3. Operation Principle

In order to characterize the modulation capacity, modulation efficiency (extinction ratio per length, i.e., ME) is defined as the optical loss difference (dB/μm unit) between the "Off" state and the "On" state for the DGOM: $ME = \alpha_{Off} - \alpha_{On}$, and the insertion loss can be defined as optical loss of "On" state α_{On}, where optical loss of DGOM can be calculated by the imaginary part of the effective mode index following $\alpha = 40\pi(\log_{10}e)Im(n_{eff})/\lambda$, ($\lambda = 1550$ nm) [8]. To obtain the effective mode index n_{eff} of the guided mode for the proposed waveguide, we use the modal (or eigenvalue) analysis method with the COMSOL multi-physics software [18] to solve the eigen-mode of DGOM. In Fig. 2(a), when $\mu < 0.65$ eV, we find that the optical loss of DGOM changes dramatically with the chemical potential. When the chemical potential of graphene with a low voltage is near the Dirac point ($\mu \ll h\nu/2 \approx 0.4$ eV), electronic transition occurs and electrons are excited by incident photons to generate electron-hole pairs, which causes large absorption of the DGOM. When the chemical potential is larger than $h\nu/2$, the interband transition is blocked due to Pauli blocking effect and absorption of graphene decreases sharply. Thus the strong changes in the optical loss of the proposed waveguide form the "On" and "Off" states of the modulator. The high optical loss ($\sim$1.78 dB/μm when $\mu = 0$ eV) of the DGOM can be set as the "Off" state, while the low optical loss ($\sim$0.2 dB/μm when $\mu = 0.55$ eV) can be set as the "On" state of the modulation. As a result, the modulation efficiency of the proposed modulator is $\sim$1.58 dB/μm, which is better than previous

Table 1
Comparison of Graphene-Based Electro-Absorption Modulators

Reference/year	ME (dB/μm)	3-dB Modulation length (μm)	Insertion loss (dB/μm)	Bandwidth (GHz)	Energy consumption (fJ/bit)	Note
M. Liu [4]/2011	0.1	30	-	1.2	880	Experimental values
M. Liu [6]/2012	0.16	18	0.1	1	1000	
H. Dalir [26]/2016	0.067	45	0.03	35	1400	
D. Ansell [10]/2015	0.03	100	-	-	-	
A. Phatak [8]/2016	0.144	20	0.07	-	-	Analytical/ numerical values
B. Huang [25]/2016	0.37	8.1	-	400	145	
Y. Wang [13]/2017	0.4	7.5	0.43	-	-	
ours	1.58	1.9	0.2	610	137	

results as shown in Table 1; And the insertion loss, equal to ~0.2 dB/μm at the "On" state, is lower than other plasmonic modulators as well [12], [13]. In addition, when the chemical potential is set to be a higher level ($\mu > 0.65$ eV), the DGOM has an oscillating absorption because standing-wave states of graphene SPP are excited at the two graphene layers with respect to the tip-to-tip region of Ag waveguide. Thus, there is a cut-off point ($\mu = 0.65$ eV) for our design, i.e., higher chemical potential region ($\mu > 0.65$ eV) with strong graphene SPP [19] can't be used to form a reliable and efficient modulator.

As depicted in Fig. 2(b), the intrinsic SPP mode of the proposed modulator is strongly confined by face-to-face corners of Ag waveguide inside the tip-to-tip gap which forms a diagonal mode. In traditional plasmonic modulators, optical field is compressed inside slot gap but spreads along the vertical direction, few optical field is used to interact with graphene in vertical direction because thickness of graphene is only ~0.34 nm. But in our proposed modulator in Fig. 2(b), it is obvious that most field of diagonal SPP mode is confined in tip-to-tip gap in both horizontal and vertical directions to interact with graphene stacks by employing edge plasmonic effect. Besides, the diagonal SPP mode overcome the polarization mismatch between graphene and previous wedge-to-wedge and flat plasmonic waveguides [10], [20]. And diagonal SPP mode with deep-subwavelength confinement also avoid unnecessary metal losses via reducing the contact area with the metal, ensuring a low insertion loss for plasmonic modulator.

