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سوئیچ پلاسمونیک کریستال تراهرتز مبتنی بر گرافن

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چکیده- در این مقاله یک سوئیچ پلاسمونیک کریستال مبتنی بر گرافن در فرکانس تراهرتز ارائه شده است. مقدار عبور از ساختار و انعکاس از بالای قطعه به صورت عددی و در یک شبیه سازی سه بعدیمحاسبه شده است. اثرات تغییرات در شعاع حفره‌های دایره‌ای و همچنین ثابت شبکه در ساختار کریستالی بر روی طیف عبور قطعه بررسی شده است. افزایش پتانسیل شیمیایی که معادل است با افزایش ولتاژ بایاس منجر به شیفت فرکانسی در طیف عبور ساختار می‌شود. از این رو از این ساختار می‌توان به عنوان یک سوئیچ ON/OFF در فرکانس تراهرتز استفاده کرد. نسبت انقراض برای این سوئیچ 8dB و از دیگر مزایای این ساختار این است که به راحتی ساخته می‌شود.

کلید واژه-گرافن، سوئیچ تراهرتز، ساختار پلاسمونیک کریستال

Graphene-Based Terahertz Plasmonic Crystal Switch

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Abstract-In this paper, a plasmonic crystal switch is presented based on the graphene at the terahertz frequency. The amounts of transmission through the structure and reflection on the top of the device have been calculated numerically. The effects of changes in the radius of the circular aperture and the lattice constant of the crystalline structure were assessed on the transmission spectrum of the device. An increase in the chemical potential which is equivalent to an increase in the bias voltage leads to a frequency shift in the transmission spectrum in the structure. Hence this structure can be used as an ON/OFF switch in terahertz frequency. The extinction ratio for this switch is 8 dB and another advantage of this switch is that this structure can be easily fabricated.

Keywords: Graphene, Terahertz Switch, Plasmonic Crystal structure.

1. Introduction

Recently, devices that work at terahertz frequency (0.1-30 THz) have been progressed due to high bit rate and ultra-wide bandwidth in optical communications. As an instance of such devices, optical sources [1], detectors [2], sensors [3], and switches [4-6] can be mentioned. One of the crucial problems in such photonic devices is their large dimensions due to the waveguide in these devices. Plasmonic succeed to overcome this problem and so that, devices with dimensions smaller than the wavelength were designed [7, 8]. Accordingly, the application of Surface Plasmons (SPs) is day-to-day accelerated. This science can be used in the electronic and photonic circuits separately, so that by spontaneous wave propagation in each of these fields, no disturbance is occurred in transferring data, and this can cause an increase in the capacity of data transformation in the integrated circuits.

One of the significant restrictions in the plasmonic devices is that metals especially in the terahertz frequency act as a perfect electric conductor, which this issue disrupts the confinement of the SPs and makes plasmonic devices with high power consumption and low time response [9, 10]. Using graphene as two-dimensional material overcomes this problem, and therefore, graphene is used for propagation of the SPs waves especially at the terahertz frequency [11]. This fact has been proven that graphene accepts SPs properly and can transform them with low loss, long lifetime, and high confinement [12-14]. Plasmonic provides the possibility of decreasing the optical components below the wavelength and can also act as a bridge between electronic and photonic circuits. [15].Plasmonic switches have received a great deal of attention because of their advantages such as ultra-compact, high bandwidth, and low power consumption. Make use of the patterned graphene can excite the plasmonic modes and it causes absorption in the structure and therefore, passing through the structure is negligible. This design can be used as an ON/OFF switch in which the OFF state is considered in the absorption frequency and when the plasmonic modes are excited and then by an increase in the chemical potential which is equivalent with an increase in the applied bias voltage, the frequency spectrum is shifted toward higher frequencies and this causes an increase in the transmittance in that specific frequency and the switch will be ON.

The rest of the paper is organized as follows. The basic equation of the graphene surface conductivity and the relation of the applied bias voltage with the chemical potential of the structure are mentioned in section 2. Then the outputs and results of the simulations are shown in section 3, and finally, the paper is concluded in the conclusion.

