Atomic-scale mantle cloak using a graphene monolayer

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Abstract

Following our recent findings on making ultra-thin and moderately broadband mantle cloaks using metasurfaces, we investigate the possibility to apply these concepts to the thinnest possible cloak, composed of a single layer of graphene atoms, operating in the far-infrared spectrum. We show that an atomically thin graphene monolayer may drastically suppress the scattering of a given object, while at the same time preserving the moderately broad bandwidth of operation typical of mantle cloaks.

1. Introduction

One of the most exciting applications of metamaterials and metasurfaces consists in the possibility of suppressing the total scattering of a given object at the frequency of interest using suitably designed cloaking layer [1]-[3]. Recently, we have put forward the theoretical idea of using metasurfaces or frequency-selective surfaces to realize ultrathin mantle cloaks, with advantages of low cost, relatively broad bandwidth, and easiness of fabrication at microwaves and radio-frequencies using properly patterned metallic screens. Here we further extend the notion of surface cloaking to the THz and far-infrared spectrum using the thinnest possible cloaking surface: an atom-thick graphene monolayer [Fig. 1(a)], which may be characterized as an infinitesimally thin conductance (impedance) surface transverse to its surface. Graphene has intriguing reactive properties at THz frequencies, which may be used for tailoring the surface current, producing *anti-phase* scattered fields and thus achieving the effect of scattering cancellation. Different from naturally available 3D-crystalline graphite or diamond, artificially-synthesized graphene is effectively their 2D version, consisting of a planar atomic layer of carbon atoms bonded in a hexagonal structure [4]. The complex surface conductivity of a graphene monolayer $\sigma = \sigma' + j\sigma''$ may be obtained using Kubo formula [6]:

$$\sigma(\omega,\mu_c,\Gamma,T) = \frac{je^2(\omega - j2\Gamma)}{\pi\hbar^2}\left[\frac{1}{(\omega - j2\Gamma)^2}\int_0^\infty E\left(\frac{\partial f_d(E)}{\partial E} - \frac{\partial f_d(-E)}{\partial E}\right)dE - \int_0^\infty \frac{\partial f_d(-E) - \partial f_d(E)}{(\omega - j2\Gamma)^2 - 4(E/\hbar)^2}dE\right], \quad (1)$$

where $f_d = 1/(1+\exp[(\varepsilon - \mu_c)/(k_B T)])$ is the Fermi-Dirac distribution, E is energy, ω is the radian frequency, μ_c is the chemical potential, T is the temperature, e is the electron charge, $\hbar$ is the reduced Planck's constant, and Γ is the electron-phonon scattering rate (inverse of momentum relaxation time τ^{-1}), due to the carrier intraband scattering. For simplicity, here we use a constant value of $\tau = 10^{-12} s$, which is consistent with the ballistic transport features of graphene, whose mean free path was measured to be up to 500nm at room temperature and larger than 4 μm at low temperature. The first term in (1) corresponds to the intraband electron-photon scattering process, which can be evaluated as

$$\sigma_{intra} = -j\frac{e^2 K_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left[\frac{\mu_c}{K_B T} + 2\ln\left(\exp\left(-\frac{\mu_c}{K_B T}\right) + 1\right)\right], \quad (2)$$

where the real part of σ_{intra} contributes to the energy absorption. The second term in (1) corresponds to the direct interband electron transition and, for $\hbar\omega, |\mu_c| \gg k_B T$, it can be approximated as [6]:

$$\sigma_{inter} = -j\frac{e^2}{4\pi\hbar}\ln\left[\frac{2|\mu_c| - \hbar(\omega - j2\Gamma)}{2|\mu_c| + \hbar(\omega - j2\Gamma)}\right]. \tag{3}$$

