A micro-scaled graphene-based tree-shaped wideband printed MIMO antenna for terahertz applications

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Abstract
A tree-shaped graphene-based microstrip multiple-input and multiple-output (MIMO) antenna for terahertz applications is proposed. The proposed MIMO antenna is designed on a $600 \times 300 \ \mu m^2$ polyimide substrate. The designed MIMO antenna provides a wide impedance bandwidth of 88.14% (0.276–0.711 THz) due to the suggested modifications in the antenna configuration. The MIMO design parameters like total active reflection coefficient (TARC), mean effective gain (MEG), envelope correlation coefficient (ECC) and diversity gain (DG), channel capacity loss (CCL) are evaluated, and their values are found within acceptable limits. The proposed MIMO structure offers $MEG \leq -3.0 \ dB$, $TARC \leq -10.0 \ dB$, $DG \approx 10 \ dB$, $CCL < 0.5 \ bps/Hz/s$ and $ECC < 0.01$ at the resonant frequency. At the resonant frequency, the isolation between the radiating elements of the proposed MIMO antenna is recorded as $-52 \ dB$. The variations in operating frequency and S-parameters are also analyzed as a function of the chemical potential ($\mu_c$) of the graphene material. The parametric analysis, structural design evolution steps, surface current distribution, antenna characteristics parameters and diversity parameters are discussed in detail in this paper. The designed MIMO antenna is suitable for high-speed short-distance communication, video-rate imaging, biomedical imaging, sensing and security scanning in the THz frequency band.

Keywords THz communication · MIMO antenna · Wideband · Diversity gain · Chemical potential · Isolation

1 Introduction

Over the last few decades, the modern trend of wireless communication shows increasing demand for faster data rates and as a result, an outstanding evolution has been witnessed in the field of wireless communication technology [1, 2]. The remarkable research developments in mobile communication systems (3G to 5G) have opened up many new application opportunities by ensuring enhanced data connectivity [3–5]. So, it is becoming essential to have a massive operating frequency spectrum to meet the requirements of next-generation communication applications. But, in the coming future, 5G technology in the mm-wave band will not be sufficient to satisfy the global need of gigantic data rate in terabits/sec (Tbs) and enormous channel capacity for rapidly growing applications like Tbps Internet of things (Tera-IoT), ultra-wideband THz space communication and secure high-speed short-range indoor communication [6, 7]. The possible key wireless technology can be terahertz wireless communications (Tera Com) with its potential operating bands from 0.3 to 10 THz (as per IEEE standard) to fulfill the future demands of wireless systems [8]. In present
years, the researchers are carrying out tremendous research activities on shorter wavelength terahertz communication to unlock and utilize its wider segments of available bandwidth for future large-scale applications in civilian and commercial domains. However, apart from promising opportunities, critical issues like very high propagation path loss and limited communication distance are also associated with THz communications. It is worthy to note that the characteristics of THz antenna directly influence the performance of THz systems. So, the compact efficient THz antennas are in high demand for the radiation and detection of THz waves. Significant contributions have been reported by investigating the advantageous properties of conducting materials like gold [9] and graphene [10–13] for designing highly efficient THz antennas. The requirements of high performance characteristic parameters for micro/nano-scaled THz antenna have created many new challenges as well as possibilities that will definitely help in the advancement of antenna technology. The widely reported THz antenna designs include the metallic antenna [14], dielectric-radiator based antenna [15], photonic crystal based antenna [16], on-chip antenna [17], metamaterial loaded antenna [18], substrate integrated waveguide (SIW)-based antenna [19], leaky wave antenna [20], lens antenna [21], graphite antenna [22] and horn antenna [23]. However, the complex design process, higher manufacturing cost, larger dimensions and difficulty in integration with planar circuits are the major concerns of these THz antenna structures. On the other hand, with the growing popularity of planar technology, microstrip antenna has become the point of attraction for terahertz short-range wireless applications due to its various advantages like low cost, design simplicity, light weight and compact size. Despite significant advantages, it suffers from narrow bandwidth which limits its applications in the wide THz regime. So, the challenge is to design compact, less voluminous antennas with wide operating bandwidth to support multiple applications in the THz frequency band. In the literature, researchers have designed and reported some compact THz antennas but they are capable to operate with very narrow bandwidths of 5.85% [24], 8.2% [25], 3.78% [26] and 6.67% [27], which restricts their suitability for a wideband short-distance high-speed wireless THz communications. So, the researchers have proposed different design methods to improve the bandwidth of the microstrip antenna in the THz regime by implementing photonic crystal structures [28, 29], photonic crystal-based frequency selective surface [30], electromagnetic crystal substrate [31], unslotted simple rectangular patch [32, 33], adding superstrate [34] and incorporating slots on patch [23]. Also, a multi-layer array antenna is investigated and proposed in ref [35]. However, these reported THz antenna structures show improvement in operating bandwidth at cost of a larger antenna dimension. The authors of these reported papers designed only single antenna element for single-input single-output wireless communication systems and also these reported wideband single element THz antennas face the challenge of fading for high-speed short-range wireless applications at THz frequency band. This issue of signal fading can be easily overcome by utilizing the spatial diversity multiple-input and multiple-output (MIMO) technique [36, 37]. In this context, very recently in the year 2021, Okan [38], has published his findings on THz 2 × 2 MIMO antenna which exhibits an impedance bandwidth of 0.114 THz (from 0.093 to 0.207 THz, 76% fractional bandwidth) and isolation less than −17 dB but at the cost of large antenna dimension of 2000 × 1000 × 100 µm³. In [39], Singh et al. reported another MIMO antenna of 1600 × 800 mm² dimension that operates from 0.618 to 1 THz with 57.96% fractional bandwidth.