2. SIMULATION AND METHODS

Surface conductivity of graphene under the condition of $\mu_c >> k_B T$ can be written by Drude-like form [16, 17]

$$\sigma_g(\omega) = \frac{ie^2 \mu_c}{\pi \hbar^2 (\omega + i\Gamma)} \tag{1}$$

where e is the electron charge, $\hbar$ is reduced Plank constant, μ_c is the chemical potential and $\Gamma = e v_F^2 / \mu_e \mu_c$ is the scattering rate, with $\mu_e \sim 10^4\ \mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$ and $v_F \sim 10^8\ \mathrm{cm} \cdot \mathrm{s}^{-1}$ representing the electron mobility and Fermi velocity in graphene. Then the effective permittivity of graphene is given by $\varepsilon_g = \varepsilon_b + i\sigma_0/(\omega\varepsilon_0\Delta)$ [18-20], where $\Delta \sim 0.34$ nm is the thickness, and ε_b is the average effective permittivity of the effective medium surrounding the patterned graphene. The relation of the chemical potential and the applied bias voltage is given by [21]

$$|\mu_c| \approx |E_f(V)| = \hbar v_f \sqrt{\pi a_0 |V - V_{Dirac}|} \tag{2}$$

where $V_{Dirac} = 0.8V$ is voltage offset, $v_f = 9 \times 10^5 m/s$ is Fermi velocity, and $a_0 \approx 9 \times 10^{16}\ m^{-2} V^{-1}$ is estimated from a single capacitor model.The structure of the patterned graphene placed on hBN/Si is shown in Fig. 1. Terahertz waves enter from the top of the structure and exit from the bottom of the structure. These waves excite plasmonic modes around each circular hole in the graphene surface. In this figure, *a* represents lattice constant and *d* is the diameter of the holes on the graphene surface.According to our calculations the transmittance in this structure is independent of the polarization of the input light.

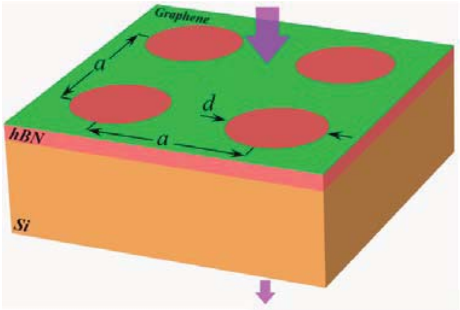

Fig. 1: Graphene-based plasmonic crystal structure

3. RESULTS AND DISCUSSION

By considering a=3μm and d=2.5μm, transmission through the structure and reflection from the top surface are computed by COMSOL software in 3D simulation and the results are presented in Fig. 2.

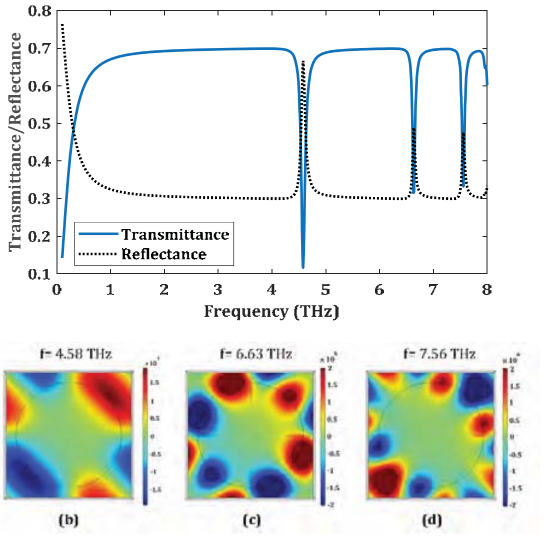

Fig. 2: a) Transmittance and reflectance for structure with a=3μm, d=2.5μm, and μ_c=0.4 eV. Electric field profile for a) f=4.58 THz, c) f=6.63 THz, d) f=7.56 THz.

Because of the degeneracy that happened in the band structure of some frequencies, in these frequencies the plasmonic mode can be coupled and excited with a free space input wave. Having the effective refractive index for structure, we can easily obtain the SPs wavelength $\lambda_{SP}=\lambda_0/\mathrm{Re}(n_{eff})$ and propagation length $L_{SP}= \lambda_0/(2\pi \mathrm{Im}(n_{eff}))$. According to the thickness and prmittivity of each part we can find the effective index of structure n_{eff}= 1.68 and therefore we can obtain λ_{SP}.As can be observed in Fig. 2, at the 4.58, 6.63, and 7.56 THz the plasmonic modes are excited around the circular holes. Therefore, absorption has occurred in these frequencies and the transmittance in these frequencies is insignificant. The profiles of the electric field for these frequencies are shown in Fig. 2. The effect of changing the diameter of circular holes on the transmission spectrum is shown in Fig. 3.

