Graphene-Based Tunable Broadband Polarizer for Infrared Frequency

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Abstract
This paper proposes the tunable graphene-assisted polarizer structure which is working on the infrared frequency range. The tunable polarizer has been designed by a three-layered structure of silica, graphene, and gold. The polarizer behavior of the structure is analyzed for the frequency range of 3 to 12 THz. The tunability of the structure is analyzed for the different values of Fermi energy which is a tunable parameter of the single-layer graphene sheet. Polarizer response is derived in terms of different performance parameters such as reflectance, phase variation, phase difference, polarization conversion rate, and effective refractive indices. Graphene-based polarizer structure is investigated for the co-polarization and cross-polarization input incident conditions to check linear to circular polarization conversion. It also shows an effective refractive index response to check the metasurface behavior of the polarizer for the 3 to 12 THz range. We have observed that the polarization amplitude becomes stronger for the higher Fermi energy value of the graphene sheet. The reflection amplitude is achieved up to 90%. Results of the proposed polarizer structure can be used to design the various electro-optical structure which operates in the lower terahertz range.

Keywords  Polarizer · Tunability · Infrared · Metasurface · Graphene · Ultrathin · Terahertz

1 Introduction
Metamaterials are materials that are artificially fabricated. Dimension-reduced metasurfaces have attracted a lot of interest due to their practical implementation and extremely excellent light modeling capabilities when compared to those provided by conventional planar interfaces [1]. Structural components are arranged to form thin and dense arrays in two dimensions (2-D). As a result of their resonant nature, they have special characteristics [2]. Metasurfaces are simple to make and do not take up much space. They can control electromagnetic waves at optical and microwave frequencies [3], which is a one-of-a-kind ability. Lenses, holograms, and other optical devices may be constructed from this meta-atom-based material. As a result, in radiophysics, frequency selective surfaces (FSSs) are employed rather than optical metasurfaces, which are more recent inventions [4–7].

Small-scale production costs and ultrathin thickness make graphene a desirable material for a wide range of applications of electrical and optical devices [8]. Using the metamaterial, we may create novel optical characteristics that normal materials lack, such as a perfect lens, hyperbolic dispersion, or a negative index of refraction [9–12]. Graphene consists of six carbon atoms and a single atomic thick structure. Graphene is very popular because of its excellent thermal, electrical, and optical characteristics [13]. Graphene is also commonly used in the construction of many reconfigurable devices such as gratings [14], tunable absorbers [5, 15], polarizers [9], and leaky-wave antennas [16]. A variety of physical parameters such as chemical potential, temperature, frequency, and dispersion rate may be adjusted to change its configuration [17]. The intra-band conductivity model of graphene can be investigated by the Dirac cone [18]. It has been analyzed that graphene provides the control action by an external magnetic field or electrostatic [19] that varies from one material to another. Also, a high electrical/optical conductivity can be observed with the adaptation of graphene from the near-infrared spectrum [20] to the far-infrared region [21]. The conception of graphene-based photonics systems is based on creating integrated geometry
using single-layered sheets. The principle of constructing metamaterial (MM) and graphene polarization structures can be explored by taking into consideration the various geometries of the graphene sheet [6, 22]. Polarizers are structures that can be used as electromagnetic filters for the development of periodically directed structures [23]. They can be used as electromagnetic equipment for different types of applications that may include radiographic antennas, metamaterial, stealth systems, reduction in radar cross-sections, etc. [24]. Using terahertz absorption graphene material and a polarizer, several research studies have been performed on the selective surface-based structure as mentioned in [25] and [26]. The graphene-based polarizers can mainly be tuned with the help of chemical graphene potentials and the frequency which can be altered and can be modified externally [27]. For the graphene-assisted derives to have a metamaterial effect, it is essential to figure out the characteristics like transmittance and reflectance. Different graphene-based device physical characteristics may be used to reconfigure the attributes’ variability. Additionally, the graphene-based metasurface can get beyond the thickness and tuneability issues [28]. Metasurfaces based on single-layered graphene sheets may be made on substrate like silica [6], aluminium [29], or gold [28]. This is because the device shapes made from a single graphene sheet, such as T-shape [30], L-shape [31], rectangular split ring shape [32], or C-shape [9], may be customized to fit the graphene-based metasurface. Creating the shape of this structure might be having difficulty in fabrication process. The solution for creating simple graphene patch-based structure can be realized by oxygen plasma based source [33] or digital light processing (DLP) lithography-based devices.