This motivated the authors of this paper to design and analyze a compact microstrip MIMO antenna with wide impedance bandwidth and better diversity performance for high-speed short-range wireless communication systems in the THz band. In this paper, the authors have designed a two-element spatial diversity multiple-input multiple-output (MIMO) THz antenna which occupies less area and offers much better impedance bandwidth compared to the reported single element antennas [28–35], array antenna [35] and MIMO antennas [38, 39]. The reason behind the selection of spatial diversity MIMO antenna is to exploit its multipath characteristics to provide high data rate, better channel capacity, interference mitigation, extended coverage and improved signal reliability by avoiding fading.

In this proposed work, a tree-shaped MIMO antenna is designed using a polyimide substrate. The polyimide substrate is utilized due to its wide popularity in micro-scaling applications. It exhibits exceptional characteristics like, chemical resistance, thermal stability and mechanical toughness all together. It is one of the popular dielectric material for the designing terahertz antennas due to its cost-effectiveness, low dielectric constant and excellent electrical insulation properties (high breakdown field, low dielectric loss factor and low conductivity). Graphene is employed as the conducting material to design the patch and gold is used at the ground plane of the suggested antenna configuration. In this proposed terahertz antenna model, the polyimide as a substrate, graphene and gold as conducting materials are employed to achieve the best possible characteristic parameters for the suggested antenna geometry. Due to the suggested patch and monopole ground plane structure in the design, the operating bandwidth of the proposed MIMO structure is improved. The proposed MIMO structure with an attractive size of 600 µm × 300 µm maintains the impedance bandwidth from 0.276 THz to 0.711 THz with Reflection Coefficient (S₁₁) ≤ −10 dB. The suggested MIMO antenna is useful for high-speed short-range communication in indoor
environments, video-rate imaging, biomedical imaging, sensing and security scanning in the terahertz frequency band.

