Electrically tunable mantle cloaking utilizing graphene metasurface for oblique incidence

Research highlight 1

Research highlight 2

Tunable dual polarized cloaking with graphene strips metasurface

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Abstract

A metasurface based on graphene strips is proposed to cloak a dielectric cylinder under illumination of TE and TM polarized incident waves. According to the in plane effective surface impedance tensor for the considered metasurface and the required surface impedance for achieving invisibility under TE and TM polarized impinging waves, the geometrical parameters of the covering structure and characteristics of graphene are obtained. Numerical simulations show radar cross section reduction for TE and TM polarizations. Furthermore, the introduced metasurface is able to cloak the cylinder for incoming waves with circular polarization. In addition, it is shown that by properly adjusting the chemical potential of graphene, the required surface impedance to have cloaking for the two polarizations in other frequencies can also be achieved, this results in a tunable dual polarized cloaking.

Keywords: Anisotropic Metasurface, Graphene, Invisibility, Mantle Cloaking.

1. Introduction

Recently, there is a significant interest in cloaking techniques which make objects undetectable in a frequency range (1)-(9). Different approaches have been proposed for cloaking purpose such as transformation optics (10), (11) and plasmonic cloaking (12), (13). Mantle cloaking is one of the most effective methods showing notable performance and comfortable realization (14), (15). Since in a mantle cloak, the object is covered by a thin metasurface, the proposed cloaking devices have low profile and weight and good flexibility to be formed in a desired shape (16), (17). At microwave frequencies, patterned metallic sheets have been used as the covering metasurface to achieve the required surface impedance aimed at cancelling the scattered field of the object by producing an anti-phase scattered wave (18), (19).

Many studies have been done to make dielectric and conducting cylinders invisible especially for TM_z polarized incident wave propagating in the X direction. For example in (20), single and multiple dielectric cylinders have been investigated. Covering the cylinders by width-modulated microstrip line based mantle cloak has significantly reduced their scattering. In (21), radar cross section (RCS) of conducting cylinders have been remarkably suppressed by coating them with patterned metallic surfaces. Some researches have been devoted to increase cloaking bandwidth. For instance in (22) and (23), metasurfaces based on disks with different sizes have been utilized to cover dielectric cylinders and spheres, respectively in order to create resonances in different frequencies leading to a broad bandwidth.

Graphene is a single layer of carbon atoms. It has attracted significant attention because of its interesting properties (24). One of the most important characteristics of graphene is its tunability which results in designing various tunable and reconfigurable devices in electronics and photonics (25), (26) such as: switches and logic gates (27)-(29), reconfigurable lenses (30), (31), tunable polarization converters (32), (33) and tunable absorbers (34). Tunable mantle cloaking can also be achieved with graphene monolayers or patterned graphene metasurfaces. In (35), scattering of a dielectric cylinder under illumination of TMz polarized oblique incidence has been reduced using a graphene monolayer. Graphene monolayer is inductive in terahertz range and therefore can not cloake conducting cylinders which need capacitive surface impedances (36). Instead in (24), a nonostructured graphene metasurface with negative reactance has covered a conducting cylinder in order to make it invisible. In the both cases, frequency of cloaking has been tuned by changing the chemical potential of graphene.

The majority of researches related to cloaking have been done with consideration of TM_z polarized impinging wave propagating in the X direction. This is because this incident wave produce more pronounced scattered fields compared to TE polarized impinging wave (37). However, the scattered field from a TE_z illuminated wave is not negligible and in some applications it is necessary to cloak a cylinder under illumination of a TE_z polarized wave. Dual polarized mantle cloak can be a good choice to reduce scattering from a cylinder for both TE and TM polarizations. To achieve mantle cloaking for TE and TM polarizations, an anisotropic metasurface should be designed.

With an anisotropic metasurface, one can independently control the surface impedance in each direction, leading to achieve the required values of it for both polarizations in a given frequency (38). We propose graphene strips as a covering metasurface whose surface impedance tensor has been derived in (39). In (38), dual polarized cloaking has been achieved in a fixed frequency. However, in our proposed structure, the frequency of dual polarized cloaking can be tuned by adjusting the chemical potential of graphene.

The paper includes four sections. In section 2 the metasurface to achieve the considered goal is designed. In section 3, numerical results of radar cross section (RCS) for uncloaked and cloaked cylinders are illustrated proving scattering reduction for TE, TM and circular polarizations. Furthermore, tunability of the proposed structure is verified. Section 4 concludes the paper.