Inspiring from the other designs of the polarizer structures, we have presented the simple graphene and gold resonator patch-based broadband metasurface polarizer structure. For the suggested metasurface polarizer, various physical characteristics including reflectance, cross-polarization, and polarization conversion rate (PCR) are examined as well as wide-angle incident values are calculated. In the first section of the manuscript, the design of the polarizer is presented. The second section of the manuscript shows the mathematical model of graphene. Discussion of the different physical parameters and results derived from the designed polarizer is shown in the last section of the manuscript.

2 Polarizer Design and Graphene Conductivity Model

2.1 Graphene-Based Broadband Polarizer Design

Figure 1 depicts the graphene-gold resonator-based tunable broadband polarizer in a 3D (three-dimensional) perspective. As shown in Fig. 1, a rectangular gold slab is put on top of a single-layer graphene sheet and a silica material slab. The different dimensions of the structure can be defined as follows: \( H = 1.5 \, \text{µm} \), \( W = 7.6 \, \text{µm} \), \( L = 7.6 \, \text{µm} \), \( g_l = 3 \, \text{µm} \), \( g_w = 4 \, \text{µm} \), \( R_w = 0.2 \, \text{µm} \), \( R_h = 6.5 \, \text{µm} \), and \( R_l = 5 \, \text{µm} \). The input incident wave of range 3 to 12 THz is excited from the \( Z \)-direction. The design of the suggested structure takes periodic boundary conditions in the \( X \)- and \( Y \)-axes into account. The structure is excited by the different polarized conditions (\( X \)- and \( Y \)-polarized) from the top of the structure. The perfectly matched layered condition is sent in the vertical direction. The infrared wave has a 1-W power value and is launched from the top of the structure on the \( Z \)-axis. Figures 2 and 3 are showing transmittance, reflectance coefficients, and phased variation response for the initial structural dimensions mentioned above in this section.

![Fig. 1](image_url)

**Fig. 1** (a) Schematic of broadband polarizer using graphene-based structure for far-infrared frequency spectrum with periodic array structure. (b) Unit cell dimensions of the structures are defined as follows: \( H = 1.5 \, \text{µm} \), \( W = 7.6 \, \text{µm} \), \( L = 7.6 \, \text{µm} \), \( g_l = 3 \, \text{µm} \), \( g_w = 4 \, \text{µm} \), \( R_w = 0.2 \, \text{µm} \), \( R_h = 6.5 \, \text{µm} \), and \( R_l = 5 \, \text{µm} \). Polarized input wave is excited from the \( Z \)-direction. There are periodic boundary conditions for \( X \)- and \( Y \)-directions.
2.2 Graphene Conductivity Model

The Kubo formula may be used to describe the conductivity of a single graphene sheet [19]. The finite element technique is used to analyze the proposed polarizer structure (FEM). A graphene surface conductivity model, which may be constructed using the formulas in Eqs. (1)–(4), is used to examine the suggested structure. Equations (2)–(4) illustrate the graphene conductivity model in terms of intramodal and intermodal conductivities.

\[ \varepsilon(\omega) = 1 + \frac{\sigma_s}{\varepsilon_0\omega \Delta} \]  

\[ \sigma_{\text{intra}} = -\frac{je^2}{\pi\hbar^2(\omega - j2\Gamma)} \left( \frac{E_i}{k_B T} + 2\ln\left( e^{-\frac{E_i}{k_B T}} + 1 \right) \right) \]  

\[ \sigma_{\text{inter}} = -\frac{je^2}{4\pi\hbar} \ln\left( \frac{2|E_i| - (\omega - j2\Gamma)\hbar}{2|E_i| + (\omega - j2\Gamma)\hbar} \right) \]  

\[ \sigma_s = \sigma_{\text{inter}} + \sigma_{\text{intra}} \]  

