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A type of all-optical logic gate based on graphene surface plasmon polaritons

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ABSTRACT

In this paper, a novel type of all-optical logic device based on graphene surface plasmon polaritons (GSP) is proposed. By utilizing linear interference between the GSP waves propagating in the different channels, this new structure can realize six different basic logic gates including OR, XOR, NOT, AND, NOR, and NAND. The state of "ON/OFF" of each input channel can be well controlled by tuning the optical conductivity of graphene sheets, which can be further controlled by changing the external gate voltage. This type of logic gate is compact in geometrical sizes and is a potential block in the integration of nanophotonic devices.

1. Introduction

Graphene with a thickness of 0.34 nm is composed of a single layer of carbon atoms arranged in a honeycomb lattice. As a new type of two dimensional (2D) material, it has inspired keen interest of worldwide researchers owing to its amazing properties in optoelectronics [1–4]. Firstly, its carrier mobility can approach 200,000 $\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$, which provides a prospect of manufacturing high-speed optoelectronic devices. Moreover, incident light can strongly couple with graphene and then motivate the graphene surface plasmon polaritons along the surface of graphene sheet [5–7]. It is well known that surface plasmon polaritons (SPPs) is the collective oscillation behavior of free electrons on the surface of metal material motivated by external sources. Based on the properties of SPPs, many kinds of sub-wavelength photonic devices have been investigated theoretically and experimentally. Because these devices can overcome the diffractive limit of light [8,9], they have become one of the most popular technologies in optoelectronic domain. But GSP waves show more favorable characteristics than SPPs, such as extreme electromagnetic confinement, relatively lower dissipative loss and dynamic tunability by changing the chemical potential, temperature and so on [2,10]. Thus it provides much more flexibility than metal to construct compact nano-devices in photonic integration [11–14].

Electronic logic gate has been a vital component in signal processing and transmission devices. However, electronic logic gate has shown some drawbacks in the applications, such as latency and race condition glitches, resulting in the reduction of safety and reliability. However, all-optical logic gates can compensate for the defects so as to attract considerable attention [15–17]. In Ref. [18], cascaded logic gates in nanophotonic plasmon networks are studied and the authors demonstrate that a plasmon binary NOR gate can be realized through cascaded OR and NOT gates in four-terminal plasmonic nanowire networks. In Ref. [19], realizations of nanoscale integrated all-optical XNOR, XOR, NOT, and OR logic gates using plasmonic slot waveguides based on linear interference between surface plasmon polariton modes are reported. Then in Ref. [20], the authors investigate the properties of subwavelength graphene-based plasmonic waveguide performing as a THz switch or AND/OR logic gate. By far, the previously demonstrated all-optical logic gates can be divided into two major classes: one based on linear optical interferences [18,19,21–25], and the other enabled by nonlinear optical effects [26–31].

Inspired by the reported results, in this paper, the theory of linear constructive or destructive interference will be utilized to realize various logic gates based on GSP. The paper is organized as follows: Section 1 is a brief introduction to the paper; Section 2 is about the device structure and basic properties of graphene; the different logical states are investigated in detail in Section 3, and then the conclusion is drawn in Section 4.

2. Geometric structure and basic concepts

The graphene is usually modeled as a two-dimensional material with its thickness of $t = 0.34$ nm. Its tunability depends on the complex

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surface conductivity, which is modeled by the intraband contributions and interband transitions [32] as $\sigma = \sigma_{intra} + \sigma_{inter}$. The first and second term of it can be respectively written as:

$$\sigma_{intra}(\omega) = \frac{ie^2 k_B T}{\pi\hbar^2(\omega + i2\Gamma)}\left[\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\frac{\mu_c}{k_B T}} + 1\right)\right] \quad (1)$$

$$\sigma_{inter}(\omega) = \frac{ie^2}{4\pi\hbar}\ln\frac{2|\mu_c| - (\omega + i2\Gamma)\hbar}{2|\mu_c| + (\omega + i2\Gamma)\hbar} \quad (2)$$

