Dual capacitive-inductive nature of graphene metasurface: transmission characteristics at low-terahertz frequencies

Yashwanth R. Padooru*, Alexander B. Yakovlev*, Chandra S. R. Kaipa*, George W. Hanson†, Francisco Medina‡, and Francisco Mesa§

*Center for Applied Electromagnetic Systems Research (CAESR),
Department of Electrical Engineering, University of Mississippi, University, MS 38677-1848, USA

†Department of Electrical Engineering, University of Wisconsin–Milwaukee, Milwaukee, WI 53211, USA

‡Department of Electronics and Electromagnetism, University of Seville, Seville 41012, Spain

§Department of Applied Physics 1, University of Seville, Seville 41012, Spain

***Abstract*—We report on the dual nature (capacitive and inductive) of the surface impedance of periodic graphene patches at low-terahertz frequencies. The transmission spectra of a graphene-dielectric stack shows that patterned graphene exhibits both the low-frequency (capacitive) passband of metal patch arrays and the higher-frequency (inductive) passband of metal aperture arrays in a single tunable configuration. The analysis is carried out using a transfer matrix approach with two-sided impedance boundary conditions, and the results are verified using full-wave numerical simulations.**

I. Introduction

In recent years, there has been considerable interest in the analysis of electromagnetic transmission through a variety of stacked periodic surfaces, due to their broad range of filter applications. For example, these include a stack of metal apertures (mesh-grids) at microwave [1] and infrared frequencies [2], a stack of metallic patch arrays at microwave frequencies [3], metal–dielectric and aperture/mesh–grid–dielectric stacks at optical frequencies [4], and more recently a stack of graphene sheets–dielectric layers at low-terahertz frequencies [5]. Also, various graphene metasurfaces have been designed at microwave and terahertz frequencies, with potential applications including filters, absorbers, and polarizers. Of particular interest is the low-terahertz band which has seen an increase in graphene applications, due to the low real part of its surface conductivity, forming a low-loss surface reactance.

In this work, we continue our study of transmission properties of a graphene-dielectric stack at low-terahertz frequencies [5], with the graphene monolayers replaced by 2-D periodic graphene patches (*metasurface*) with a typical geometry shown in Fig. 1. We demonstrate that because of its relatively long electronic mean-free path, graphene *metasurface* can exhibit both the low-frequency passband/stopband characteristics of capacitive periodic metallic patches and the complementary inductive nature of mesh-grid arrays (also exhibited by graphene monolayers at low-terahertz frequencies). The analysis is carried out with a transfer matrix approach for dielectric slabs and two-sided impedance boundary conditions applied at the graphene patch-dielectric interfaces. In all numerical results the full graphene intraband and interband conductivity is used [6], [7]. Because of the sub-wavelength dimensions, the patches are accurately represented by a closed-form analytical surface impedance expression, obtained as a quasi-dynamic solution of the scattering problem. The analytical results are validated against full-wave numerical simulations (HFSS) [8].

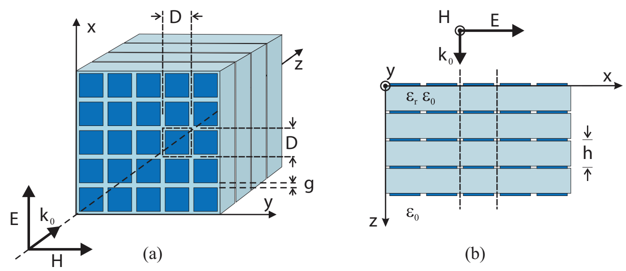

Fig. 1. Geometry of a stack of periodic graphene patches separated by dielectric slabs with a plane wave at normal incidence. (a) 3-D view and (b) cross-section view.

II. Theory

A plane wave with the electric field oriented along the x-direction is incident normally on a multilayer stack of graphene patch arrays with period D and gap g between the patches, separated by dielectric slabs with relative permittivity ε_r and thickness h, as shown in Fig. 1. It is assumed that the parameters of the patch arrays and that of the dielectric slabs in each layer are the same. For a patch array as depicted in Fig. 1, since the dimensions of the unit-cell are assumed to be sub-wavelength the patch array surface in each layer can be characterized by a homogeneous surface impedance Z_s [9],

$$\begin{aligned} Z_s &= Z_{s1} + Z_{s2} \\ &= \frac{D}{(D-g)\,\sigma} - j\frac{\pi}{2\omega\varepsilon_0\varepsilon_r^{qs} D \ln\left\{\csc\left(\frac{\pi g}{2D}\right)\right\}}, \end{aligned} \quad (1)$$

Authorized licensed use limited to: Universidad de Sevilla. Downloaded on May 29,2020 at 16:40:00 UTC from IEEE Xplore. Restrictions apply.

where σ is the conductivity of graphene given in Ref. [7], $\varepsilon_r^{qs} = \varepsilon_r$ for interior layers and $\varepsilon_r^{qs} = (\varepsilon_r + 1)/2$ for layers at the top and bottom interfaces. One can represent the above impedance as a series R-L-C circuit $Z_{s1} + Z_{s2}$, where the first impedance corresponds to the series R-L given by the product of the resistive-inductive surface impedance $Z_s = 1/\sigma$ and the geometric factor $D/(D-g)$. The second impedance Z_{s2} corresponds to a capacitive impedance associated with the patch geometry and background environment.