The specifications and values of the parameters which are presented in the above equation have been described in Table 1. When the gate bias voltage is varied, the graphene Fermi potential becomes as follows: \( E_F = \frac{\hbar v_F}{\sqrt{\pi CV_{bg}}} \), where \( C = \varepsilon_0 \varepsilon_r \frac{d}{H} \) is electro-statistic capacitance per unit area. The parameters like \( -\varepsilon_0 \) is defined as permittivity of free space, \( \varepsilon_r \) (2.25) is defined as permittivity of silica material, and \( H \) (1.5 µm) describes the thickness of the silica layer. Complicated results will be produced using the graphene conductivity equation. The graphene surface resistance and reactance are both affected by this equation. Due to the graphene sheet’s FEM simulation computation, the graphene surface’s \( X \) and \( Y \) destinies have been given values like \( J_x = E \sigma_x \), and \( J_y = E \sigma_y \). The suggested polarizer structure would use a tetrahedral Delaunay tessellation meshing condition. The meshing is adjusted to a maximum and lowest size of 150 nm and 15 nm. The meshing growth rate is set at 0.6.

2.3 Possible Graphene Polarizer Fabrication Methods

The most common methods used for creating two-dimensional material and single-layer graphene are chemical vapor deposition (CVD) [34] as well as MBE [35] and cleavage [36].

![Graphene Conductivity Model](image1.png)
![Graphene Conductivity Model](image2.png)
techniques. It is possible to transfer wet and dry transition structures, such as using various techniques such as atomic force nanolithography [37], plasmonic structures lithography [38], and nanospheric process [39]. A complicated structure on the top layer of the graphene material can be fabricated via nano-spheric lithography [39] and lithography of nanoplasmonics devices [38]. As seen in [38], where lithography technologies for plasmonics device fabrication process have been applied, resulting in graphene composite with high quality and versatile complex nano- and microstructures. The transfer process of gold structure on the graphene layer can be realized by the process of transfer printing of graphene using gold film [37]. The experimental procedure for producing a gold surface with a pattern may be seen in [37]. CVD and electron beam lithography methods may alternatively be used to manufacture the proposed structure, as described in [39]. Another process for fabricating and providing tunability operation in graphene-based polarizer structure using CVD, DLP laser lithography, and ion gel formation. In this fabrication method, the CVD process is used for forming graphene on copper foil. This graphene can transfer on the substrate by using a wet transfer process [40, 41], and ammonium persulfate solution can be used for copper removal. The oxygen plasma at specific values of power can be applied to create a graphene patch structure [33]. The metal grids/meatal patch can be formed on the top of the graphene using DLP laser lithography. The ion gel of 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide and poly(vinylidene fluoride-co-hexafluoropropylene) can be used for provide the tunability of the graphene for different biased voltage [42, 43].

