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Circuit modeling of graphene absorber in terahertz band

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ABSTRACT

Here we develop and extend a transmission line method (TLM) to analyze the performance of graphene assisted metamaterial (GM) devices working in the terahertz (THz) band. We demonstrate that a circuit model can be presented for different parts of the device including graphene and also the patterned metallic sheet by analyzing the distribution of surface induced current. In pursuit of evaluating the efficiency and accuracy of our proposed method, we compare its results, obtained from an easy to implement MATLAB code for a typical GM absorber with those obtained from full wave simulations. The excellence of the proposed method in terms of computation time (showing more than 3 orders of magnitude reduction in run time) and memory resource besides producing results with acceptable agreement with the results of full wave simulation (with an error less than 5%) versus incident angle, dielectric thickness and chemical potential, nominates it as a promising approach to simulate other graphene-based devices.

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1. Introduction

While myriad applications are envisioned for the terahertz (THz) gap region of the electromagnetic spectrum (roughly from 100 GHz–10 THz), it has remained among the least studied frequencies due to the lack of proper response of the most natural materials to THz frequencies and efficient laboratory facilities [1]. THz metamaterial absorbers (MA) are among the most interested THz components due to their potential applications in sensing, imaging, and detecting [2–4]. Most of the reported absorbers can only operate at a certain frequency or a finite range of frequencies and their tuning can only be accomplished by careful altering of the geometries or reconstructing the supporting substrates, which is certainly a difficult task and sometimes impossible after fabrication [5–7]. To overcome this limitation and achieve broadly dynamic tunability of THz MA, the tunable interactions have been represented recently [8,9] through integration with active materials such as graphene; a newly isolated two dimensional allotrope of carbon with fascinating electrical and optical properties [10,11]. The gate voltage tunability of graphene conductivity is a great merit that makes it as a good candidate to fabricate dynamically tunable absorbers. Besides that, the planar nature of graphene and its atomic thickness nominate it for highly integrated circuits.

There is always a demand for exploiting efficient approaches in analysis and simulation of optical devices which can provide good accuracy besides minimizing the required memory and run time. Although, in recent years, full wave analysis based on different numerical techniques are widely employed to simulate the performance of graphene assisted absorbers such as finite element method (FEM) [12,13], finite difference time domain (FDTD) technique [14–16], finite integration technique [17,18], and so on, however, transmission line method (TLM) offer benefits compared to them in terms of run time and memory which is worthy of exploring. While a TLM approach is proposed in [19] for simulation of MA, no RLC circuit is reported for the copper part of the structure and the authors for this part have used the data obtained from finite integration technique. In fact, they have employed a hybrid technique. In this contribution, we aim to propose a RLC circuit for copper section. By this way, the structure can be fully simulated by TLM. The reflection spectra of the absorber for different structural and graphene parameters and also normal and oblique illumination with different incident angles is calculated with our developed TLM-employing curve fitting- and the results are compared with the results of full wave simulation and the hybrid approach in [19]. The good agreement between the results, the easy implementation of the proposed TLM with a MATLAB code besides the noticeable reduction in run time by more than 3 order of magnitude make it a desire candidate to study the graphene assisted MA absorber.

2. Structure

A schematic of the unit cell of the studied GM absorber composed of a copperfilm and a graphene sheet separated by a

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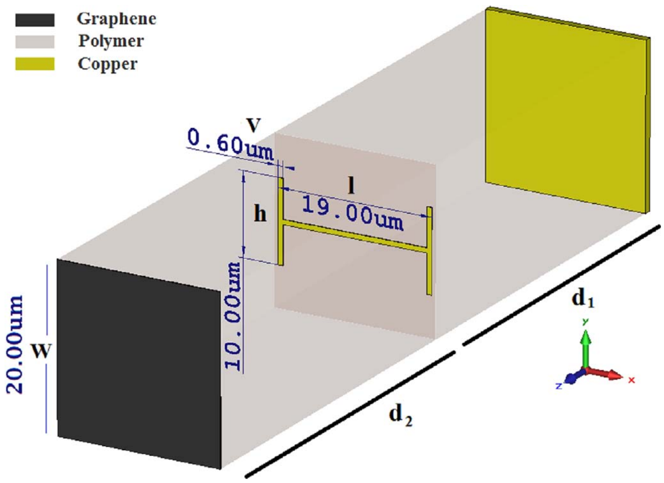

Fig. 1. A perspective of the studied absorber.

