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Cloaking of Cylindrical Objects with Graphene-Metasurface Structures for Low-Terahertz Applications

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Abstract—**It is a common practice for most of the theoretical studies to assume an ultra-high mobility and/or high value of chemical potential for graphene to realize its various functionalities such as perfect absorption, transmission, cloaking, etc. However, it is very difficult to actually fabricate such nano-patterned graphene structure, thus compromising its practical performance, despite the appeal of theoretical predictions. In this paper, we present a graphene-metasurface structure, taking inspiration from the design in 'X. Wang and S. A. Tretyakov, IEEE Trans. Antenna Propag., vol. 67, no. 6, 2019'. When this specific metasurface is enveloped around cylindrical objects, the scattering width of the object reduces noticeably, thereby implying the cloaking effect. Our design utilizes extremely low values for mobility and chemical potential of graphene, making it highly desirable for practical applications.**

I. Introduction

The idea of invisibility has enthralled humanity for centuries, naturally making it an object of utmost interest to the scientific community. As such, an astounding amount of research has been dedicated to achieving electromagnetic invisibility and several approaches have been reported over the past couple of decades. Some of the widely used methodologies include transformation optics, conformal mapping, plasmonic cloaking, etc. There are certain drawbacks involved with these methods though, such as use of complex bulk volumetric metamaterials and a very high refractive index profiles for the cloak. Consequently, a different technique, based on the concept of mantle cloaking, was recently proposed to make an object electromagnetically invisible at microwave frequencies [1]. However, implementation of the mantle cloak metasurface becomes tedious at higher frequencies such as terahertz (THz) and infrared (IR), due to the increase of losses in metallic elements. Accordingly, one of the favorable materials utilized to implement the mantle cloaking method at low-THz frequencies is graphene.

Graphene, an allotrope of carbon, consists of a single layer of sp2-bonded carbon atoms arranged in a 2D honeycomb lattice. Graphene gained popularity due to its exceptionally high tensile strength, stable thermal and mechanical properties, optical transparency and special electronic properties, among others. The surface conductivity of graphene, based on the Kubo formula [2], plays a major role in its analysis for numerous electromagnetic applications. The functionality of graphene is further enriched by its inherent plasmonic-like properties in the THz and IR spectrum since plasmonic effects are associated to cloaking and invisibility. The anomalous polarization properties of graphene seem naturally inclined to manipulate the scattering of objects. In this regard, a mantle cloak consisting of a simple, graphene monolayer is demonstrated to enable bistatic scattering reduction for dielectric objects in the THz spectrum [3]. The obvious disadvantage here is the intrinsically inductive nature of a graphene monolayer in the low-THz range, rendering it unsuitable to cloak conducting objects, as it requires a capacitive surface impedance. Thus, graphene nano-patches, possessing a dual capacitive/inductive surface reactance at low-THz frequencies is introduced in [4]. It is seen that both dielectric and conducting objects are satisfactorily cloaked by properly tuning the surface impedance of graphene metasurface. The mantle cloaking method using graphene metasurface is further extended to cloak elliptical structures, which possess non-symmetric geometries unlike circular cylinders [5]. In the aforementioned papers, graphene with extremely high mobility (more than 20000 $cm^2V^{-1}s^{-1}$) is utilized. However, the typically reported mobility of CVD graphene is only around 1000 $cm^2V^{-1}s^{-1}$ owing to the impurities and defects introduced during graphene growth and transfer, which is unavoidable. To compensate for the poor carrier mobility, many experimental works resort to increasing the chemical potential of graphene ($\approx$ 1 eV), but this may disrupt the band structure of graphene, compromising its tunability. In [6], a novel structure, positioning a graphene sheet on a specific metasurface substrate, is presented by X. Wang et al. It shows that a perfect and strongly tunable absorption is always possible even in very weakly doped graphene, without strict requirements of the carrier mobility.

In this paper, we make use of a graphene-metasurface structure inspired by the design in [6], to facilitate cloaking of PEC (perfect electrical conductor) cylindrical objects (circular and elliptical) at low THz frequency. Our metasurface design (see Fig.1) employs a graphene monolayer with very low mobility (2000 $cm^2V^{-1}s^{-1}$), corresponding to a low value of scattering time $\tau = 20$ fs and a low chemical potential $E_F = 0.1$ eV, placed on a substrate embedded with periodic arrays of metallic patches. By wrapping this structure around cylindrical objects and properly choosing the structural parameters, a considerable amount of scattering cancellation is observed, thus providing the cloaking effect to the objects.

II. Graphene Metasurface Cloaks

The schematic of the cloak designed with a graphene-metasurface is illustrated in Fig. 1(a). As seen in the figure, an array of thin metallic patches (period 'D' and gap 'g') is placed periodically on a dielectric substrate. The period of this array is kept small compared to the wavelength, to avoid the propagating Floquet modes. The graphene monolayer sheet is then transferred directly onto this metallic patch array. Now, an interesting phenomenon occurs as a direct result of this; in all the graphene-metal contact areas, graphene gets shorted by the highly conductive metal, making the effective part of graphene which is not shorted, to resemble a fishnet-like pattern (see Fig. 1(b)). This patterned graphene-metasurface is then wrapped around PEC cylinders (refer to Fig. 1(c) for a circular cylinder and Fig. 1(d) for an elliptical cylinder) to obtain scattering cancellation at a desired frequency.