From (2)-(3), it is found that the surface conductivity approximates to $e^2/(4\hbar)$ when $\hbar\omega \gg 2|\mu_c|$ (visible region), consistent with recent experiments. One the other hand, at relatively low frequencies (THz and far-infrared region), the intraband contribution may dominate and the ballistic transport may render graphene a low-loss inductive surface, which plays an analogous role as reactive metasurfaces and frequency-selective surfaces at radio frequencies. More interestingly, the surface conductivity of graphene is sensitively dependent on the chemical potential (Fermi energy), which is largely tuned by electrostatic gating (gate voltage), doping profile (density of type of carriers) and chemical post-treatment (i.e. surface carboxylation and surface thiolation [5]). Furthermore, the chemical potential of graphene is determined by the carrier density as

$$n_s = \frac{2}{\pi(\hbar v_F)^2}\int_0^\infty E\left[f_d(E-\mu_c) - f_d(E+\mu_c)\right]dE \ , \tag{4}$$

implying that an ultrathin and dynamically tunable *mantle cloak* may be made of graphene and integrated circuitry. For example, in a bottom-gate configuration the graphene monolayer may be grown on an insulating silicon dioxide (SiO_2) thin layer with $\varepsilon_{ox} = 3.9$, and an applied voltage on the polysilicon gate may tune in real-time the graphene properties. In this scenario, the 2-D surface charge density is controlled by the displacement current on either side of a charged surface $D_n = \varepsilon_{ox} V_g / d_{ox} = e n_s / 2$. Typically, the chemical potential of graphene may be tuned from -1 eV to 1 eV.

2. Graphene mantle cloaking

In order to show the potential of graphene for cloaking we start from a simple 1-D scenario in which we want to suppress the reflection from a planar dielectric slab at the desired frequency. Figure 1(a) illustrates the proposed graphene cloak: a graphene monolayer with $\mu_c = 0.128$ eV ($\tau = 10^{-12}$s and room temperature 300 K are assumed throughout this study) supported by a SiO_2 film on top of the dielectric slab to be cloaked, with thickness $d = \lambda_0/5$ and relative permittivity $\varepsilon_d = 5$ (i.e. MgF or KBr). Figure 1(b) shows the power reflection of cloaked and uncloaked dielectric slabs versus the frequency of operation, calculated using analytical results based on a transmission-line model. The cloak was designed to suppress the scattering at $f_0 = 3$ THz ($\hbar\omega_0 = 12.3$ meV). It is surprising that an atomically thin graphene layer can provide a strong scattering suppression equivalent to the one of an ideal lossless mantle cloak with surface reactance $X_s = 1248\,\Omega$. The slight difference between the graphene cloaking (green line) and an ideal reactive surface (dashed line) is due to the material dispersion and absorption contributed by the real part of the intraband scattering, which depends on several factors, including impurities, defects, and dangling bonds at the surface of SiO_2. We should specifically notice that a polysilicon gate can be architectured behind the SiO_2 layer, thus switching *ON/OFF* this graphene cloak, possibly making this performance externally tunable.

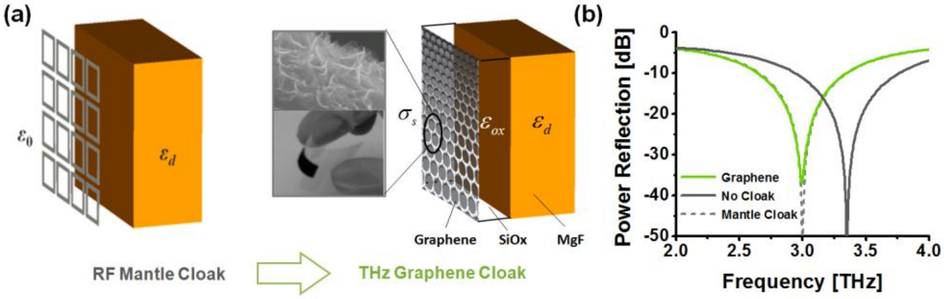

Fig. 1: (a) Illustration of a graphene cloak (the inset shows graphene flakes obtained using MPCVD). (b) Power reflection for a $\lambda_0/5-$slab of MgF or KBr ($\varepsilon_d \sim 5$) (1) with ideal mantle cloak $X_s = 1248\,\Omega$ (gray dashed), (2) with graphene on a $1.56\,\mu m$ SiO_2 film (green dashed), and (3) without cloak (gray solid).

