Graphene Based Metasurface with Tunable Dual Band Mid-Infrared Cross Polarization Converter

Vinit Singh Yadav¹, Sambit Kumar Ghosh², Somak Bhattacharya³, Santanu Das⁴

¹Department of Electronics Engineering, Indian Institute of Technology (BHU) Varanasi, Uttar Pradesh-221005, India
²Department of Ceramic Engineering, Indian Institute of Technology (BHU), Varanasi, Uttar Pradesh-221005, India
³vinitsy.ece16@iitbhu.ac.in, ⁴sambitkrgosh.rs.ece17@iitbhu.ac.in, ³somakbhattacharyya.ece@iitbhu.ac.in, ⁴santanudas.cer@iitbhu.ac.in

Abstract: In this article, we report a dual band mid-infrared cross polarization converter using graphene-based metasurface. The proposed graphene-based metasurface comprises of periodical double L-shaped perforated graphene on the top surface of metal backed SiO₂. The proposed structure converts the incident linearly polarized wave into the cross-polarized component at 32.39 THz with peak polarization conversion ratio of 99.95% and 99.66%. The structure is ~ λ/6 thin with respect to the lowermost frequency of polarization conversion.

Keywords: Graphene, metasurface, cross-polarization conversion (CPC), polarization conversion ratio (PCR).

I. INTRODUCTION

Mid-infrared frequency band is generally used in sensing, spectroscopy and various other communication applications [1]. Graphene is a two-dimensional, monolayer structure of sp² bonded carbon atoms placed on honeycomb lattice [2]. It can be regarded as an emerging material in mid-infrared region [3]. Graphene shows a wideband tunability due to its strong plasmonic and Fermi Dirac electronic response through altering its chemical doping and electrostatic tuning [4,5], making it as an attractive material in mid-infrared regime. In the past decade a number of components as absorbers, cloaks, photodetectors and modulators have been developed on the basis of graphene plasmonic structures [6 - 8]. A new era of graphene has been started with the properties of electromagnetic induced transparency [9, 10], anomalous refraction in different frequency regime [11] and optical polarization encoding [12].

The most of the polarization converters and optoelectronic components are composed of metallic structures, thus making it confined to function only in a specified frequency range [13 - 15]. However by using graphene metasurface, frequency can be dynamically tuned by varying the Fermi energy of graphene through the use of chemical doping or electrical tuning. Cheng et al. proposed an array of L-shaped perforated graphene sheet, with tunable single-band cross polarization converter, which converts linearly polarized incident light into cross polarized light in mid-infrared region [16, 17].

In this paper, we have proposed a dual band mid-infrared cross polarization converter based on graphene metasurface. The unit cell of metasurface consists of dual L-shaped perforated graphene sheet, on the top surface of metal backed SiO₂. When a linearly polarized wave is incident on the surface, the cross-polarization component of the wave gets reflected at 32.39 THz and 38.96 THz. The corresponding polarization conversion ratios (PCR) at these two frequencies are calculated as 99.95% and 99.66%, respectively.

II. DESIGN OF THE STRUCTURE

![Fig. 1: Schematic and functional diagram of the graphene based metasurface exhibiting dual band cross polarization conversion at mid-infrared region.](image)

The schematic and functional diagram of the proposed cross polarization converter (CPC) graphene metasurface is shown in Fig. 1. It consists of an array of periodic double L-shaped ring of a perforated graphene sheet imprinted over an insulating layer backed by a metal plane. The metal plane is made of gold film with the thickness of 100 nm and the conductivity is given as 4.56×10⁷ S/m. The insulating layer...
is considered as a dielectric film of SiO$_2$ with thickness of $d = 1500$ nm; and its dielectric constant is taken to be 2.1 at the frequency of operation. In Fig. 1, $V$ shows the external applied potential to the graphene, which is used to control the conductivity of graphene. The unit cell of the proposed graphene based metasurface is shown in Fig. 2, where the geometrical dimensions are optimised as $p = 200$ nm, $l_1 = 150$ nm, $l_2 = 95$ nm, $w_1 = 20$ nm, $w_2 = 25$ nm. The top view and side view of the unit cell are shown in Fig. 2(a) and Fig. 2(b) respectively. The incident electric field, magnetic field and direction of wave propagation are also provided in Fig. 2(a).