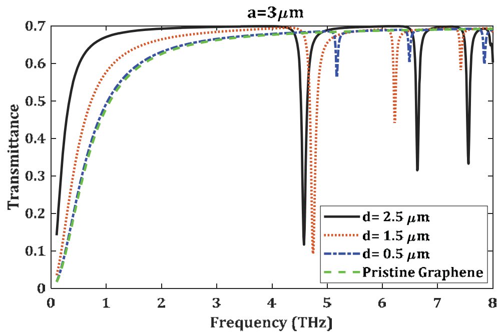

Fig. 3: The transmittance of the structure for different diameters of the circular hole on the graphene surface and a=3 μm and μ_c=0.4 eV.

In Fig. 3, for a=3μm and d= 0.5, 1.5, 2.5μm, and pristine graphene, the transmittance for the structure is shown. As can be seen in this figure, in the case that there is no hole in the graphene surface and on the other words for the pristine graphene, terahertz waves can pass through the device in all frequencies and plasmonic modes cannot be excited. By the increase in the diameter of circular holes on the graphene surface, plasmonic modes can be excited and the amount of absorption is increased. Besides, the exciting modes are shifted toward the lower frequencies by an increase in the diameter of the holes.In the next step, by keeping the diameter of circular holes constant by d=2.5µm, the effect of an increase in the lattice constant of crystalline structure for different values of a= 3, 4, 5µm on the transmittance of the device is shown in the Fig. 4.

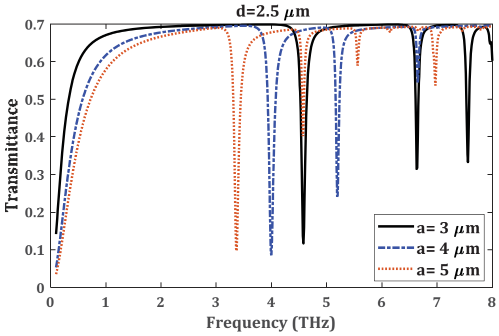

Fig. 4 Transmittance of the structure for different lattice constant and d=2.5 µm, μ_c=0.4 eV.

As can be depicted from Fig. 4, by an increase in the lattice constant a frequency shift has occurred in the exciting plasmonic modes to the lower frequencies. In all the simulations performed so far, the chemical potential was considered μ_c=0.4 eV. In this section, the effect of chemical potential change on the transmission spectrum is assessed. As can be seen in equation (2), an increase in the bias voltage increases the chemical potential. In Fig. 5, the effect of an increase in the chemical potential on the transmission spectrum is shown for a=3 µm and d=2.5 µm and different values of chemical potentials μ_c=0.3 and 0.4 eV.

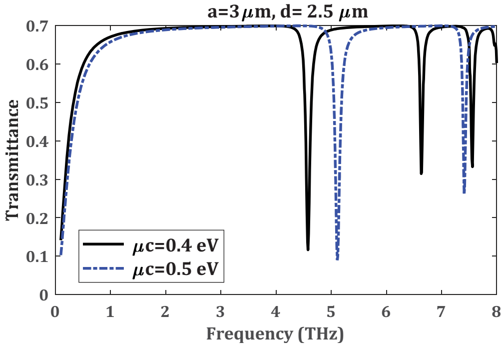

Fig. 5 Transmittance of the structure for different chemical potential and a=3µm, d=2.5µm.

According to Fig. 5, an increase in the chemical potential causes a frequency shift to the lower frequencies. At 4.58THz and in the μ_c=0.4eV and indeed before switching, the plasmonic mode is excited and the switch is OFF, now with an increase in the chemical potential to μ_c=0.5eVat 4.58THz, the output is increased to 0.7 and the switch becomes ON and in this case, the extinction ratio is 8db.

4. CONCLUSION

In summary, this paper attempt to present a graphene-based plasmonic crystal ON/OFF switch. This switch can be easily fabricated by located the patterned graphene on the hBN/Si in which terahertz waves incident from the top of the structure. With performing 3-dimensional simulations in COMSOL software first, the transmission and reflection for this structure were calculated. Then the effects of changing in the diameter of circular holes, and lattice constant were assessed. Finally, with changing in the chemical potential we showed how we can use this structure as an ON/OFF switch. The advantages of this switch are its extinction ratio which is 8 dB and the structure of this switch that can be easily fabricated.

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