Nanoscale Plasmonic Switch at Far Infrared Frequencies Using Graphene

Jieer Lao[1], **Jin Tao**[2,3], **Qi Jie Wang**[2,3], **and Xu Guang Huang**[1]

[1]Laboratory of Photonic Information Technology
South China Normal University, Guangzhou 510006, China
[2]OPTIMUS & NOVITAS, School of Electrical and Electronic Engineering
Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[3]CDPT, Centre for Disruptive Photonic Technology, School of Physical and Mathematical Sciences
Nanyang Technological University, Singapore 637371, China

Abstract— Nanoscale plasmonic switch based on graphene at far infrared frequencies are proposed and designed. Mode-guiding switching/mode-cutoff analyses are given for the modulation function. High modulation depth and bandwidth can be obtained. This plasmonic graphene-based switch can be used to promote the performance of current switches in the integrated optical field, providing another method for interconnect in ultrahighly integrated photonic circuits.

1. INTRODUCTION

Graphene, a single sheet of sp^2-bonded carbon atoms, has attracted much attention due to its outstanding and intriguing properties [1]. The electro-optical switches using graphene have been the subject of much interest both theoretically and experimentally in the recent years [2, 3]. However, most of them are based on electro-absorption, which is relied on the modulation of the interband or intraband transition. Less work has been done in the electro-refraction with different Fermi level, which can also be employed in the modulation mechanism.

In this paper, we provide a different principle and method, the gate-voltage-controlled mode-guiding switching/mode-cutoff mechanism, to achieve the modulation function. The proposed structure has the advantages of large modulation depth and width bandwidth, which can be used to promote the performance of current switches in the integrated optical field, providing another method for interconnect in ultrahighly integrated photonic circuits.

2. MODELING AND NUMERICAL RESULTS

Electronic and optical characteristics of 2D graphene as a function of frequency, temperature, and carrier density have been analytically and experimentally studied in many papers [4–6]. The complex surface conductivity of graphene including intraband and interband transitions is estimated within the random-phase approximation [7] as:

$$\begin{aligned}\sigma(\omega) \;=\; & \frac{2ie^2k_B\mathrm{T}}{\pi\hbar^2(\omega+i\tau^{-1})}\ln\left[2\cosh\left(\frac{E_f}{2k_BT}\right)\right] \\ & +\frac{e^2}{4\hbar}\left\{\frac{1}{2}+\frac{1}{\pi}\arctan\left(\frac{\hbar\omega-2E_f}{2k_BT}\right)-\frac{i}{2\pi}\ln\left[\frac{(\hbar\omega+2E_f)^2}{(\hbar\omega-2E_f)^2+(2k_BT)^2}\right]\right\}. \qquad (1)\end{aligned}$$

Here $\hbar$ is the reduced Planck's constant, ω is the angular frequency, τ is the carrier relaxation time, k_B is the Boltzmann constant, T is the temperature. Surface plasmon polariton (SPP) waves can be supported in a 1D slab waveguide constructed with an ideal graphene sheet sandwiched between dielectric mediums above and below. Under the condition of space wave vector $k_0 \ll k_{sp}$, the effective index N_{eff} of the 1D graphene waveguide can be approximately calculated as follows, based on Eq. (4) in Ref. [4]:

$$N_{eff} \equiv k_{sp}/k_0 = \varepsilon_0\frac{\varepsilon_{r1}+\varepsilon_{r2}}{2}\frac{i2\omega}{\sigma(\omega)}, \qquad (2)$$

where k_0 and k_{sp} are respectively vacuum and the plasmon wave vectors, and ε_{r1} and ε_{r2} are the dielectric constants of the mediums above and below the graphene, respectively. By applying different voltage patterns to the graphene strip, guiding or cut-off modes with low or high attenuation coefficient can be formed.