where ω is the angular frequency, $T = 3$ K is temperature, e is the charge of an electron, $\hbar$ is the reduced Planck's constant, k_B is the Boltzmann's constant, μ_c is the chemical potential or Fermi energy. $\Gamma = 0.43$ meV is scattering rate or relaxation constant, and it is relevant to the carrier relaxation time which will determine the carrier mobility. When the imaginary part of the conductivity is positive, the graphene sheet will have the properties like novel metal, namely, it can support propagation of TM type plasmonic mode. Fig. 1(a) and (b) show the real part and imaginary part of the conductivity as a function of the frequency f_0 according to Eq. (1) when $\mu_c = 0.15$ eV and $\mu_C = 0.065$ eV respectively [32]. It can be clearly found that there exists a frequency range in which the imaginary part of optical conductivity is negative when $\mu_c = 0.065$ eV, while it is always positive when $\mu_c = 0.15$ eV. Their real parts remain positive in the whole frequency range.

Below we will use this property to design our logical gate. It is well known that the effective mode index of TM wave supported by graphene sheet embedded in the uniform dielectric can be given as:

$$n_{eff} = \sqrt{\varepsilon_c - \left(\frac{2n_c}{\eta_0\sigma}\right)^2} \quad (3)$$

where η_0 is the intrinsic impedance of free space. If the circumambient media is air then its dielectric constant is $\varepsilon_c = n_c^2 = 1$. At this time, it is easy to obtain that the effective mode index $n_{eff} \approx 69.39 + 0.72i$, GSP wavelength $\lambda_{GSPs} = \lambda_0/Re\left(n_{eff}\right) \approx 144$ nm and the propagating length of GSP wave $L_{GSPs} = \lambda_0/2\pi Im\left(n_{eff}\right) \approx 2192$ nm when chemical potential $\mu_c = 0.15$ eV, operating frequency $f_0 = 30$ THz, working wavelength $\lambda_0 = 10$ μm. The normalized propagating length can be set as $L_m = L_{GSPs}/\lambda_{GSPs} \approx 15$. If the circumambient media is set as SiO_2 with $\varepsilon_c = 1.5$ while keeping other parameters unchanged, then $n_{eff} \approx 156.13 + 1.63i$, $\lambda_{GSPs} \approx 64$ nm, $L_{GSPs} \approx 974$ nm and $L_m \approx 15$. It proves that the confinement of GSP becomes stronger when the background medium changes from air to SiO_2, and that is helpful for the miniaturization of integrated optical devices. But for the case of $\mu_c = 0.065$ eV, GSP wave is not supported. It is well known that the propagating length depends on various losses. In addition, in Ref. [33], the authors find that the damping effects for GSP wave are relevant to its coupling with optical phonons, and this effect is mainly decided by the lifetime of GSP, which is largely decided by the graphene relaxation constant $\Gamma = 1/2\tau$. Here τ is the carrier relaxation time. Fig. 2 demonstrates the dependences of L_{GSPs} on the operating frequency for different Γ and μ_c. It can be found that L_{GSPs} decreases as the frequency increases. When the other parameters are fixed, L_{GSPs} will increase with the increase of chemical potential or with the decrease of relaxation constant. Thus the results shown here tells people again that one can control the propagation loss in designing the graphene based optical devices by properly adjusting the chemical potential and relaxation constant of graphene. In this paper, as a special case, we will use the chemical potential 0.15 and 0.065 eV according to Ref. [32] to determine whether the graphene sheet can support the transmission of GSP wave or not. At the same time, the choice of relaxation constant 0.43 meV corresponded to the carrier relaxation time of about 0.76 ps is rather conservative to feature the actual loss of graphene due to the fact that $\tau > 1.5$ ps has been experimentally achieved in freestanding graphene [34]. In fact, one can dope the graphene sheet by tuning the external gate voltage at a desired operating frequency. An approximate closed-form expression between the chemical potential and the gating voltage can be given by [35]

$$\mu_c = \sqrt{\frac{\pi\varepsilon_0\varepsilon_r V_g}{et}} \quad (4)$$

where ε_r is the permittivity of buffer layer medium between the graphene sheet and substrate, ε_0 is the permittivity of free space, t is the thickness of buffer layer medium, V_g is the gating voltage applied to the graphene sheet and the substrate.

