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Circuit model for Electrically Controlling the Graphene-based meta- lens

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Abstract- In this research, we propose a circuit model (CM) for a THz meta-lens. The meta-lens is composed of a single graphene layer on a silica substrate and a gold film above the graphene layer. The gold film is etched by an array of cross-shaped apertures (CSAs) with different size and orientations to control the abrupt electromagnet wave. The focal length of the meta-lens can be electrically controlled by applying a voltage to the graphene sheet. The CM of the meta-lens is initialy introduced without considering the graphene layer. The complete model is then presented, considering the graphene layer, for two different polarizations, TE and TM. The model is different for the two polarizations to verify the proposed models, we sum the outputs of the models for the two polarization and compare the result to the output of the FDTD numerical method, where we use a circulary polarized wave as the sum of the TE and TM polarizations. The comparision shows a good agreement between the results.

Keywords: Circuit model, Graphene, meta-lens, metasurface.

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1. Introduction

In this work, a simple circuit model (CM) of a unit cell of meta-lens consisting of monolayer graphene and a gold metasurface is proposed and analyzed for the first time. The results of the FDTD technique are in good agreement with those of the CM approach. The metasurface is composed of cross-shaped apertures with different lengths and rotation angles. By changing of the Fermi energy of the graphene, the amplitude and the phase of the transmitted THz wave can actively be controlled without need to refabricate the meta-lens structure which results in saving material, cost, and time.

2. The Structure and Numerical Analysis Method

The schematic view of the proposed unit cell of the meta-lens consisting of a monolayer graphene on a silica substrate with refractive index of 1.4 is given in Figure 1. A gold film with thickness of 50 nm with etched cross-shaped apertures (CSAs) is placed on the graphene layer. The gate voltage of V_g is applied to graphene by metal electrode. The patterned gold layer is used to change the scattering characteristic of the incident electromagnetic wave. When the aspect ratio of the CSA is higher than 5, the amplitude of the transmitted THz wave increase. So, we supposed the width of the CSA as 20 µm with different lengths L and rotation angles, which are arranged in the x and y directions with period of 200 µm [1]. The surface conductivity of graphene is expressed by the Kubo formula [2]. Right hand circular polarized (RHCP) THz wave is launched on the structure. In the CM, we consider two polarizations TE and TM then add the results of the two polarization and comparison with result of FDTD model.

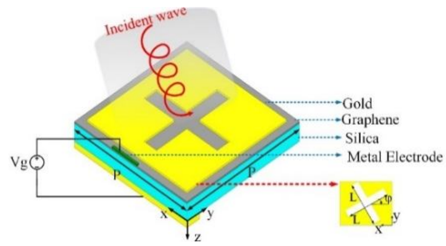


Figure 1: Schematic view of the unit cell of the THz meta-lens structure.

3. Circuit Modeling

CM of the proposed THz meta-lens structure without consideration of graphene is shown in Figure 2 (a). The impedances of air, Silica, and Au are respectively Z_0 ,$Z_{Silica} = \frac{Z_0}{\sqrt{\varepsilon_{r,Silica}}}$, and $Z_{Au} = \frac{Z_0}{\sqrt{\varepsilon_{rAu}}}$where Z_0 =377 Ω, is the free space impedance, $\varepsilon_{rSilica}$ and ε_{rAu} are the dielectric constants of Si and Au, respectively. Au is modeled by Drude model matching well with the experimental results [3]. We have modeled the capacitance and inductance of the structure, C_{CSA}, and L_{CSA} as:

$$C_{CSA} = \varepsilon_0 \frac{A}{d}, L_{CSA} = \frac{\mu A}{L} \tag{1}$$

where A, d, and μ are respectively the area of CSA, the thickness of CSA, and free space permeability. The transmission of the structure without graphene is calculated by $T = \sqrt{\frac{\varepsilon_{r,Silica}}{\varepsilon_0}} \left|\frac{E_t}{E_i}\right|^2$ where $\varepsilon_{r,Silica}$, E_t, and E_i are respectively the dielectric constant of Silica, the transmitted electric field, and the incident electric field. CM results are compared with FDTD simulation ones for different lengths of CSA in Figure 2 (b). As the length of the CSA increased, the resonant frequency decreased and redshift occurs.

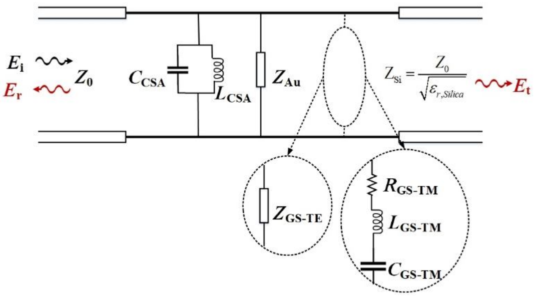
3.1. CM Approach of TM mode

Based on [4,5], a graphene sheet (GS) for TM polarization can be modeled with parallel R-L-C circuit. We consider the first mode (n=1) for simplifying our calculations. The CM of the proposed meta-lens for TM mode is given in Figure 2.The resistance, inductance, and capacitance values of the first TM mode for parallel R-L-C circuit are achieved by [4]:

