Conformal and polarization adjustable cloaking metasurface utilizing graphene with low radar cross section for terahertz applications

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Abstract
Metamaterials with precisely chosen negative permittivity and permeability are preferable to cloak the target without scattering. In this work, a metasurface is designed by using graphene as conducting material to cloak a target cylinder under the instancing of TM and TE polarized waves in terahertz range of frequencies. The electric sheet impedance and magnetic sheet admittance played the crucial role to achieve the cloaking with good scattering reduction. Various incident angles are simulated and analyzed for obtaining the good radar cross section (RCS). The proposed metasurface resonates at three different frequencies in terahertz range of 3.8 THz, 9 THz and 13.8 THz and the bandwidth of the three resonating frequencies are 3.5–4.58 THZ, 8.8–9.5 THz and 13–14.98 THz respectively. In addition, the parametric analysis of chemical potential and relaxation time shows effective results in scattering reduction. The monostatic and bistatic RCS are simulated, which results high scattering reduction under different polarizations of different incident angles. The proposed structure is adjustable to various angle of incidence with less than 40 dB scattering reduction for various selected frequencies.

Keywords Radar cross section · Chemical potential · Relaxation time · Terahertz

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1 Introduction

Recently, the researchers concentrated highly on the electromagnetic (EM) cloak, which has become an existing topic and leading to an interesting phenomena and applications such as communications (Si and Lv 2008; Vellucci et al. 2017; Tsakmakidis et al. 2019), invisibility (Choudhury and Jha 2013; Greenleaf et al. 2007), and nonintrusive sensing (Soric et al. 2104; Fleury and Alù 2014). An innovative way to achieve EM cloak is, metamaterials, which are being used to manage the scattering of waves from RF to optical domains (Wong et al. 2017). The main approaches of EM cloak are transformation optics (Chen et al. 2010; Zhang 2011; Kundtz et al. 2010), transmission-line cloaking (Alitalo et al. 2008; Danaeifar et al. 2012; Tretyakov et al. 2009; Vehmas et al. 2011) and scattering cancellation (Farhat et al. 2015; Younesiraaad et al. 2021; Hamzavi-Zarghani et al. 2019, 2020; Pratik et al. 2021) by using the carpet cloak method.

Cloaking approaches have been shown to produce greatly essential tool to detect electromagnetic radiation with minimal disruption, particularly at terahertz frequencies. The transformation optics method uses anisotropic and inhomogeneous materials to bend an EM wave around the target with no reflection, resulting in effective invisibility in the near-infrared region (Tao et al. 2018). The problem raised for cloaking with those materials is obtaining high ohmic loss and narrow bandwidth with different resonant frequencies (Güney et al. 2009). As a result, metasurface have gotten a lot of interest for scientists (Chen et al. 2013). The metasurface has several advantages like high transparency, light-matter interaction and low ohmic loss which has gotten an interest for the researchers (Hamzavi-Zarghani et al. 2019, 2020; Forouzmand and Yakovlev 2015; Emadi et al. 2018). Other important properties attracted towards metasurface are its optical and electrical tunability, that allows for the modelling of variety of tunable and reconfigurable devices such as: switches and logic gates (Kim et al. 2016), tunable absorbers (Liu et al. 2019), polarization converters (Hamzavi-Zarghani et al. 2018) etc.

The incorporation of a metamaterial in cloaking is, obtaining multiple bands with good reflection coefficient values, better radar cross section as compared to the uncloked object and metastructure is shielding something from view by controlling electromagnetic radiation i.e., objects in the defined location are still present, but incident waves are guided around them without being affected by the object. Graphene is introduced as the conducting material and is well suited for terahertz applications. But the problem raised is graphene not suits for cloaking applications because it is inductive and terahertz frequencies, need capacitive surface impedance (Padooru et al. 2013). To solve this case, a negative reactance nanostructured graphene metasurface (Chen et al. 2013) is used to wrap over the cylindrical object that has been made invisible. In consideration, with all the above issues, frequency of cloak is tuned by varying the chemical potential value. Most of the researchers consider TM polarized wave propagating in x-direction. The surface impedance can be controlled individually using the anisotropic metasurface, achieving both polarization in a given frequency (Monti et al. 2015, 2013; Bilotti et al. 2008; Zhang et al. 2007; Moosaei and Neshati 2021). However, in proposed structure, the conducting cylinder is covered by the designed metasurface with graphene by altering its chemical potential which is the important feature in the proposed work.