2. Designing an anisotropic metasurface based on graphene strips

Figure 1 shows a dielectric cylinder under illumination of TE and TM polarized plane waves. The Z component of electric and magnetic fields for TM and TE polarizations can be written in terms of Bessel and Hankel functions as follows, respectively (40):

$$E_i = \hat{z}\ E_0 \sum_{n=-\infty}^{\infty} j^{-n} J_n(\beta_0 r)\ e^{jn\phi} \tag{1}$$

$$E_s = \hat{z}\ E_0 \sum_{n=-\infty}^{\infty} j^{-n}\ c_{n(TM)}\ H_n^{(2)}(\beta_0 r)\ e^{jn\phi} \tag{2}$$

$$E_{in} = \hat{z}\ E_0 \sum_{n=-\infty}^{\infty} j^{-n}\ a_{n(TM)}\ J_n(\beta r)\ e^{jn\phi} \tag{3}$$

$$H_i = \hat{z}\ E_0 \sum_{n=-\infty}^{\infty} j^{-n} J_n(\beta_0 r)\ e^{jn\phi} \tag{4}$$

$$H_s = \hat{z}\ E_0 \sum_{n=-\infty}^{\infty} j^{-n}\ c_{n(TE)}\ H_n^{(2)}(\beta_0 r)\ e^{jn\phi} \tag{5}$$

$$H_{in} = \hat{z}\ E_0 \sum_{n=-\infty}^{\infty} j^{-n}\ a_{n(TE)}\ J_n(\beta r)\ e^{jn\phi} \tag{6}$$

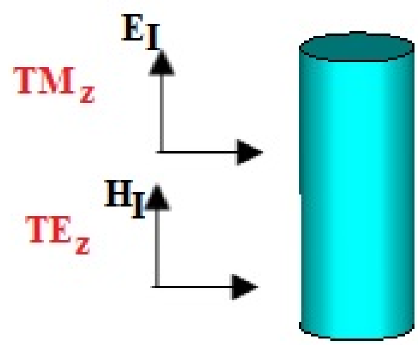


Figure 1: Dielectric cylinder under TE and TM polarized incident wave

where J_n and $H_n^{(2)}$ are Bessel function of the first type and Hankel function of the second type, respectively. β_0 and β are propagation constants in the air and in the cylinder with defined relative permitTivity. Subscripts i, s and in represent incident field, scattered field and the field inside the object, respectively.

Applying boundary conditions of continuity of tangential electric field and discontinuity of magnetic field as a result of introducing the covering metasurface, and by considering the following relations:

$$H_{\phi(TM)} = \frac{1}{jw\mu}\frac{\partial E_{z(TM)}}{\partial r} \tag{7}$$

$$E_{\phi(TE)} = -\frac{1}{jw\epsilon}\frac{\partial H_{z(TE)}}{\partial r} \tag{8}$$

one can achieve scattering coefficients for the two polarizations. By equating the scattering coefficients to zero, the required surface impedances for the both polarizations are obtained.

In (38), it has been shown that the required surface impedance to achieve cloaking are different for TE and TM polarizations and invisibility can not be achieved for the two polarizations simultaneously at the same centre frequency with an isotropic metasurface. Therefore, an anisotropic metasurface should be designed whose surface impedance is set in each direction, independently. Graphene strips as the covering metasurface are considered for this purpose. The proposed structure is shown in Fig. 2. For the planar configuration it exhibits a surface impedance tensor as follows (41):

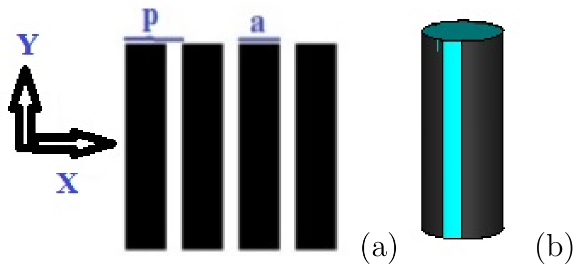


Figure 2: (a) Structure of graphene strips, (b) A dielectric cylinder coated by graphene strips.