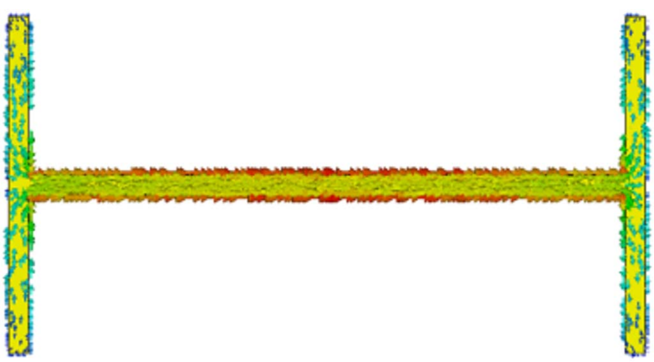

Fig. 2. Surface current of the cut-wire shape made from copper.

dielectrice medium (Polyimide tan $\delta = 0.0027$) located upon a metallic ground plane is depicted in Fig. 1. The thickness of the patterned copper film is t=0.02 μm.

The analysis of the induced surface current distribution on copper part can be used to develop a RLC circuit for it. The intense current in the horizontal leg of the depicted case in Fig. 2 is due to the transverse magnetic (TM) polarization of the normal incident wave, which can bring a strong inductance nature for this part. Besides that, this high intensity current increases the copper temperature which in turn enlarges its resistivity. In lateral legs, the lower intensity current introduces lower inductance and resistivity. There is also a mutual inductance between these two legs, which in the result of the opposite circular rotation of current would be negative. In addition, the charge accumulation on the lateral legs which makes them as the plates of a capacitor may add a capacitance characteristic to this section. By increasing the incident angle and deviating from normal case, the intensity of induced current in the horizontal (lateral) leg decreases (increases) which lead to a corresponding variation of the resultant resistance and inductance. A current source placed in series with the equivalent resistance and inductance of the horizontal leg or more easily, a voltage source in parallel with the equivalent circuit of the lateral leg can be used to model the source of the induced current.

3. Results and discussion

According to the above discussion, a circuit model is proposed to study the absorption of the proposed structure. This model demonstrates well agreement with full wave simulation in THz

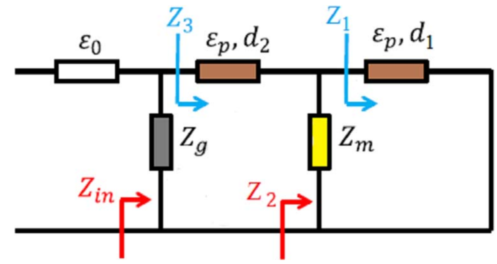

Fig. 3. Circuit model for the proposed absorber.

regime. The structure is simulated with full wave simulation software CST Microwave Studio. The scattering parameters are calculated by a frequency-domain electromagnetic solver such as surface current. The unit cell is simulated with mirror symmetry boundary conditions (PMC/PEC) to model a periodic array of cut wires. In other words, this boundary condition means that the incident wave is in the TM mode. In the circuit model, the graphene conductivity is defined by Kubo formula. At the THz regime, when $\hbar\omega \ll 2\mu_c$ the contribution of interband transition of electrons in graphene conductivity is negligible and the surface conductivity can be simplified as (with $e^{j\omega t}$ time harmonic variation) [20,21].

$$\sigma_g = \frac{je^2K_BT}{\pi\hbar^2(\omega - j\tau^{-1})}\left(\frac{\mu_c}{K_BT} + 2\ln\left(\exp\left(-\frac{\mu_c}{KT}\right) + 1\right)\right) \tag{1}$$

where K_B is the Boltzmann's constant, μ_c is the chemical potential representing the graphene Fermi level, $-e$ is the electron charge, ω is the angular frequency, $\hbar$ is the Planck's constant, T is the temperature and the relaxation time of electrons is taken $\tau = 0.1$ ps [22]. All simulations are performed in the room temperature. Due to the ultrathin nature of the patterned H shape film, made from copper and the graphene sheet, compared to the operating wavelength, they can be treated as conductive films with the surface impedances of Z_m and Z_g, respectively. Polymer layers in the transmission line, can be modeled as either inductance or capacitance depending on its thickness in order to satisfy the obligated absorption performance. An obliquely incident wave onto the GM absorber with an incident angle of θ is studied. Based on the TLM, an effective analog circuit model is established in Fig. 3, where ε_0 is the dielectric constant of vacuum and ε_p=3.5ε_0 represents the dielectric constant of the polyimide in the THz band regime. Under illumination of metamaterial embedded structure with TM polarization, the following relations are derived for the equivalent impedance of different sections [23].

$$Z_1 = jZ_p.\ \tan(k_{zp}d_1) \tag{2}$$

$$Z_2 = \frac{Z_1.\ Z_m}{Z_1 + Z_m} \tag{3}$$

$$Z_3 = \frac{Z_p(Z_2 + jZ_p.\ \tan(k_{zp}d_2)}{Z_p + jZ_2.\ \tan(k_{zp}d_2)} \tag{4}$$

where d_1=d_2=10 μm is the thickness and Z_p is the impedance of dielectric intermediate layers, also k_{zp} is the propagation constant of propagating THz wave in this region. According to [24,25], graphene ribbons can be modeled as optical circuit elements. Considering W=D=20 μm for the studied periodic ribbons in [24], leads to a continuous graphene sheet which can be characterized

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