### 3 Results and Discussion

#### 3.1 Tunability Response and Refractive Coefficient Value

Mathematical modeling of graphene gives an idea to control conductivity using external parameters. Many factors may affect graphene conductivity in general, including temperature, Fermi energy, frequency, and rate of scattering. Different Fermi energies are used to examine the tunability behavior of the proposed broadband polarizer structure. Figures 2 and 3 show the proposed structure’s reflectance and transmittance response for various polarization modes. The dimensions for the initial coefficient calculations (Figs. 2 and 3) are as per the initial definition given in the design section. Figure 2a shows the reflectance response for the X-polarization structure. Similarly, the transmittance response for the X-polarizer wave is shown in Fig. 2b. The structure’s tunable characteristics are found in the frequency range of 3–12 THz. The graphene Fermi potential is varied between 0.1 and 0.9 eV. Figure 3a–b show the reflectance coefficient and transmittance coefficient response for the Y-polarized wave. The reflectance coefficient is defined as $R_{ij} = \frac{E_{j}^{\text{reflect}}}{E_{i}^{\text{inc}}} \left| (i,j = x,y) \right.$, where $E_{j}^{\text{reflect}} (j = x,y)$ is the $x$ or $y$ component of the reflected wave and $E_{i}^{\text{inc}} (j = x,y)$ is the $x$ or $y$ component of the incident wave [44]. Variation in $R_{xx}$ and $R_{yy}$ amplitudes is due to the dipole moment created for different input incident wave conditions. Overall covered area of rectangular gold and graphene shape of the graphene patch is considered as rectangular with $K_{x} \neq K_{y}$ and $g_{x} \neq g_{y}$ condition. A significantly bigger difference in wavelength shift is achieved by making a larger difference between the length–width of the graphene and gold structure. The resonating frequency of the graphene depends on the length and width of the structure by considering the function $f = \sigma \frac{E_{r}}{L}$ [45], where $E_{r} = \mu_{e} = \text{Fermi energy}$ of the graphene sheet. The graphene sheet of the structure will generate the high electric field concentration at specific values of frequency. This dipole moment generates because of the energy concentration over the surface of the graphene sheet. In this structure, the energy concentration is responsible because of the gold resonator edges and graphene sheets edges. This collective plasmonic resonance condition makes the electric field concentration high and makes the device as a reflector. These plasmonics resonance electric field values are shown in inset images (Y–Z plane of field concentration) of Fig. 4a. The field concentration at X–Y plane is shown in Fig. 5a, b. From the above response, we have calculated that the different geometries of graphene and gold structure can create different resonance points at different resonating frequencies.
3.2 Phase Variation and Polarization Conversion Rate