$$z_{yy} = z_s \; \frac{p}{a} \tag{9}$$

$$z_{xx} = z_s \; \frac{a}{p} + \frac{g}{p \; \sigma_c} \tag{10}$$

$$\sigma_c = \frac{j\omega\epsilon_0 p}{\pi} \; \ln\csc(\frac{\pi g}{2p}) \tag{11}$$

where p and a are periodicity and size of the strips, respectively, $g = p - a$ is the gap distance between two strips and z_s is the surface impedance of graphene. Surface conductivity of graphene which is revers of surface impedance is modeled by Kuba formula (42), (43). It is the sum of *intra* and *inter* conductivity:

$$\sigma_{intra} = -j\frac{K_B e^2 T}{\pi\hbar^2(w - 2j\tau^{-1})}[\frac{\mu_c}{K_B T} + 2\ln(e^{-\frac{\mu_c}{K_B T}} + 1)] \tag{12}$$

$$\sigma_{inter} = \frac{je^2}{4\pi\hbar} \ln\left(\frac{2|\mu_c| - (w - j\tau^{-1})\hbar}{2|\mu_c| + (w - j\tau^{-1})\hbar}\right) \tag{13}$$

where K_B is Boltzmanns constant, e is the electron charge, μ_c is the chemical potential, τ is the relaxation time, T is the temperature and $\hbar$ is the reduced Plank′s constant. The chemical potential of graphene can be adjusted by applying different bias voltages resulting in different surface impedances.

To design the proposed metasurface the following steps have been followed:

1. Obtaining the required surface impedance of the metasurface (z_{yy}) for achieving invisibility for TM_z polarization, using the formula (14) from (14) which is useful for infinite cylinder:

$$z_{yy} = \frac{2}{\omega a_1 \epsilon_0 (\epsilon_r - 1)} \tag{14}$$

where a_1 and ϵ_r are radius and relative permittivity of the cylinder. In our study, for finite cylinder optimization is needed.

2. Obtaining the required surface impedance of the metasurface (z_{xx}) for achieving invisibility for TE_z polarization. There is no closed form expression for cloaking a cylinder under illumination of TE polarization (38). the required surface impedance can be achieved by optimization.

3. Choosing the characteristics of graphene and obtaining its surface impedance (z_s).

4. Achieving the ratio of p/a using eq. (9).

5. By knowing the ratio of g/p from p/a, σ_c is achieved using eq. (10).

6. The periodicity of the strips (p) will be obtained by eq. (11) and by knowing the ratio of p/a ,the width of srtips (a) is also obtained.

3. Results and Discussions

Here we aim to cloak a dielectric cylinder with radius of $a_1 = 10\mu m$ and relative permittivity of $\epsilon_r = 4$ for TE and TM polarizations at a reference frequency of $f_r = 2.5$THz. The required surface reactance to achieve invisibility for TE and TM polarizations are obtained as: 234Ω and 404Ω, respectively. We choose the characteristic of graphene as: $\mu_c = 0.4$eV, $\tau = 1$ps and $T = 300$K resulting in $z_s = j333.7\Omega$. Following the procedure in the previous section we obtain a=19.2μm and p=24μm. It is worth noting that because the number of strips covering the cylinder should be integer and the obtained periodicity and size of the stirps lead to a non integer number of strips, optimization is needed. The optimized values for z_{xx} and z_{yy} is illustrated in Fig. 3 which at 2.5THz are very close to ones which have been achieved analytically.

Figure 4 shows RCS of uncloaked and cloaked cylinders for TM and TE polarizations illustrating simultaneous scattering reduction at 2.5THz for the two considered polarizations. It can also be seen that scattering reduction for TM polarization is much more than that of polarization. We refer to (37) which provides an explanation for the reason of this difference. It is illustrated that for TM polarization, the scattering related to the first harmonic is more pronounced than the other harmonics and by canceling the scattering of the first harmonic, significant RCS reduction can be achieved. However

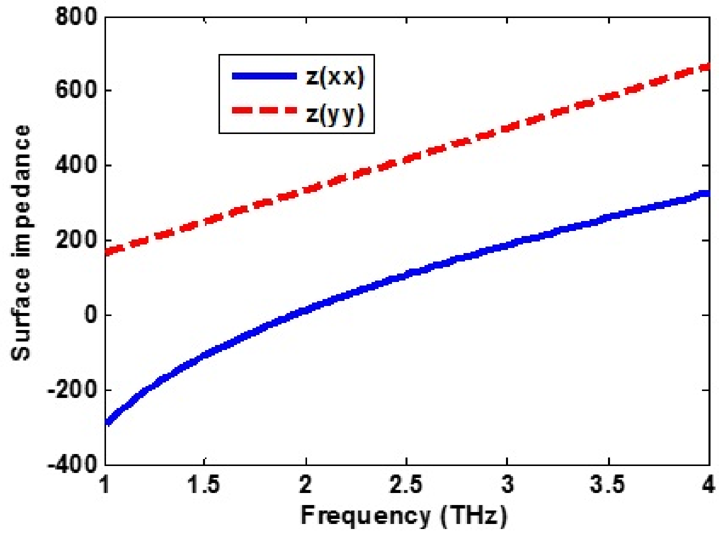


Figure 3: The surface impedance tensor elements z_{xx} and z_{yy} for the optimized parameters of the proposed structure.