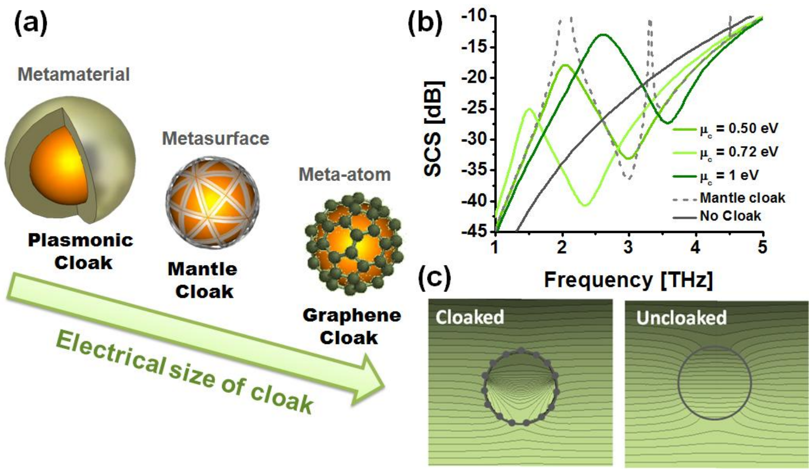

Fig. 2: (a) Evolution of scattering-cancellation-based cloaks. (b) Total SCS of a dielectric sphere with diameter $D = \lambda_0 / 5$ and $\varepsilon_d = 5$, with (1) lossless mantle cloak ($X_s = 222.5\Omega$) (gray dash), (2) graphene cloak with different chemical potential (green), and (3) without (gray solid) cloak. (c) Uniform phase distribution of H field on the E plane for the graphene-coated object at the frequency of operation, compared with the uncloaked one.

Having proven that graphene is an excellent candidate to suppress the scattering from a planar object at the desired frequency, we extend the same concept to a 3-D scenario. Figure 2(a) shows the evolution of scattering-cancellation-based cloaks and its corresponding size reduction, from the bulk plasmonic metamaterial [1] to an atomically thin graphene-wrapped fullerene cloak considered here. Figures 2(b) and 2(c) respectively show the total scattering cross section (SCS) and phase distribution of magnetic field on the E plane for a dielectric sphere with diameter $D = \lambda_0 / 5$ and relative permittivity $\varepsilon_d = 5$, coated by graphene monolayers with chemical potential μ_c varied from $0.5\,\text{eV}$ to $1\,\text{eV}$. These results are obtained using Mie-Lorenz theory [1],[3]. We see in Fig. 2(b) how the scattering suppression is evident at the frequency of operation $f_0 = 3\,\text{THz}$ using this graphene coating with $\mu_c = 0.72\,\text{eV}$. Comparing with an ideal lossless mantle cloak, a slight difference is due to material dispersion and absorption. It is striking to see in Fig. 2(b), that the frequency of operation can be tuned over a wide range of frequencies by varying the chemical potential.

3. Conclusions

We have proposed here the realization of an atomic-scale surface cloak using graphene at infrared frequencies. We have applied Lorenz-Mie theory using the surface conductivity (impedance) of graphene, as obtained from microscopic quantum transport model. Our results show great potentials in the THz gap of scattering-cancellation-based cloaks, where metasurfaces and metamaterials, available at radio-frequencies, are difficult to be made and, unfortunately, natural plasmonic materials, which mostly exist at near-IR and visible frequencies, may completely lose their functionality in the THz band.

References

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