The phase is defined as $\Phi_{ij} = \arg\left(\frac{E_{R}^{\text{reflect}}}{E_{i}^{\text{inc}}} \right) (i, j = x, y)$. The phase difference between the reflected wave and the incident is presented as $\Delta \Phi = \Phi_{xx} - \Phi_{yy}$. Fig. 4a shows a comparison of the reflectance coefficient's response to both incident polarized waves. Figure 4b depicts the phase difference between the two polarized waves. For the $X$-polarized incident wave situation, we have seen a polarization variation of $-80$ to $10^\circ$. Similarly, we have observed $-80$ to $-10^\circ$ of the polarization variation for the $Y$-polarized incident wave condition. A rise in the reflectance for the same range of the polarization variation can be observed in Fig. 4a. The phase difference between both of these waves is observed to be more than $90^\circ$. Overall, it is found that the phase difference of $90^\circ$ has been distinguished over the range of 6 to 7 THz with higher values of reflectance amplitude. Similarly, $60^\circ$ of the phase differences has been observed in the range of 8.8 to 9.5 THz. The plasmon resonance effect at different frequency points over the graphene surface is shown in Fig. 4a. The plasmon resonance is derived at the different resonating points of high amplitude peak of reflectance amplitude. In the $X$-polarizer incident light condition, the resonating normalized electric field intensity ($E_z$) is observed at 3.3 THz, 5.9 THz, and 8.8 THz. Similarly, in the $Y$-polarized incident light condition, the $E_z$ was observed at 3.3 THz, 6.85 THz, and 9.5 THz. Since these locations have a high resonant frequency, the electric field concentration on the graphene sheet’s edges is evident. These points of high electric field intensity generate strong dipole moments for higher values of reflectance. The variation in the phase difference for the different values of frequency and applied graphene Fermi potential is shown in Fig. 5. Figure 5a shows the variation in the phase for $X$-polarized wave. Figure 5b depicts the phase variation for an incident wave that is $Y$-polarized. Inset images of each figure show the variation in the electric field intensity $E_z$ for different resonating points. A $90^\circ$ phase variation in $E_z$ response for two of the resonating points can be observed. For the $X$-polarized incident wave, the maximum phase difference variation is seen in the $-100$ to $20^\circ$ range. Phase variation is found to be between $-100$ and $-10^\circ$ for incident waves that are polarized in the $Y$-direction. A phase difference between $X$- and $Y$-polarized waves is shown in Fig. 5c. The phase differences of about $-20$ to $100^\circ$ in both incident waves can be observed in Fig. 5c. The elliptical polarization of the input incident wave will be generated when $R_{xx} \neq R_{yy}$ and $\Delta \Phi = 90^\circ$ conditions satisfy. Similarly, circular polarization of the input incident wave can be generated when $R_{xx} = R_{yy}$ and $\Delta \Phi = 90^\circ$ conditions satisfy. We can observe such conditions in Fig. 4a, c. This behavior proves the working of the proposed structure as linear to the elliptical and linear to the circular polarizer. The polarization conversion rate is defined as $\text{PCR} = \left|R_{xy}\right|^2 / \left[\left|R_{xx}\right|^2 + \left|R_{yy}\right|^2\right] [46]$ to reveal the performance of the proposed polarizer as a behavior of cross-polarization. Figure 6a, b show the PCR results for $X$–$Y$ cross-polarization and $Y$–$X$ cross-polarization, respectively. Inset figures are showing the $E_z$ components of the different resonating points for both cross-polarization effects. Values of PCR are observed more than 90% in both of the cases. Tunable behavior of PCR can be achieved by applying different frequencies and Fermi energy. It is also observed that for the higher chemical potential, the value of PCR is more than 80% for the different Fermi energy bands. The high PCR values at the same band as the high reflectance values proved the functionality of the linear to elliptical/linear to circular polarization conversion. The conditions of $\text{PCR} = 0.5$ and phased difference $= 90^\circ$ need to satisfy to identify the linear to circular polarization behavior. The effective PCR values for this conversion are identified in 3.5–6 THz of the band in $X$-polarized condition. Similarly, the PCR condition in $Y$-polarized input conditions is observed at 4.5–10 THz of the band. The PCR values will help to choose the effective frequency and chemical potential for specific terahertz frequency polarization conversion. This PCR response also gives the wideband and tunable band of polarization.
Fig. 5 Calculated phase difference response and phase variation response for the input function of frequency and Fermi energy of the graphene sheet. Phase variation for (a) X-polarized wave ($\Phi_{xx}$) and (b) Y-polarized wave ($\Phi_{yy}$). Inset: $z$-components of the electric field intensity for different resonating points. (c) Phase difference for both polarized waves ($\Delta\Phi$).
conversion. Reflectance behavior for the wide-angle incident response is investigated for the range of 0 to 80° of the incident angles. Figure 7 shows the wide-angle incident reflectance coefficient variation for $X$- and $Y$-polarized incident waves. Constant reflectance below the 4 THz frequency has been observed for $X$-polarized incident wave condition. It is also observed (Fig. 7a) that for $X$-polarized wave, a constant reflectance response is below the 60° for a higher frequency range (>8 THz). Similarly, it is observed constant reflectance response for below the 60° of incident angle on 3 to 6 THz range. The wide-angle incident graph is derived by applying the 0.9 eV to the graphene sheet.

### 3.3 Cross-polarization Behavior and Effect of Physical Parameters

Figure 8a, b illustrate the combined response of the reflection coefficient for the co-polarized and cross-polarized wave. Figure 8a shows the co-polarization $R_{xx}$ and cross-polarization $R_{yx}$ for the $X$-polarized wave conditions. Similarly, Fig. 8b shows the co-polarization $R_{yy}$ and cross-polarization $R_{yx}$ for the $Y$-polarized incident wave conditions. PCR and the phase difference response between co and cross-polarization have been illustrated in Fig. 9a, b for $X$- and $Y$-polarization incident wave conditions. The effect in reflectance amplitude for

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**Fig. 6** Calculated PCR response of the different cross-polarization graphene-based polarizers as the function of Fermi energy and incident frequency. (a) PCR response for $X$-$Y$ cross-polarization and (b) $Y$-$X$ cross-polarization. Inset: electric field intensity, $E_z$, values for the different resonating points

**Fig. 7** Reflectance response calculated from the input wave’s broad incidence angle. (a) Wide-angle response for the $X$-polarized incident wave. (b) Wide-angle response for $Y$-polarized wave. The Fermi energy of the calculated response is chosen as 0.9 eV

**Fig. 8** (a) Reflection coefficient for the cross-polarization ($R_{yx}$) and co-polarization ($R_{xx}$) for input wave condition as $X$-polarized, (b) PCR and phase difference response
different values of physical parameters is presented in Figs. 10 and 11. Figure 10 shows a variation in reflectance amplitude as a function of frequency and $R_h$. Figure 10a, b show the variation in reflectance for $X$-polarized and $Y$-polarized wave.