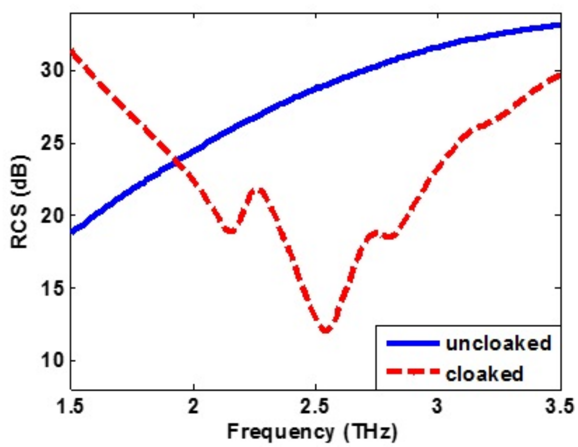
for TE polarization, the first three harmonics have very similar amplitude and by canceling one harmonic, the other harmonics still play their role in the scattered field.

We exploit the extraordinary property of graphene to achieve tunable invisibility by changing chemical potential of graphene. Figure 5(a) and (b) shows radar cross section of the cloaked cylinder with graphene strips for different chemical potentials. The figure indicates a shift in frequency of cloaking to 2.1THz and 2.8THz with chemical potential of 0.25ev and 0.55ev, respectively.

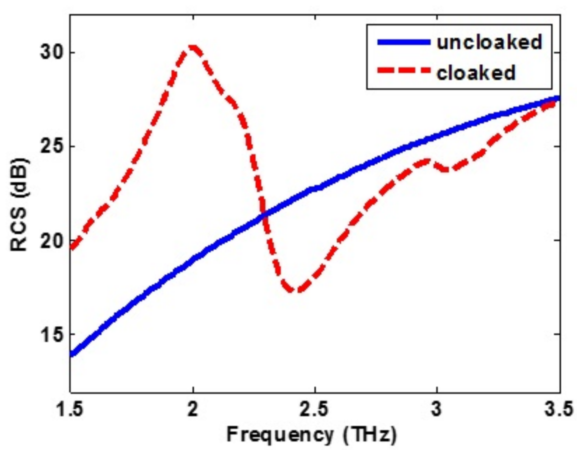
Distribution of the electric field related to TE and TM polarizations for uncloaked and cloaked cylinders is shown in Fig. 6 which depicts that covering the cylinder by the designed graphene strips reduces scattering for the two polarizations so that the incident plane waves pass the object with a small perturbation.

Numerical results obtained by two commercial softwares CST Microwave Studio and HFSS confirm RCS reduction for TM polarization in $\phi = 0°$ plane and for TE polarization in plane $\theta = 0°$ in polar system are shown in Fig. 7. Furthermore, the results from the two softwares show good agreement.

The designed grphene srtips can operate as a covering metasurface for invisibility purpose also for circular polarization. This claim is proved in

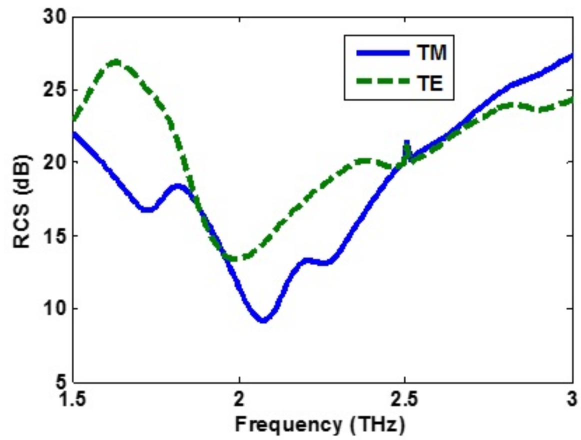


(a)

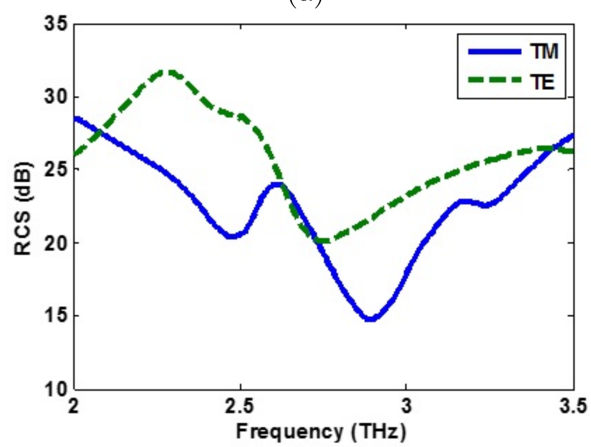


(b)

Figure 4: RCS of uncloaked and cloaked cylinders with anisotropic metasurface for (a)TM polarized incident wave and (b)TE polarized incident wave



(a)



(b)

Figure 5: RCS of uncloaked and cloaked cylinders with anisotropic metasurface for TE and TM polarizations with the chemical potential of (a) 0.25ev and (b) 0.55ev.