It is well known that the electromagnetic field mode excited on the graphene sheet is TM mode and of which only the fundamental one can propagate a long distance with tight mode field confinement characteristics. So in terms of the coordinates used in this paper, the amplitude of $\left|H_z\right|$ component is mainly discussed. Fig. 3(a) and (b) show the propagation profiles of $\left|H_z\right|$ respectively for the cases of either supporting the GSP wave propagation or not. It can be seen that the simulation results agree well with the above analytical results. It has been demonstrated in Ref. [36] that a quarter-circle-shaped graphene film with larger curvature radius can satisfy the phase matching condition. So the GSP waves propagating along graphene sheets connected by a quarter-circle-shaped bending are also simulated, and the length of bending parts have been set as $0.5\lambda_{GSPs}$. One can find from Fig. 3(c) that even if the graphene sheet is bended, the GSP wave can also propagate with very low bending loss [37]. In Fig. 3(d), the length difference between the two input channels is set as $1.5\lambda_{GSPs}$ and it cannot only ensure that there is no field coupling between the two channels and maintain a compact geometry structure, but also meet the condition of destructive interference (will be given below in Eqs. (5) and (6)). Thus the destructive interference will happen when GSP waves propagate along these two channels and it is clear that after the destructive interference, there is almost no field propagating in the output channel. All the cases shown here are helpful to design compact photonic devices based on the graphene sheet. In this paper, a type of all-optical logic gate has been designed by using the above characteristics of shaped graphene sheet. Numerical simulations based on finite element method (FEM) with the perfectly matched layer (PML) absorbing boundary conditions are carried out to investigate the basic logic states. During simulation, the graphene is treated as a zero thickness layer and characterized with surface current, which is given by $J = \sigma E$, where J is the surface current density, and E is the electric component of the GSP. Convergence tests are carried out by optimizing the mesh to ensure the accuracy of calculation results. The triangular meshes are used with maximum element size of 10 nm and minimum element size of 0.03 nm around the graphene. Because the graphene width in z-direction is large enough, so 2D simulations enable to accurately approximate the calculation, and it could also effectively save the computer memory and calculation time. In addition, dipoles with same frequency are respectively placed at the left edge [36] of each channel to excite and propagate GSP wave when channel chemical potential is controlled to 0.15 eV, otherwise, if it is 0.065 eV, the GSP cannot be excited.

The schematic diagram of the graphene-based all-optical logic gate device is shown in Fig. 4. For experimental consideration or for the future real application, the designed structure can be embedded in SiO_2 medium or others. The fabrication methods can refer to those in Refs. [38–41] (see Appendix). For the aim of simplicity, the background material is set as air in this paper for the purpose of simplifying the numerical simulation and the effect of the dielectric environment will not be discussed. If the background material is changed to SiO_2 for real applications, the electric field mode confinement will become stronger and similar phenomena can also be observed. As a result, it is possible to create more compact devices. All the branches of graphene sheets can be modulated by connecting to an electrical source. As for the regions adjacent to different channels, there are two cases to avoid the occurrence of different graphene layers in different locations. One is the end to end approach, the other is the overlap between graphene layers. For the former case, as long as the end to end distance between graphene channels is close enough, most of the power energy can be transferred from one end to the other. For the latter case, when the result reported in [42] is used, if the gap between two graphene layers is very small, the needed coupling length, over which the power is completely transferred from one layer to the other, will be also very small. Calculation shows