It is observed that the large frequency shifts over the 3–12 THz range of different values of $R_h$. $R_h$ varied from 1.5 to 6.5 μm. Figure 11 shows a variation in reflectance as a function of frequency and $R_l$. Reflectance varies with polarization, as seen in Fig. 11a, b, depending on the value of $R_l$. A large frequency shift of about 3 to 12 THz range for different values of $R_l$ can be remarked. Values of $R_l$ are varied from 1 to 5 μm. From the response of the parameter changes and reflectance amplitude, we can conclude that the performance of the polarizer can be controlled from various physical parameters. The physical parameters values are ultimately affected by the resonance condition of the structure. The resonance condition is depending on $f_r \alpha \sqrt{E_f/L}$ where the changes in structure dimensions are directly related to resonance values. The physical dimensions of the overall structure also make changes in PCR and phase difference values. These results will apply to identify the specific resonance frequency where the linear to circular polarization conversion generates.

3.4 Effective Refractive Indices

The effective refractive indices of the proposed polarizer structure are calculated from the equation given in [47]. The metamaterial state of the proposed structure can be identified from Figs. 12 and 13. Figure 12 shows the

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**Fig. 9** (a) Reflection coefficient for the cross-polarization ($R_{xy}$) and $C_0$-polarization ($R_{yy}$) for input wave condition as Y-polarized, (b) PCR and phase difference response

**Fig. 10** Calculated reflectance coefficient values for (a) $X$- and (b) $Y$-polarized incident wave conditions as a function of frequency and $R_h$

**Fig. 11** Calculated reflectance coefficient values for (a) $X$- and (b) $Y$-polarized incident wave conditions as a function of frequency and $R_l$
variation on the effective refractive index for the different Fermi energy values and frequencies. Figure 12a, b show the real and imaginary part of the effective refractive index for the $X$-polarized incident wave condition. Similarly, Fig. 13a, b show the variation in the real and imaginary values for the effective refractive index for the $Y$-polarized wave condition. It is observed that the negative values of the effective refractive index on both polarization modes will ultimately prove the behavior of the polarizer as a metamaterial device. Values of the effective refractive index also change as the function of graphene Fermi energy and frequency as observed in Figs. 12 and 13.

4 Conclusion

In conclusion, the graphene-based tunable broadband polarizer is investigated over 3–12 THz of the far-infrared frequency range. The polarizer structure is investigated to identify the cross-polarization and co-polarization behavior for the different polarized input conditions ($X$- and $Y$-polarization). The graphene-based polarizer that has been suggested can be tuned for various graphene Fermi energies. A wide variety of frequency-dependent PCR values for cross-polarization and co-polarization show how the polarizer structure behaves. The refractive indices values from reflectance and transmittance were also calculated to analyze the behavior as a metamaterial device. The proposed polarizer structure can be used in a broad range of the terahertz frequency due to the wide bandwidth of the reflectance response. The wide-angle incident behavior up to 60° of the input waves has been observed. New tunable terahertz devices for electro-optical structures operating at lower terahertz frequencies may be developed as a consequence of the findings reported in this manuscript. The graphene-based polarizer structure’s simple, small, and adjustable form makes it ideal for use as a fundamental building component in large terahertz integrated systems.

Author Contribution Vishal sorathiya conceive the project, simulated the proposed structure, generated the results, and contributed to writing the manuscript for this research. S. K. Patel supervises the overall project at every stage.

Availability of Data and Material Raw data of the computed results were generated at Marwadi University. Derived data supporting the findings of this study are available from the corresponding author on request.

Declarations

Ethics Approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Consent to Participate Not applicable
Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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