This work is briefly written as follows: Sect. 2 provides the design and analysis of proposed metasurface unit cell with graphene and analytic formulation for the dielectric cylinder under different incident angles and expressions for required electric sheet impedance ($Y_{es}$) and magnetic sheet admittance ($Z_{ms}$) to acquire invisibility for the given angle of
plane wave. Section 3 describes the total scattering width of conducting cylinder obtained by full wave simulations. Moreover, the RCS of the cloaked and uncloaked cylinders are provided for comparison. Reflection coefficient of metasurface with cloaked cylinder in terahertz range of frequency is shown. Section 4 summarizes the conclusion of the work.

2 Design of unit-cell and terahertz cloak with different incidence angles

The schematic geometry of the designed cloak covered with metasurface is shown in Fig. 1 with incident plane wave on z-direction. The structure of the designed unit cell is shown with a dielectric substrate of loss tangent 0.0027 and $\varepsilon_r = 3.5$ relative permittivity. Polyimide is used as a dielectric substrate with 0.1 mm thickness. The structure consists of single split ring resonator as an outer ring, and two opened O-slots with a rectangular strip added in the middle of the O-slots. A single rectangular strip is designed at the bottom side to exhibit the metamaterial properties in terahertz frequencies. The unit cell structure is designed with the graphene as a conducting material. Polyimide and graphene are the materials used for the design. Polyimide is a flexible and conformal substrate material that has good loss tangent and thermal conductivity. Graphene has essential features like low ohmic loss and transparency. The geography is intended for the incidence wave, which relates to the TM wave that illustrates the cloaked cylinder as illustrated in Fig. 1. The unit cell model with different parameters is visual in Fig. 2 with iterations, 3D view, front and back view.

The optimized geometrical values of the designed structure are shown in Table 1 of the unit cell in CST Microwave Studio. The parameters shown in the table are simulated in µm which are suitable for terahertz applications.

The designed unit cell structure is shown in Fig. 2 with no of iterations performed shown in Fig. 2a–d. The optimized unit cell with parameters is shown in Fig. 2f, g as front view and bottom view respectively. Figure 2e shows the 3-dimensional view of the proposed unit cell with a substrate thickness of 0.1 µm which exhibits the lower scattering output. The structure designed is patterned in array form to wrap on the conducting cylinder of finite height and radius. Figure 3 shows the unit cell in array form excited with different angles of plane wave towards the surface. In this design, the z-component
The fields for TM polarized wave can be written as follows (Younesiraad et al. 2021),

\[ E^{(1)} = \bar{E} E_0 \sum_n j^{-n} e^{i n \phi} \left( A_n J_n(K_d \rho) + B_n Y_n(K_d \rho) \right) \]

\[ H^{(1)} = \bar{H} H_0 \sum_n j^{-n} e^{i n \phi} \left( A'_n J'_n(K_d \rho) + B_n Y'_n(K_d \rho) \right) \]

for \( b < \rho < a \)
where $Y_n(.)$ and $J_n(.)$ are first order and the second order Bessel functions respectively. $H_n^{(2)}(.) = J_n(.) - jY_n(.)$ is the Hankel function, $k_0$ and $\eta_0$ are the wavenumber and intrinsic impedance in free space and $\eta_d = \eta_0/\sqrt{\varepsilon_{\text{eff}}}$. $A_n$, $B_n$ and $R_n$ are unspecified coefficients that are to be calculated at $\rho = a, b$. According to the primary assumption that the cylinder’s radius is thought to be quite modest in comparison to the wavelength, we examine a presumption as $|R_n|^2 + |A_n|^2 + |B_n|^2 = 1$. Using this relation, the magnetic sheet admittance ($Z_{\text{ms}}$) and electric sheet impedance ($Y_{\text{es}}$) are calculated by applying the formula (Younesiraad et al. 2021). The magnetic sheet impedance and electric sheet admittance plays a vital role in reducing the scattering width by using the proposed metastructure, and also, scattering bandwidth can be simultaneously adjusted.