The structure is designed and simulated by using the frequency domain solver of the CST Microwave Studio Software, which uses the finite element method. In CST simulator, the graphene is modelled as an anisotropic medium. In the simulation process periodic boundary conditions have been assumed along x-y plane. The tabulated surface impedance boundary condition has been defined in graphene surface whose conductivity is given in (1). Here, the surface conductivity of graphene can be given by Kubo formula [18].

$$\sigma(\omega, \mu, \Gamma, T) = \frac{4 e^2}{\pi \hbar} \left[ 1 - \int_0^{\omega/2\Gamma} \left( \frac{\partial f_0(-\epsilon)}{\partial \epsilon} - \frac{\partial f_0(\epsilon)}{\partial \epsilon} \right) d\epsilon - \int_{\omega/2\Gamma}^{\omega} \left( f_0(-\epsilon) - f_0(\epsilon) \right) d\epsilon - 4 \int_0^{\omega/2\Gamma} \frac{\epsilon}{\hbar} F_0(\epsilon) d\epsilon \right]$$  (1)

The first term in (1) is due to intraband contribution, and the second term attributes to the interband contributions. The intraband term in (1) can be evaluated as shown in (2).

$$\sigma_{\text{intra}}(\omega, \mu, \Gamma, T) = -\frac{4 e^2 \kappa T}{\pi \hbar \omega (\omega - j2\Gamma)} \left( \frac{\mu \kappa T}{\mu \kappa T} + 2 \ln \left( e^{\frac{\mu}{\kappa T}} + 1 \right) \right)$$  (2)

The interband conductivity can be approximated for $\kappa T \ll |\mu|, \hbar \omega$ as shown in (3), where $e$ is the electron charge; $T = 300K$ is the room temperature; $\omega$ is the frequency of incident electromagnetic wave; $\hbar = h/2\pi$ is the reduced Planck constant; $\tau$ is the electron relaxation time taken as 0.5 ps and its minimum value can be 0.2 ps [19]; $\mu$ is the chemical potential of the graphene and assumed to be 0.9 eV.

$$\sigma_{\text{inter}}(\omega, \mu, \Gamma, 0) = -\frac{4 e^2}{\pi \hbar} \ln \left( \frac{2|\mu|-\left( \omega - j2\Gamma \right) \hbar}{2|\mu|+\left( \omega - j2\Gamma \right) \hbar} \right)$$  (3)

### III. SIMULATED RESULTS

The property of polarization converter can be given with a generalized reflection matrix as given in (4).

$$R = \begin{pmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{pmatrix}$$  (4)

Here, the matrix elements $R_{ij}$ stands for reflection ratio of the $i-j$ polarization conversion and their subscripts $i$ and $j$ can be replaced by $x$ and $y$, respectively. Here the proposed unit cell structure is diagonally symmetric, making $R_{xx} = R_{yy}$ and $R_{xy} = R_{yx}$. Here we have discussed only $R_{xy}$ and $R_{yx}$, by assuming $y$-polarized incident wave.

![Fig. 3: Frequency response of co-polarized and cross-polarized reflection coefficients of the graphene based metasurface whose unit cell is shown in Fig. 2.](image)

The co-polarized and cross polarized reflection coefficients ($R_{xx}$ and $R_{xy}$ respectively) are shown in Fig. 3. Here the applied potential of graphene is taken as 0.9 eV. From Fig. 3, two separate reflection peaks in $R_{xy}$ have been observed at 32.35 THz and 38.96 THz with respective values of -1.46 dB and -4.56 dB. At the same frequencies, two distinct minima have been observed in the co-polarization reflection mode of values -30.97 dB and -28.57 dB. The polarization conversion ratio (PCR) can be defined in (5), and is plotted in Fig. 4.
The peak PCR values of 99.95% and 99.66% are realized at 32.35 THz and 38.96 THz. These two frequency bands have fractional bandwidth of 7.50% and 1.51% with respect to center frequencies. The FWHM bandwidths of the PCR are 2.43 THz and 0.62 THz. For normal incidence of electromagnetic wave, in the first resonating band the peak polarization angle of the reflected wave is 88.76°. Similarly for the second resonating band the peak polarization angle of the reflected wave is 86.65°.