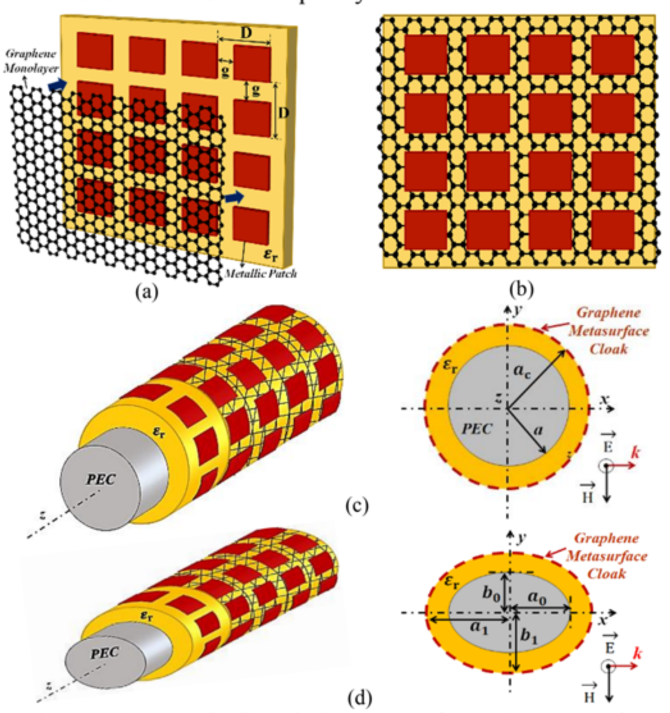

Figure 1. (a) Schematic, (b) equivalent structure for graphene-metasurface cloak and cloaked configurations for (c) circular PEC cylinder and (d) elliptical PEC cylinder.

All the geometrical dimensions mentioned in this paper are measured in μm. The structural parameters for the circular PEC cylinder (Fig. 1(c)) are: $a_c = 11$, $a = 10$, $\varepsilon_r = 16$, $D = 15$ and $g = 1.75$; whereas for the elliptical PEC cylinder (Fig. 1(d)) are: $a_0 = 10.04$, $b_0 = 6.67$, $a_1 = 12.5$, $b_1 = 10$, $\varepsilon_r = 10$, $D = 14.18$ and $g = 2.25$. It is evident from the Figs. 2 and 3 that the graphene-metasurface cloaks substantially reduce the scattering width of the circular and elliptical cylinders, respectively, which in turn facilitates the desired cloaking of the cylindrical objects. Figures 2(a) and 3(a) provide a comparison of plots for increasing values of the chemical potential at $\tau = 20$ fs (corresponds to a low mobility value of 2000 $\mathrm{cm^2V^{-1}s^{-1}}$) for the cloaked cylinders. Note that a considerable decrease in the scattering width is observed even at a very low chemical potential of $E_F = \mu_c = 0.1$ eV. In addition to this, we have also illustrated the frequency tunability feature of our design at $\tau = 200$ fs (corroborated by Fig. 2(b) for circular and Fig. 3(b) for elliptical PEC cylinders) by varying the chemical potentials.

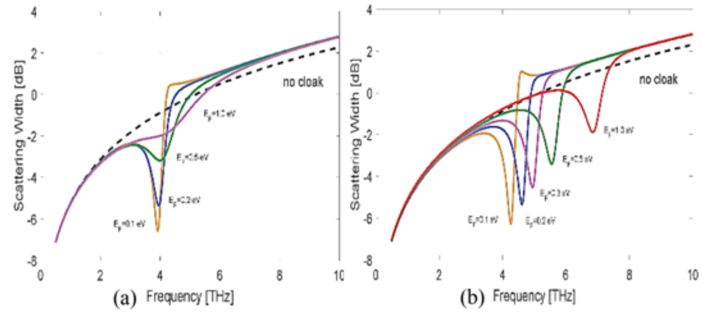

Figure 2. Analytical scattering widths for the circular PEC cylinder at different chemical potentials for (a) $\tau = 20$ fs, (b) $\tau = 200$ fs.

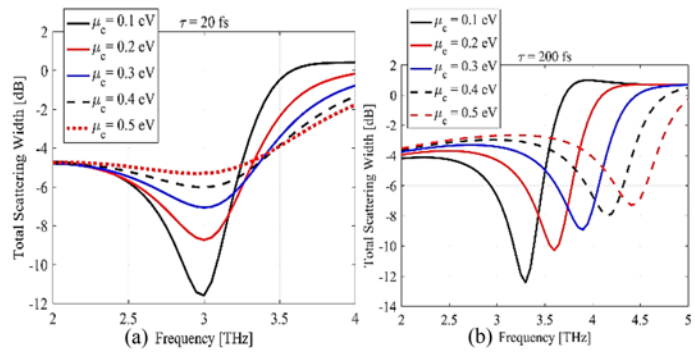

Figure 3. Analytical scattering widths for the elliptical PEC cylinder at different chemical potentials for (a) $\tau = 20$ fs, (b) $\tau = 200$ fs.

III. Conclusion

In this paper, we have presented a unique construct for cloaking of circular and elliptical PEC cylinders. This design involves the use of graphene-metasurface cloaks, which adopts the mantle cloaking approach to bring about reduction in the scattering width of the cylindrical objects. In particular, we successfully demonstrate the cloaking effect even with the use of low quality graphene, exemplifying the potency of our design for practical applications.

Acknowledgment

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