UC Irvine
UC Irvine Previously Published Works

Title

Graphene-based hyperbolic metamaterial at terahertz frequencies

Permalink

https://escholarship.org/uc/item/30b0x890

ISBN

9781557529725

Authors

Othman, Mohamed AK
Guclu, Caner
Capolino, Filippo

Publication Date

2013

DOI

10.1364/cleo_qels.2013.qtu3a.5

Copyright Information

Peer reviewed

Graphene-based Hyperbolic Metamaterial at Terahertz Frequencies

Mohamed A. K. Othman, Caner Guclu, and Filippo Capolino

Department of Electrical Engineering and Computer Science, University of California, Irvine, Irvine, CA, 92697, USA
f.capolino@uci.edu

Abstract: We introduce graphene-based hyperbolic metamaterial for terahertz frequencies. The LDOS as well as the scattered power by a microsphere at its surface are enhanced by orders of magnitude, and controlled via chemical potential.

OCIS codes: (160.3918) Metamaterials; (230.4170) Multilayers

1. Introduction

Hyperbolic metamaterials (HMs) are composite materials that exhibit hyperbolic iso-frequency wavevector dispersion, and allow propagation of waves in an extremely wide spatial spectrum in contrast to the much limited propagating spectrum in free space. This unusually wide propagating spectrum results in a huge increase of local density of states (LDOS) leading to applications such as super absorption of near fields and engineering the decay rate of molecules emission [1-3]. At optical frequencies, metal-dielectric multilayers are often employed for implementing HMs in which metals contribute to achieving an effective negative permittivity for transverse electric field. At far- and mid- infrared frequencies, we instead propose graphene, a two dimensional hexagonal lattice of carbon atoms, as a potential building block for multilayer HM designs where graphene acts as a low loss inductive layer similarly to metal layers at optical frequencies. Graphene shows negligible dispersion and its sheet conductivity can be effectively tuned with the adjustment of graphene layers' chemical potential by electrostatic biasing [4-6]. In this work, we model graphene-dielectric multilayers through a simple homogenization scheme for obtaining the effective medium parameters and then provide physical insight to the hyperbolic dispersion and its conditions. Then we utilize the multilayer metamaterial for enhancing the LDOS and the scattered power by a microsphere located on top of it, and show the tunability of the enhancement via controlling the chemical potential of graphene. The absorption mechanism of scattered field investigated in this study can lead to novel absorber designs when numerous scatterers are located on top of HM.

2. Hyperbolic dispersion in graphene-dielectric multilayer

Fig. 1(a) depicts a graphene-dielectric multilayer on top of a silicon substrate. An individual graphene sheet is characterized by the local isotropic sheet conductivity σ as described in [5]. The infinitesimally-thin graphene sheets are separated by dielectric layers with subwavelength thickness d (equal to the period), and relative permittivity $\varepsilon_d = 2.2$, for instance. When the period d is extremely subwavelength, the multilayer can be modeled as a homogenous uniaxial anisotropic medium with effective relative permittivity tensor $\underline{\varepsilon}_{eff} = (\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{y}}\hat{\mathbf{y}})\varepsilon_t + \hat{\mathbf{z}}\hat{\mathbf{z}}\varepsilon_z$, where $\varepsilon_t = \varepsilon_d - j\sigma/(\omega\varepsilon_0 d)$ and $\varepsilon_z = \varepsilon_d$. Using this effective medium approximation (EMA), the wavevector dispersion relation for TM^z waves is found as $k_z^2/\varepsilon_t + \left(k_x^2 + k_y^2\right)/\varepsilon_z = k_0^2$ where the wavevector is given by $\mathbf{k} = k_x\hat{\mathbf{x}} + k_y\hat{\mathbf{y}} + k_z\hat{\mathbf{z}}$ and k_0 is the wavenumber in free space. If each graphene sheet is adequately inductive, then we have $\mathrm{Re}\{\varepsilon_t\} < 0$ and $\varepsilon_z > 0$, eventually giving rise to the desired hyperbolic dispersion. We show in Fig. 1(b) the hyperbolic wavevector dispersion $\mathrm{Re}\{k_z\} - k_x$ at 5 THz obtained via EMA for a multilayer with $d = 100$ nm, where, for instance, we assume $k_y = 0$. As shown in Fig. 1(b), the spatial spectrum of TM waves with $|k_x| > \sqrt{\varepsilon_d} k_0$ can propagate inside the HM, in contrast to the limited propagating spectrum in free space with $|k_x| < k_0$. Thus evanescent waves in free space generated by sources close to the HM surface can couple to the propagating waves in the HM. Accordingly, this phenomenon results in a dramatic increase of LDOS by orders of magnitude, which in turn can be utilized for enhancing the spontaneous emission of emitters located near or in the HM. One can observe in Fig. 1(b) that the hyperbolic dispersion can be effectively controlled by the chemical potential, noting an advantage of using graphene as a building block of HMs at mid- and far-infrared. Although EMA provides physical insight to the propagation of waves in HMs, it fails to model the spectral features due the periodicity of the