\[
PCR = \left| \frac{R_{xy}}{R_{yy}} \right|^2
\]  

(5)

Fig. 4: Polarization conversion ratio (PCR) response of the graphene based metasurface whose unit cell is shown in Fig. 2.

Fig. 5 represents the surface current distributions between the top graphene pattern and the bottom gold ground, and a current loop is formed in the dielectric spacer layer for these two resonant modes at 32.39 THz and 38.96 THz. For the first resonant frequency, when the electric field is along the positive \(y\)-axis, the induced magnetic field appears perpendicular to the current flow direction, the two components of the magnetic fields are parallel and perpendicular to the incident electric field direction. The perpendicular magnetic field component cannot cause cross polarization, because the incident magnetic field is parallel to this induced magnetic field component. The induced magnetic field component which is parallel to the incident electric field, can induce the electric field in the direction along \(y\)-axis and generates the cross polarization. The same physical mechanism applies for the higher resonant frequency of 38.96 THz. Fig. 5 shows that most of the current distribution is concentrated at the corner and edges of the double L-shaped hollow structure. Here, the base current and surface currents are anti-parallel to each other at both resonating frequencies, as evident from Fig. 5. This leads to formation of current loop within the dielectric from top to bottom of it, which is perpendicular to the direction of incident magnetic field. Hence we can say that magnetic resonance occurs at both the resonating frequencies, 32.39 THz and 38.96 THz. These magnetic resonances are confirmed from the magnetic field distributions at 32.39 THz and 38.96 THz, illustrated in Fig. 6.

IV. STUDY OF PCR UNDER DIFFERENT CHEMICAL POTENTIAL

For the conventional polarizers or other devices, where we do not use graphene, the tunable property of operating frequencies is dependent almost totally on the size of structure. The Fermi energy of graphene material is tunable and can be tuned from -1 eV to 1 eV by chemical doping or electrical gating. By altering the Fermi energy of graphene, its complex surface conductivity changes. Thus the operating frequency bands can be easily controlled over a wide frequency range.
The frequency response of PCR has also been studied under normal incidence for different Fermi energy levels as illustrated in Fig. 7. It is evident from Fig. 7 that the lowermost frequency can be tuned from 24.09 THz to 32.36 THz while the applied Fermi level is changed from 0.5 eV to 0.9 eV.

Fig. 7 shows that by altering the Fermi energy of graphene the peak PCR frequencies undergo blue shift and here we get the maximum PCR of more than 99% in both the resonating frequency bands for the applied chemical potential of $\mu = 0.9$ eV. The shift in PCR is due to the change in coupling strength of electromagnetic wave through the change of surface conductivity of two-dimensional single layer graphene [20].

V. CONCLUSIONS

Here, a dual band tunable mid-infrared cross polarization converter has been designed by using a three layered structure with the top surface as double L-shaped perforated graphene sheet. The structure exhibits orthogonal polarization conversion at 32.39 THz and 38.96 THz with the respective PCR values of 99.95% and 99.66%. The analysis shows that the designed polarization converter performs orthogonal polarization conversion over fractional FWHM bandwidths of $\sim 7.50\%$ and $\sim 1.51\%$ respectively with respect to the center frequencies. The two polarization conversion frequencies of both bands are caused by magnetic resonances. The structure is also studied by altering the Fermi energy of the graphene and it is observed that at Fermi energy of 0.9 eV, maximum polarization conversions can be realized at two different frequency bands. The proposed graphene metasurface structure is thin; $\sim \lambda/6$ with respect to the lowermost frequency band.

REFERENCES