As can be seen in Figure 1, a monolayer graphene sheet is sandwiched between two aluminum oxide buffer layers forming a 1D field confinement in the y-direction. Three gold-plated silicon gating pads and an end layer are on top and bottom of the structure, respectively, providing another 1D field confinement along the x-direction and dividing the structure into the core and cladding sections. By altering the voltages applied to the graphene to form different Fermi level patterns, in the on state, the SPP waves will be confined within the core region due to higher effective index of the core than the surrounding cladding layers. In the off state, by decreasing the Fermi level in the cladding, the vast majority of energy will diffuse to the cladding, only small fraction of energy remains in the core.

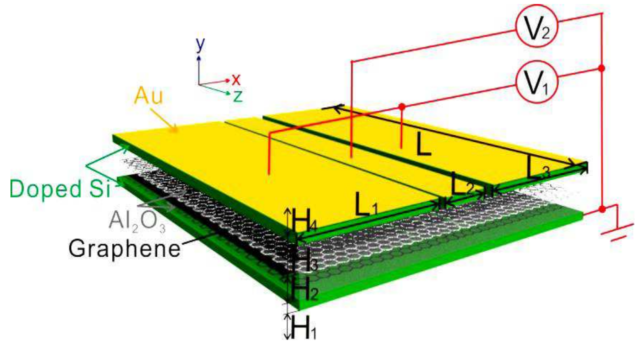
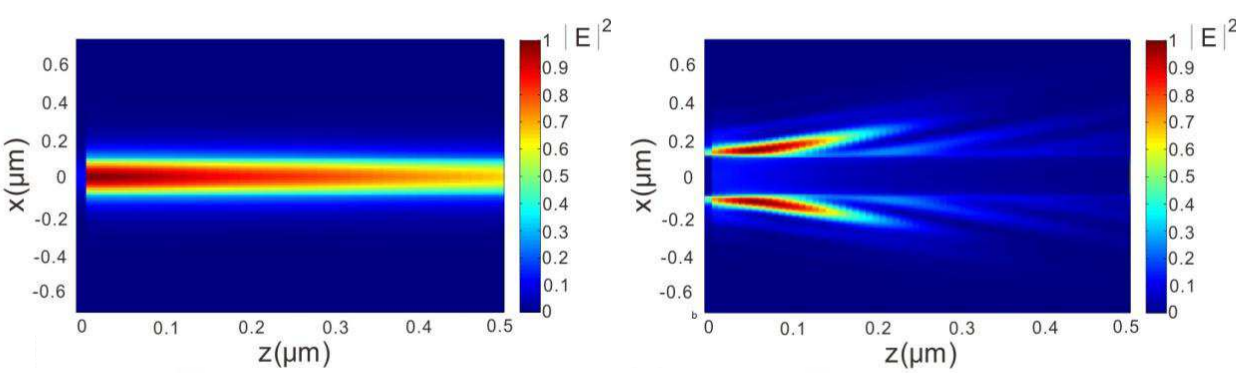


Figure 1: Schematic of the plasmonic switch configuration. The height of each layer is $H_1 = H_4 = 10\,\text{nm}$, $H_2 = H_3 = 50\,\text{nm}$. The width of the gating pads are $L_1 = L_3 = 650\,\text{nm}$, $L_2 = 200\,\text{nm}$ and the length of the waveguide is $L = 500\,\text{nm}$. This switch is fabricated on silicon substrate, which is not shown in the figure. The thickness of graphene is set to be $t_G = 0.6\,\text{nm}$ with the relaxation time of $\tau = 0.25\,\text{ps}$, the working temperature is $T = 300\,\text{K}$. Voltages will be applied to the silicon gating pads to adjust the Fermi level. Here V_1 stands for the voltage applied to the core and V_2 stands for the voltage applied to the cladding.