To investigate optical confinement and enhancement of the diagonal wedge SPP mode, we calculate the normalized mode area A_{eff}/A_0 when $\mu = 0$ eV, where $A_0 = \lambda^2/4$ is the diffraction-limited mode area in free space and A_{eff} is defined as the ratio of the total mode energy and peak energy density:

$$A_{eff} = \iint W(\mathbf{r}) d^2 r / \max(W(\mathbf{r})) \tag{3}$$

where $W(r)$ is the electromagnetic energy density [21] expressed by

$$W(\mathbf{r}, \omega) = \frac{1}{2}\mathrm{Re}\left\{\frac{d(\omega\varepsilon(\mathbf{r}, \omega))}{d\omega}\right\} |\mathbf{E}(\mathbf{r}, \omega)|^2 + \frac{1}{2}\mu_0 |\mathbf{H}(\mathbf{r}, \omega)|^2 \tag{4}$$

In (4), $\mathbf{E}(\mathbf{r})$ and $\mathbf{H}(\mathbf{r})$ are the electric and magnetic fields, respectively. By using the (3), (4), the normalized mode area A_{eff}/A_0 of DGOM is smaller than 1/1000, which is one order of magnitudes smaller than other plasmonic waveguides [22], [23]. This means that the diagonal wedge plasmonic waveguide provides strong interaction between the graphene and light field. In other words, the modulation capability of the graphene modulator is improved largely.

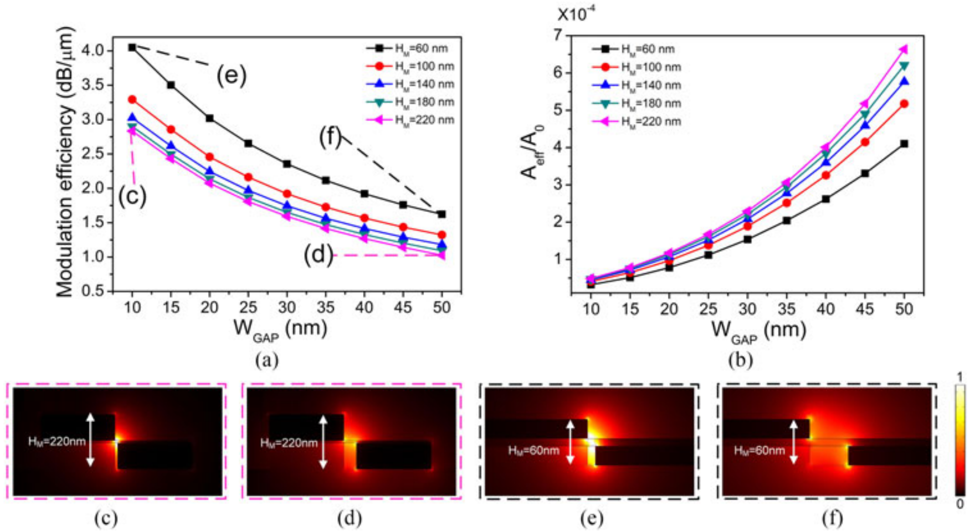

Fig. 3. Modulation efficiencies, mode area, and field distributions of DGOM with different W_{Gap} and H_M configurations while $W_{Ag} = 300$ nm. (a–b) Modulation efficiency and normalized mode area A_{eff}/A_0 versus the gap width W_{Gap} for different heights of modulator H_M; (c–f) Normalized electric field distributions for [$H_M = 220$ nm, $W_{Gap} = 10$ nm] (c), [$H_M = 220$ nm, $W_{Gap} = 50$ nm] (d), [$H_M = 60$ nm, $W_{Gap} = 10$ nm] (e), and [$H_M = 60$ nm, $W_{Gap} = 50$ nm] (f).