III. Results and Discussion

We consider a five-layer stack of graphene patch arrays with period D = 10 μm and gap g = 1 μm, separated by four dielectric slabs each with permittivity ε_r = 4 and thickness h = 10 μm. The analytical results for the transmissivity $|T|^2$ through the stack of graphene patches for different values of μ_c are depicted in Fig. 2. It can be observed that at low frequencies the graphene patch arrays (shown using the solid black lines) correspond to a capacitive surface impedance, and, consequently, the transmissivity behavior shows a passband starting from zero frequency and up to a certain upper frequency. As frequency increases the surface reactance becomes inductive and the transmissivity behavior becomes equal to that of the graphene sheets (dashed red curves). This is similar to the case of an array of apertures/mesh-grids (which are complementary to the metal patch case, and so have a complementary, i.e., inductive, nature). Clearly, the graphene patch arrays exhibit a combined effect similar to the transmission properties of (capacitive) metal patches at low frequencies and to the (inductive) aperture arrays or solid graphene sheets at higher frequencies. However, the transmission resonances in the first passband are not exactly the same as those of the metallic patches, particularly, the number of transmission resonances, due to the presence of losses in the graphene patches. Nevertheless, these transmission resonances are associated with the Fabry-Pérot resonances of the dielectric slabs loaded with the graphene patches.

IV. Conclusion

Graphene patches have been shown to have a dual (capacitive and inductive) nature at low-terahertz frequencies, which can be interpreted as the combination of the properties of a multilayer stack of metallic patches (capacitive), and the properties of a multilayer stack of contiguous graphene sheets (inductive due to large kinetic inductance of the material) in a single configuration of a multilayer stack of graphene patches. This bifunctional property of the graphene patches could be useful in the implementation and design of tunable planar filters.

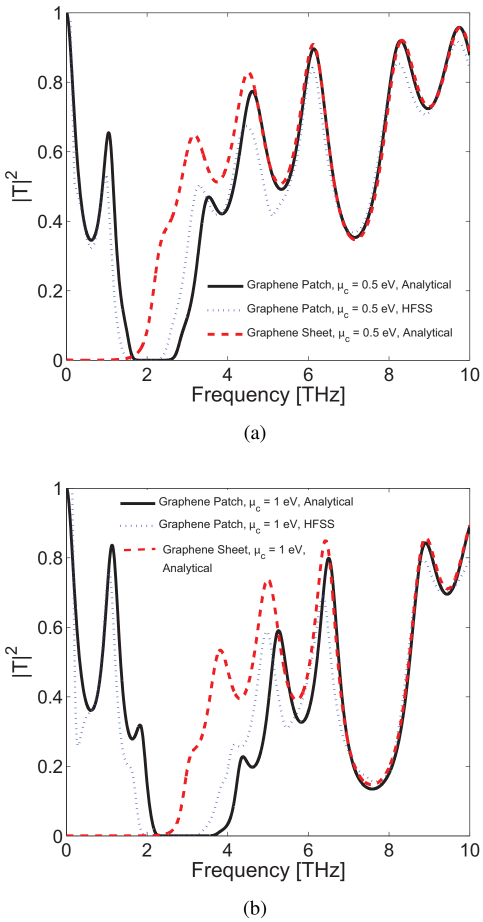

Fig. 2. Transmissivity of a five-layer stack of graphene patches and graphene sheets for (a) μ_c= 0.5 eV and (b) μ_c = 1 eV. The HFSS (dotted curves) and transfer matrix (solid curves) results are in good agreement.

References

[1] C. S. R. Kaipa, A. B. Yakovev, F. Medina, F. Mesa, C. A. M. Butler and A. P. Hibbins, "Circuit modeling of the transmissivity of the stacked two-dimensional metallic meshes", *Opt. Express*, vol. 18, p. 13309, June 2010.

[2] R. Ulrich, "Far-infrared properties of metallic mesh and its complementary structure", *Infrared Phys.*, vol. 7, pp. 37-55, 1967.

[3] C. S. R. Kaipa, A. B. Yakovev, F. Medina, and F. Mesa, "Transmission through stacked 2-D periodic distributions of square conducting patches", *J. Appl. Phys.*, vol. 109, p. 033101, Aug. 2012.

[4] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays", *Nature*, vol. 391, pp. 667-669, Feb. 1998.

[5] C. S. R. Kaipa, A. B. Yakovev, G. W. Hanson, Y. R. Padooru, F. Medina, and F. Mesa, "Enhanced transmission with a graphene-dielectric microstructure at low-terahertz frequencies", *Phys. Rev. B*, vol. 85, p. 245407, June 2012.

[6] V. P. Gusynin, S. G. Sharapov, and J. P. Carbotte, "Magneto-optical conductivity in graphene", *J. Phys. Condens. Matter*, vol. 19, p. 026222, 2007.

[7] G. W. Hanson, "Dyadic Green's functions and guided surface waves for a surface conductivity model of graphene", *J. Appl. Phys.*, vol. 103, p. 064302, 2008.

[8] HFSS: High Frequency Structure Simulator based on the Finite Element Method, ver. 12.0, Ansys Inc. [http://www.ansys.com].

[9] O. Luukkonen, C. Simovski, G. Grant, G. Goussetis, D. Lioubtchenko, A. Raisanen, and S. Tretyakov, "Simple and accurate analytical model of planar grids and high-impedance surfaces comprising metal strips or patches", *IEEE Trans. Antennas Propag.*, vol. 56, pp. 1624-1632, June 2008.

Authorized licensed use limited to: Universidad de Sevilla. Downloaded on May 29,2020 at 16:40:00 UTC from IEEE Xplore. Restrictions apply.