The equivalent $Z_{\text{ms}}$ and $Y_{\text{es}}$ can be calculated using arbitrary reflection(R) and transmission(T) coefficients according to the equivalence principle (Younesiraad et al. 2021).
By changing the geometrical values of the designed structure with its dimensions, $Y_{es}$ and $Z_{ms}$ are attained in theoretical section (Younesiraad et al. 2021) can be tuned to achieve invisibility as shown in Fig. 4. The 8*8 array of the proposed structure with its dimensions and direction of plane wave incidence is seen in Fig. 3.

The Fig. 4 shows the model of the cloak with 8*8 array wrapped over the PEC cylinder to perform the cloaking operation. The figure shows detailed view of unit cell conformally placed over the cylinder with dielectric substrate in layers and its height. The design of the cloak is done by utilizing the CST microwave studio with cylindrical bend option and simulated by using hexahedral properties of transient solver.

The surface impedance is dissimilar for TM and TE polarizations, and concealment cannot be attained for both polarizations at the same frequency. Therefore, anisotropic metasurface is used so that surface impedance is put in each required direction. Graphene as the

\[
Z_{ms} = 2 \eta_0 \frac{1 + (R - T)}{1 - (R - T)}
\]

\[
Y_{es} = \frac{2}{\eta_0} \frac{1 - (R + T)}{1 + (R + T)}
\]

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Fig. 4 8*8 array wrapped on the PEC cylinder with which acts as a cloak
conducting metasurface is appraised in this purpose. By applying the formula from Younesi-sraad et al. (2021), the surface impedance for graphene is calculated with the required THz range of frequencies. The output of the cloak with various chemical potential values and relaxation time are shown in section III. The proposed meta-structure is shown in Fig. 5 with graphene wrapped around the cylinder concerning x-propagation of incident plane wave along x and z- directions of applied electric field vector.

The incident plane wave simulates the cloak schematic and measures the RCS of the cylinder through eigen mode solver. The electric field vector is varied at different angles and simulated the monostatic and bistatic of the cloaked cylinder through CST microwave studio.

3 Results and discussion

The simulation standardizes the presentation of the designed metasurface model for the structure in terahertz range. Figure 1 shows the conducting cylinder with a radius of a = 11.324 µm wrapped by a dielectric layer of polyimide with, ε_r = 3.5 and a thickness of 0.1 mm. An outer radius of b = 11.424 µm is covered with an ultrathin metasurface with a thickness of 0.035 mm. The proposed conducting cloaked cylinder is illustrated with a TM polarization. The cylindrical structure shown in Fig. 4 has been simulated to examine the scattering coefficients of the cloak. The s11 and s21 coefficients of the cylindrical cloak are given in Fig. 6 below. From the Fig. 6, observe that the simulated cloak operates at three resonating frequencies of 3.8 THz with a bandwidth of 3.5 to 4.58 THZ, 9 THz with a bandwidth of 8.8 to 9.5 THz and 13.8 THz with a bandwidth of 13 to 14.98 THz.

The return loss values for the three resonating frequencies are 3.8THz at -24.01 dB, 9 THz at -14.187 dB and 13.8 THz at -21.525 dB. As we said that, the electric sheet impedance and magnetic sheet admittance plays a vital role in adjusting the scattering bandwidth. The following Fig. 7 shows the Y_es and Z_ms respectively.

The systematic procedure has been examined for a cylinder of infinite length because of its simplicity, however in materiality there is no infinite cylinder. The SCS for the finite cylinder is obtained. The analytical scattering cross section is given by Younesi-sraad et al. (2021), where SW is the scattering width.
where \( \lambda \) is operating frequency wavelength and ‘l’ is the cylinder length.

Figure 8 displays the simulated and analytical plot of SCS curve concerning frequency to look into the performance of the cloak that was designed. The analytically attained SCS reduction is nearly to 20 dB for normal plane wave incidence. In contrast, the SCS

\[
SCS \approx SW \frac{2l^2}{\lambda} \quad (7)
\]
is further reduced to 15 dB for simulated results at two operating frequencies of 3.8 THz and 13.8 THz. The incident wave is applied at different angles from 0° to 90°. Thus, there is no change in monostatic RCS obtained. The following Fig. 9 shows the incident angle of linearly polarized wave at 0°, 45° and 90°, respectively. The RCS plot shows that the result obtained is a bidirectional pattern independent of whether TE or TM polarization.