4. Results & Optimization

To understand the enhancement mechanisms of the gap plasmon mode and edge plasmonic effect, we investigate the geometry-dependent electromagnetic responses of the proposed waveguide. For the gap plasmon mode, we study the dependence of the two critical parameters named gap width W_{Gap} and height of modulator H_M to its modulation efficiency. In Fig. 3(a), the modulation efficiency increases as the gap width W_{Gap} decreases under different H_M. It is because that the normalized mode area A_{eff}/A_0 decreases with the gap width as illustrated in Fig. 3(b). When $H_M = 220$ nm and W_{Gap} reduces to 10 nm, the normalized mode area drops to 4.8×10^{-5} and the modulation efficiency increases to 2.8 dB/μm. As depicted in Figs. 3(c)–(f), stronger local field enhancement and tighter optical confinement are achieved with a smaller gap. And it is obvious that mode field expands outward when the gap increases. Furthermore, the modulation efficiency increases when A_{eff}/A_0 decreases with the decreasing waveguide height. According to the curves of Fig. 3(a), (b) and the mode field distribution, the waveguide height has a weak influence on the modulation efficiency if the waveguide height is sufficiently large ($\sim$200 nm). This is because the mode field confinement in the vertical direction is mainly determined by the property of the wedge SPP itself. If the waveguide height is small, however, it has a significant effect on the modulation efficiency and mode field area considering that the height of the waveguide is close to the mode field length in the vertical direction. After the parameter sweep, the best value of W_{Gap} and H_M is 10 nm and 60 nm, respectively, and A_{eff}/A_0 is reduced to 3.2×10^{-5} as well as modulation efficiency can reach 4.05 dB/μm.

Next, we investigated the sharpness of the wedge tip, which is an important geometric factor for the enhancement of edge plasmonic effect according to a fact that surface plasmon will be localized and significantly enhanced at the sharp tips of corners [10]. When $W_{Gap} = 30$ nm, the sidewall angle θ is changed from 0 degree to 50 degrees under different H_M to study the relation between the modulation performance and sidewall angle. From the calculated results as shown in Fig. 4(a), the modulation efficiency increases with the sidewall angle while A_{eff} decreases. The reason can be found in Fig. 4(c)–(f). When the angle of the sidewalls gradually increases, the light field at the gap is confined stronger in the vertical direction. Then the light gradually converges on the tips of the wedge-to-wedge plasmonic waveguide. As a result, the mode field area is reduced. Therefore, the interaction of the wedge SPP mode with graphene is strengthened. The change in the sidewall

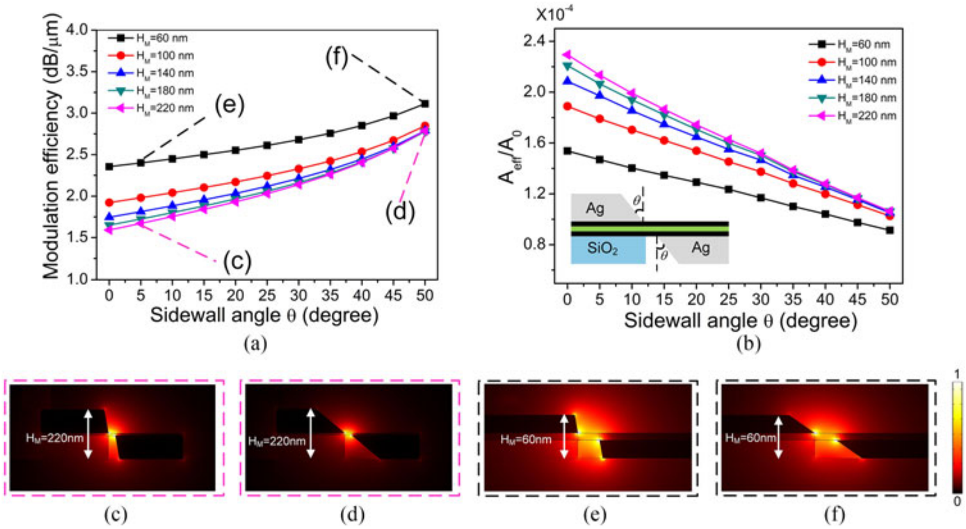

Fig. 4. Modulation efficiencies, mode area, and field distributions for DGOM with different sidewall angles θ and H_M while $W_{Gap} = 30$ nm. (a–b) Modulation efficiency and normalized mode area A_{eff}/A_0 versus the sidewall angle θ for different heights of modulator H_M; (c–f) Normalized electric field distributions for [$H_M = 220$ nm, $\theta = 5$ degrees] (c), [$H_M = 220$ nm, $\theta = 50$ degrees] (d), [$H_M = 60$ nm, $\theta = 5$ degrees] (e), and [$H_M = 60$ nm, $\theta = 50$ degrees] (f).