multilayer, as shown in [1], hence in the following we employ the more accurate transfer-matrix method for modeling wave propagation in the multilayer.
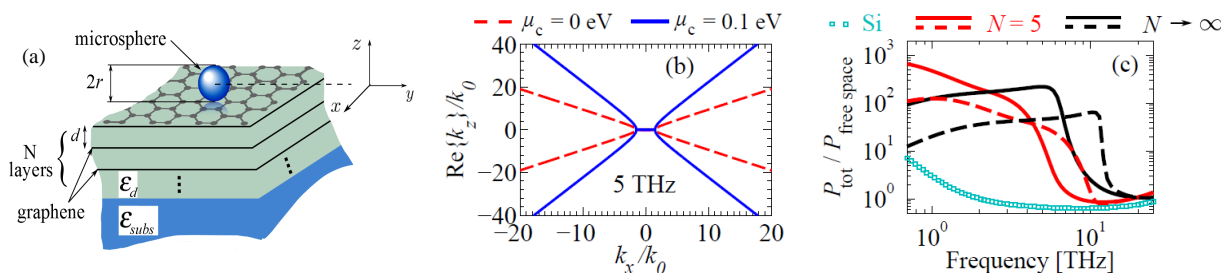

Fig. 1. (a) Multilayer graphene-dielectric metamaterial, (b) hyperbolic wavevector dispersion calculated based on EMA at 5 THz (assuming $k_y = 0$), (c) the enhancement of the scattered power $P_{tot} / P_{\text{free space}}$ by a silicon microsphere, for number of layers equal to $N = 5$ and $N \to \infty$, for two different chemical potential levels: 0 eV (dashed lines) and 0.1 eV (solid lines).

3. Enhancement of scattered power in the proximity of graphene-based HM

We show the enhancement of the power scattered by a small object in proximity of a graphene-based HM introduced above. Assume that a silicon microsphere on top of the graphene-based multilayer, as illustrated in Fig. 1(a), is excited by a plane wave propagating in the $-z$ direction. We model the silicon microsphere as a dipolar scatterer with given electric polarizability, similarly to what was done in [1].

In Fig.1(c) we show the enhancement of the total scattered power P_{tot}, by the microsphere over HM, as in Fig.1(a), with respect to the scattered power by the same microsphere in free space $P_{\text{free space}}$, following the procedure in [1]. We assume the silicon sphere radius $r = 1\,\mu m$, the layers period $d = 100\,nm$ and we consider $N = 5$ (red lines) and $N \to \infty$ (black lines), where N is the number of graphene-dielectric layers, for two different chemical potential levels: $\mu_c = 0\,eV$ (solid lines) and $\mu_c = 0.1\,eV$ (dashed lines). For comparison purposes we also report $P_{tot} / P_{\text{free space}}$ when the microsphere is directly located on top of bulk silicon. In general, multilayer cases result in much larger $P_{tot} / P_{\text{free space}}$ than the case with only the silicon substrate. For example, when $N = 5$ and $\mu_c = 0\,eV$, the scattered power enhancement is more than 10^2 till 3 THz, then it sharply decreases. On the other hand, the case $N \to \infty$ provides an enhancement of 10^2 till 6.5 THz. The frequency at which the ratio $P_{tot} / P_{\text{free space}}$ exhibits a sudden decrease corresponds to the transition from the hyperbolic dispersion to the elliptic one (~6.6 THz). Note that this transition frequency can be effectively tuned by the chemical potential, leading to several orders of magnitude control in the scattered power. For example, when $N \to \infty$, the transition occurs at 6.5 THz for $\mu_c = 0\,eV$ and at 11.5 THz for $\mu_c = 0.1\,eV$, thus we can have a significant control on the LDOS between these frequencies. Furthermore, we note that most of the scattered power is directed towards the HM side at the frequencies of hyperbolic dispersion; and that the power directed towards the HM exceeds the power directed upwards (in the $+z$ direction) by at least two orders of magnitude, not shown here for brevity.

4. Conclusion

We have introduced a tunable graphene-based HM at far- and mid-infrared frequencies, able to dramatically enhance the local density of states. We have demonstrated that the scattered power by a silicon microsphere on top of the multilayer HM is increased up to a factor of 10^3 and it can be efficiently controlled via the graphene's chemical potential. The proposed HM gives rise to novel tunable applications in terahertz and infrared regime.

5. References

[1] C. Guclu, S. Campione, and F. Capolino, "Hyperbolic metamaterial as super absorber for scattered fields generated at its surface," Phys. Rev. B, vol. **86**, p. 205130, 2012.
[2] Z. Jacob, I. I. Smolyaninov, and E. E. Narimanov, "Broadband Purcell effect: Radiative decay engineering with metamaterials," Appl. Phys. Lett., vol. **100**, p. 181105, 2012.
[3] J. Kim, V. Drachev, Z. Jacob, G. Naik, A. Boltasseva, E. Narimanov, and V. Shalaev, "Improving the radiative decay rate for dye molecules with hyperbolic metamaterials," Opt. Express, vol. **20**, pp. 8100-8116, 2012.
[4] P.-Y. Chen and A. Alu, "Atomically Thin Surface Cloak Using Graphene Monolayers," ACS Nano, vol. **5**, pp. 5855-5863, 2011.
[5] 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.
[6] A. Vakil and N. Engheta, "Transformation optics using graphene," Science, vol. **332**, pp. 1291-1294, 2011.