The finite-difference time-domain (FDTD) method is used to evaluate the optical performance with the working frequency $f = 37\,\text{THz}$. Here the Fermi level in the core section is always kept at $0.6\,\text{eV}$ while that in the cladding section are set to be $0.8\,\text{eV}$ and $0.2\,\text{eV}$ in the on and off states, respectively. Figure 2 shows the normalized light intensity profiles in the x-z plane. As N_{eff} is inversely proportional to the square of E_f, in the on state, the SPP waves are mainly confined in the core and the attenuation coefficient is $\alpha_{on} = 4.0\,\text{dB}/\mu\text{m}$ (Fig. 2(a)). Inversely in the off state, the effective index discontinuity "pull" the energy from the core to the cladding and providing higher attenuation coefficient $\alpha_{\mathit{off}} = 25.4\,\text{dB}/\mu\text{m}$. As a result, up to $21.5\,\text{dB}/\mu\text{m}$ modulation depths can be achieved. 3-dB modulation depth can be satisfied as short as $139.8\,\text{nm}$.



(a) (b)

Figure 2: Normalized light intensity propagation profiles of the structure under different Fermi level in the cladding $E_{f,cladding}$: (a) $E_{f,cladding} = 0.8\,\text{eV}$, (b) $E_{f,cladding} = 0.2\,\text{eV}$. The Fermi level in the core is always kept at $E_{f,core} = 0.6\,\text{eV}$. The working frequency is fixed at $f = 37\,\text{THz}$.

Figure 3 shows the attenuations of the structure in the on and off states, respectively. The structure we propose was studied in the 35–50 THz range. It can be seen that the attenuation stays low in the on state for $E_{f,cladding} = 0.8\,\text{eV}$ while having large difference in the off state for

$E_{f,cladding} = 0.2\,\text{eV}$. More than 15 THz can be achieved, showing good performance in term of the bandwidth.

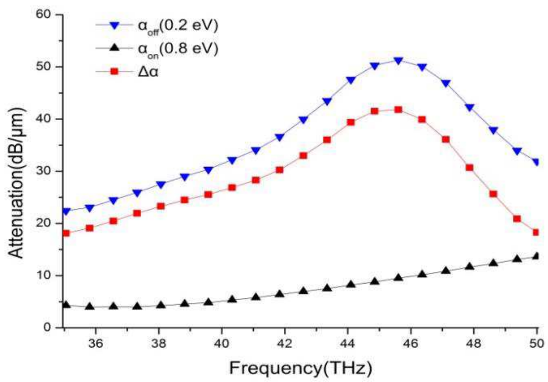


Figure 3: Attenuations of the structure as the function of frequency for $E_{f,cladding} = 0.2$, $0.8\,\text{eV}$, respectively. The Fermi level of the core is fixed at $E_{f,core} = 0.6\,\text{eV}$.

3. CONCLUSION

We have proposed and designed the nanoscale plasmonic switch based on graphene at far infrared frequencies. By altering the voltages applied to the graphene to form different Fermi level patterns, guiding or cut-off modes with low or high attenuation can be formed. Our result shows that the switch has the large modulation depth and can be operated in a wide bandwidth, showing great potential in future integrated circuits.

REFERENCES

1. Geim, A. K. and K. S. Novoselov, *Nat. Mater.*, Vol. 6, 183–191, 2007.
2. Lu, Z. L. and W. S. Zhao, *J. Opt. Soc. Am. B*, Vol. 29, 1490–1496, 2012.
3. Gosciniak, J. and D. T. H. Tan, *Nanotechnology*, Vol. 24, 185202, 2013.
4. Jablan, M., H. Buljan, and M. Soljacic, *Phys. Rev. B*, Vol. 80, 245435, 2009.
5. Yao, Y., M. A. Kats, P. Genevet, N. Yu, Y. Song, J. Kong, and F. Capasso, *Nano Lett.*, Vol. 13, 1257–1264, 2013.
6. Tao, J., X. Yu, B. Hu, A. Dubrovkin, and Q. J. Wang, *Opt. Lett.*, Vol. 39, 271–274, 2014.
7. Falkovsky, L. A. and S. S. Pershoguba, *Phys. Rev. B*, Vol. 76, 153410, 2007.