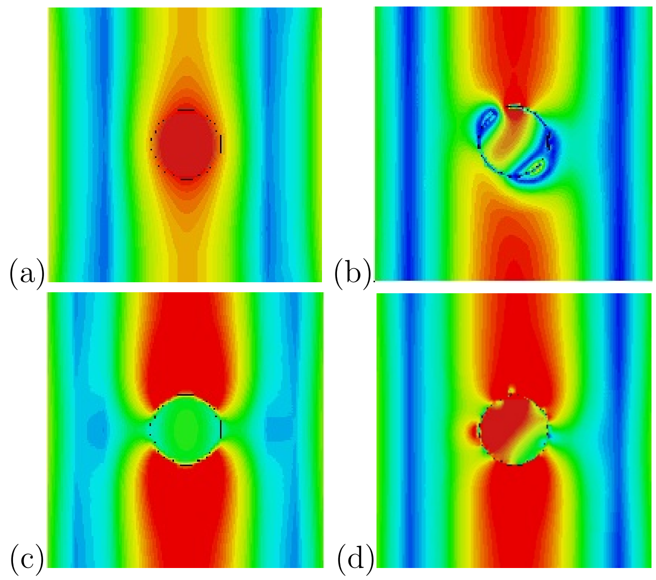


Figure 6: Electric field distribution for the (a) uncloaked and (b) cloaked cylinders for TM polarization and (c) uncloaked and (d) cloaked cylinders for TE polarization

Fig. 8 which shows scattering reduction for circular polarization at 2.5THz.

4. Conclusion

In this paper, mantle cloaking of a dielectric cylinder under TE and TM polarizations has been investigated. An anisotropic metarurface based on graphene strips has been considered. The proposed covering structure and characteristics of graphene have been designed so that the required surface impedance tensor for achieving invisibility for both polarizations has been obtained. Scattered wave from the cylinder under illumination of circularly polarized wave can also decreases with the designed metasurface. Furthermore, by properly changing the chemical potential of graphene, tunable mantle cloaking has been achieved.

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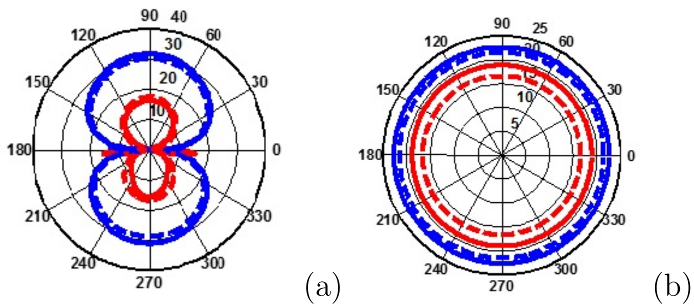

Figure 7: Polar plot of RCS related to cloaked and uncloaked cylinders for (a) TM polarized incident wave in $\phi = 0°$ plane and for (b)TE polarized incident wave in $\theta = 0°$ plane. Blue: uncloaked, Red: cloaked, Dashed line: CST, Solid line: HFSS

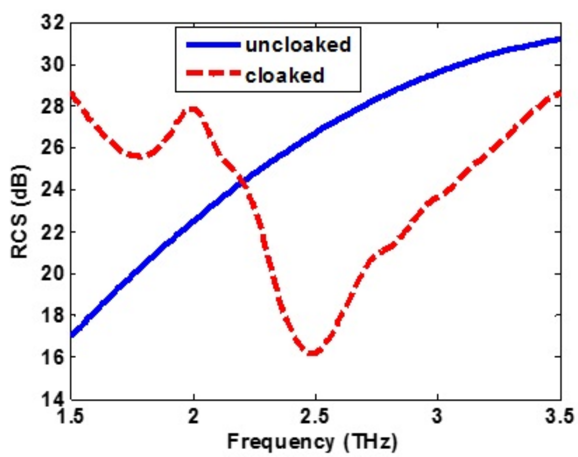

Figure 8: RCS of cloaked and uncloaked cylinders under illumination of circular polarized waves.

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