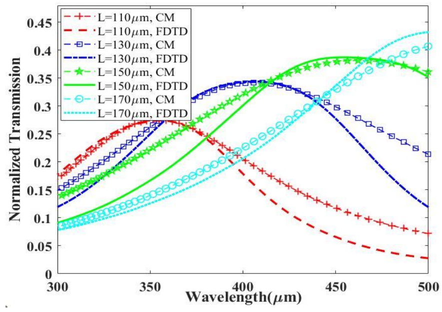
$$R_{GS-TM} = \frac{D}{S_1}\frac{\pi\hbar^2}{e^2 E_F \tau} \qquad L_{GS-TM} = \frac{D}{S_1}\frac{\pi\hbar^2}{e^2 E_F} \qquad C_{GS-TM} = \frac{S_1^2}{S}\frac{2\varepsilon_{eff}}{Q_1} \tag{2}$$

where $Q_1 = q_1\left(\frac{\pi}{W}\right)$, is the eigenvalue given in Table 1 of [4], q_1 is the first eigenvalue of the current of the GS, τ is the relaxation time, $S_1^2 \simeq \frac{8}{9}W$, D and W are the periods of the structure along the x and y directions. We set W=D for having a GS and $\varepsilon_{eff} = \frac{\varepsilon_0(1+\varepsilon_{rSi})}{2}$. The impedance of the GS for TM mode is:

$$Z_{GS-TM} = R_{GS-TM} + j\left(\omega L_{GS-TM} - \frac{1}{\omega C_{GS-TM}}\right) \tag{3}$$



(a)



(b)

Figure 2: (a) CM of the CSA without consideration of graphene, with graphene for TM and TE modes, (b) Comparison of transmission of the CSA without graphene obtained by CM approach and the FDTD numerical method for different lengths of CSA.

3. 2. CM Approach of TE mode

The CM of the proposed meta-lens for TE mode is given in Figure 2 (a). The impedance of the TE mode is calculated by:

$$Z_{GS-TE} = j\omega L_{GS-TE} + \frac{D}{\sigma_g W}4 \tag{4}$$

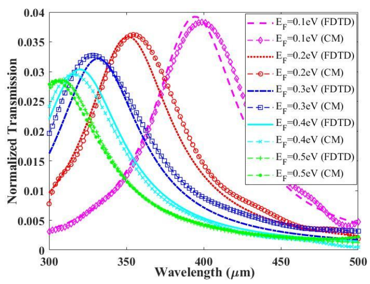
where L_{GS-TE} is the inductance of GS. This inductance is calculated by:

$$L_{GS-TE} = \frac{\eta_0 D}{c\pi} ln\left[csc\left(\frac{\pi W}{2D}\right)\right]\left(1-\sqrt{1-[(D-W)/D]^4}+\frac{\sqrt{1-[(D-W)/D]^4}}{\sqrt{1-(\eta_0 D/\lambda)^2}}\right) \tag{5}$$

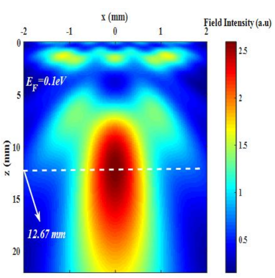
where η_0, λ and c are respectively the free space impedance, incident wavelength and the free space speed of light [6]. The transmission of TE or TM modes is obtained through [7]:

$$T_{TM}(\omega) = \frac{4Y_{Silica}Y_0}{|Y_{Silica}+Y_0+Y_{TM}(\omega)|^2}\ ,\quad T_{TE}(\omega) = \frac{4Y_{Silica}Y_0}{|Y_{Silica}+Y_0+Y_{TE}(\omega)|^2} \tag{6}$$

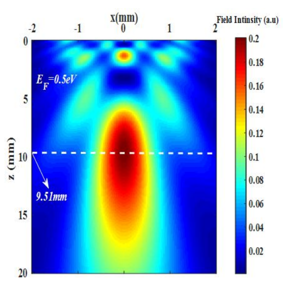
where$Y_0 = \frac{1}{z_0}$, $Y_{Silica} = \frac{1}{Z_{Silica}}$, $Y_{TM}(\omega) = \frac{1}{(Z_{GS-TM}+Z_{Au})}$ and$Y_{TE}(\omega) = \frac{1}{(Z_{GS-TE}+Z_{Au})}$ are respectively the admittances of the free space, Silica, TE mode, and TM mode [7]. Transmission spectra of the proposed meta-lens when the structure is illuminated by RHCP incident wave; for different Fermi energies are given in Figure 2 (b). The results are obtained by FDTD and CM approaches which are comply well which are shown in Figure 3(a). By increasing the chemical potential of graphene, the resonant frequency increased. So, blueshift of the transmission is detected. The normalized transverse intensity distributions on the focal plane of the transmitted RHCP light for graphene chemical potentials of 0.1 eV and 0.5 eV are respectively depicted in Figs. 3(b) and 3(c).



(a)



(b)



(c)

Figure 3: (a)Comparison of transmission of the CSA with graphene obtained by CM approach and the FDTD numerical method for different chemical potentials, (b) electric field intensity distributions of RHCP transmitted THz wave for graphene chemical potential of 0.1 eV and (c) 0.5 eV

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