angle has a significant impact on the device performance. When the sidewall angle increases to 50 degrees, the mode field area decreases to 1.06×10^{-4} and the modulation efficiency is improved to 2.78 dB/μm. On the other hand, when H_M is small, the height of the waveguide also plays an important role in concentrating the light field. As shown in Fig. 4(b), the area of the mode field decreases with the height of the waveguide. In Fig. 4(e), (f), it is found that the light field is also directly compressed by the height of waveguide ($H_M = 60$ nm) in vertically direction. A high modulation efficiency of 3.11 dB/μm can be obtained when $\theta = 50$ degrees and $H_M = 60$ nm.

In addition to the modulation efficiency, the modulation bandwidth and power consumption P are also two important figures of merits for an electro-optical modulator. The modulation bandwidth can be estimated by $f_{3dB} = 1/(2\pi RC)$, where the capacitance $C = \varepsilon_r \varepsilon_0 S/d$ can be calculated with a parallel-capacitance model in terms of graphene-Al_2O_3-graphene structure [6], [24], and the S is the face-to-face region between the two graphene layers while $\varepsilon_r = 1.746^2$ and $d = 10$ nm are the relative permittivity and thickness of Al_2O_3, respectively. Here, the series resistance R is assumed to be $\sim$80 Ω [6]. On the other hand, the energy consumption P can be calculated by $P = C\Delta V^2/4$, where C is the capacitance of modulator and $\Delta V = 13$ V is the applied voltage difference between two working points, which can be approximately calculated by $|\mu| = \hbar \upsilon_F \sqrt{\pi a_0 |V_g - V_0|}$ [25], where $\upsilon_F \approx 10^6$ m/s is the Fermi velocity, $V_0 = 0$ V is the voltage deviation caused by the pre-doping of graphene (here it is treated as an ideal case for simplicity), and $a_0 = \varepsilon_r \varepsilon_0/(de)$ is derived from the parallel-capacitance model, where e is the elementary charge. Finally, the modulation bandwidth is estimated to be 0.61 THz, and the energy consumption P is as low as 137 fJ/bit in Table 1.

It has to be noticed that an extremely small light-graphene interaction region is required in order to increase the modulation efficiency, which might become an issue that how can the light be efficiently coupled into the device itself. However, a hybrid taper coupler [16] can effectively converted the TE mode of silicon rib waveguide to SPP mode, which is similar to our situation.

5. Conclusion

In conclusion, to improve the modulation capacity, we proposed a high-efficiency graphene modulator operated at the diagonal SPP mode with an improved modulation capacity and a deep-subwavelength confinement ($A_{eff}/A_0 < 1/1000$). A large modulation efficiency of 1.58 dB/μm can be obtained with an acceptable low insertion loss of 0.2 dB/μm and a large modulation bandwidth ($\sim$0.61 THz). Furthermore, the enhancement mechanisms of the gap plasmon mode and edge plasmonic effect have also been investigated. By geometric optimization, better confinement and improving the modulation capacity is achieved. Regarding the gap plasmon mode, the modulation efficiency can reach to 4.05 dB/μm after optimizing the height and gap width of DGOM. We also find that the sharpness of the DGOM affecting the edge plasmonic effect plays a main role in the modulation efficiency. By taking full advantage of the wedge SPP enhancement, the obstacles of polarization-mismatch between the graphene and light fields can be overcome and the two-dimensional confinement can be achieved. Hence, our design can provide a better method for the development of nano-photonics devices with 2D materials.

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