Figure 9 shows the monostatic and bistatic RCS of uncloaked cylinder with wrapped metasurface. Monostatic and bistatic RCS is calculated to show the scattering suppression effect. Figure 10 shows the monostatic and bistatic RCS at various resonating frequencies of uncloaked cylinder. The result from the Figs. 9 and 10 shows that excellent performance in reducing the backward scattering is obtained by using the metamaterial structure as compared the result with uncloaked cylinder. We can say that, by comparing the RCS of uncloaked cylinder with cloaked metasurface cylinder, the reduction backscattering is high with the usage of cloaking. Monostatic and bistatic RCS are calculated with an incident plane wave of different angles at different resonate frequencies. The result shows that cloaking has good scattering suppression i.e., reduced nearly to 80 dB than an uncloaked cylinder.

Practically, it is unworkable to make a metamaterial without any loss. The impact of loss to the scattering suppression is simulated by considering various chemical potential values and the relaxation time. For this, parametric analysis is done through CST Microwave Studio with different relaxation time values and chemical potential. It demonstrates that a longer relaxation time leads to better concealing. Figure 11a shows the effect of cloak concerning the relaxation time and Fig. 11b shows the chemical potential. The tunability

![SCS comparison of three angles of incidence](image)

**Fig. 8** SCS comparison of three angles of incidence
Fig. 9 Monostatic and Bistatic RCS plot of cloaked cylinder at various selected resonating frequencies a and b 3.8THz, c and d 9 THz, e and f 13.8 THz for both polarizations
is achieved with the usage of graphene’s chemical potential value. The image depicts a shift in cloaking frequency to 2.1THz and 2.8THz, respectively, with chemical potentials of 0.1 eV and 0.5 eV.

The variation of dielectric constant and loss tangent values are observed with frequency as graphene is used as a conducting material. The fluctuation of the dielectric constant up to 18 THz is seen in Fig. 12a. The greater the metasurface size, the greater the dielectric constant at a constant operating frequency. Due to relaxation effects such as electronic and atomic polarizations, increasing operating frequency lowers the dielectric constant. The nonlinear change of the loss tangent versus frequency is seen in Fig. 12b. The loss tangent grows until it reaches 4–10 GHz, then drops to a specific value.

Figure 13 shows the electric(e) field distribution of uncloaked and cloaked cylinders. The e-field distribution shown that the proposed metasurface suppress higher scatter fields compared to others. The radiation patterns of the cloaked cylinder at various frequencies are shown in Fig. 14. Radiation patterns are simulated for multiple angles with respect to $\phi$ and $\theta$. It results that, the designed metamaterial structure is polarization independent.

A bidirectional radiation pattern is obtained for the designed metastructure for the selected resonating frequencies. Exceptional reduction of scattering is obtained for the proposed target cylinder examined in the both planes for all the incident angles.
Fig. 11 Simulated RCS of uncloaked and cloaked cylinder with proposed metasurface at different \textbf{a} relaxation time and \textbf{b} chemical potential
4 Conclusion

A flexible and conformal metasurface cloaking of a target cylinder under TM and TE polarization in the terahertz range was designed. For this purpose, an isotropic metasurface based on graphene has been considered. The designed structure’s cloaking behavior is explored by taking into consideration of the graphene metasurface’s characteristics. The proposed structure and graphene characteristics are used to improve the scattering effect and projected with RCS. By properly varying the chemical potential and relaxation time, tunability has been achieved in cloaking. The numerical analysis has performed, simulated through CST Microwave Studio, and obtained the high scattering reduction for selected resonating frequencies of 3.8 THz, 9 THz and 13.8 THz. The proposed metasurface is highly suitable for various cloaking applications in the terahertz range of frequencies like biosensors, Magnetic Resonance Imaging (MRI) and in many medical applications.
**Author contributions** KS: conceptualization, methodology, software, writing—original draft, and writing—review and editing. BTPM: validation, writing—review and editing, and supervision. BAB: editing and review. SD: investigation, analysis and supervision. SKP: Simulation, investigation and supervision. JP: optimization, investigation and supervision.

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## Declarations

**Conflict of interests** The authors declare no competing interests.

**Ethics approval** We declare that this manuscript is original, has not been published before, and is not currently considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.
**Consent to participate** Informed consent was obtained from all authors.

**Consent for publication** The authors confirm that there is informed consent to the publication of the data contained in the article.

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