The main highlights and novelties of the proposed design are as follows.

i. The proposed graphene-based planar MIMO antenna is designed with microstrip technology. Hence, it is less voluminous, light weight, easy to design and requires less implementation cost compared to other types of available THz antennas [14–21, 23].

ii. The proposed antenna exhibits a much wider − 10 dB impedance bandwidth (0.276–0.711 THz) of 88.14% compared to other reported THz microstrip antennas [24–35, 38, 39].

iii. The proposed printed MIMO antenna is designed with two radiating patch elements but still, it occupies less implementation area of 600 × 300 μm² compared to the previously reported single element antennas [28–35, 38, 39].

iv. The proposed MIMO structure offers better diversity performance parameters (MEG ≤ − 3.0 dB, TARC ≤ − 10.0 dB, DG ≈ 10 dB, CCL < 0.5 bps/Hz/s and ECC < 0.01) which helps to overcome the challenges associated with short-distance communication like signal fading, multipath propagation and increased interference. Hence it is preferable as compared to the reported single input single output (SISO) microstrip THz antenna structures [24–35] and array structure [33] to support high-speed short-distance communication at terahertz frequency with more data rate and reliability.

v. The proposed MIMO antenna provides a much better impedance bandwidth of 0.435 THz (0.276–0.711 THz, fractional BW = 88.14%) and isolation characteristics (less than − 20 dB across the entire working band) in a more compact dimension of 600 × 300 × 45 μm³ as compared to the recently reported THz MIMO antennas [38, 39].

vi. The MIMO antenna is having isolation of less than − 20 dB across the whole wideband of operation; therefore, it can be applied for point-to-point communication at THz frequency.

2 Proposed wideband THz MIMO antenna design and investigation on characteristics of graphene material in THz band

2.1 Structure of the proposed MIMO antenna

The structure of the proposed tree-shaped MIMO antenna for THz applications is shown in Fig. 1. The front face of the structure is displayed in Fig. 1a which shows the tree-shaped patch elements connected with the microstrip feed line. Figure 1b represents the rear face of the structure which indicates the partial rectangular ground planes of the proposed MIMO antenna. The suggested structure is designed by cutting the edges of a circular shaped patch suitably to form a tree-shaped metallic patch structure. On the bottom plane, individual rectangular monopole ground planes are designed for the patches to achieve wideband resonance characteristics in the operating terahertz band. The proposed MIMO design has been executed on a polyimide substrate with a dielectric constant of 4.3, loss tangent 0.004 and thickness of 45 μm. The graphene material with a thickness of 0.335 nm is considered for designing the patches on the top layer while gold as a conducting material is employed for the design consideration of the ground plane of this suggested THz MIMO antenna design. The overall area of the proposed MIMO structure is W × L = 600 × 300 μm². A microstrip feeding line of 60 μm is used to utilize the feed power for the current MIMO structure through a 50 ohms SMA connector for producing effective radiations which ensure that the maximum amount of power is transferred at the input. The major structural parameters of the proposed MIMO antenna as represented in Fig. 1 are summarized in Table 1.

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**Fig. 1** Proposed THz MIMO antenna
2.2 Design evolution of the proposed antenna

The step-by-step design analysis of the THz MIMO design is demonstrated in Fig. 2a–c. The corresponding S-parameters of each designed stage are presented in Fig. 3a, b. In stage 1 of the design evolution process, the radiating patches are considered as simple rectangular shapes with partial rectangular ground planes as indicated in Fig. 2a. In this stage, the antenna resonates at 0.628 THz with reflection coefficient $(S_{11})$ of $-20.75$ dB and transmission coefficient $(S_{21})$ of $-10$ dB. In stage 1 of the design, the antenna shows an impedance bandwidth of 266 GHz (0.486–0.752 THz).

![Design stage 1 front view (patch)](image1)

![Design stage 1 back view (ground plane)](image2)

![Design stage 2 front view (patch)](image3)

![Design stage 2 back view (ground plane)](image4)

![Design stage 3 front view (patch)](image5)

![Design stage 3 back view (ground plane)](image6)

Fig. 2 Design evolution stages of the proposed THz MIMO antenna

| Parameter | $W$ | $L$ | $a$ | $b$ | $c$ | $d$ | $e$ | $f$ | $g$ | $h$ | $s$ |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Unit      | 600 | 300 | 59.5| 52.9| 56.1| 56.1| 52.9| 22  | 59.5| 100 | 195 |
| Parameter | $i$ | $j$ | $k$ | $l$ | $m$ | $n$ | $o$ | $W_{g1}$ | $L_{g1}$ | $W_{g2}$ | $L_{g2}$ |
| Unit      | 120 | 240 | 180 | 110 | 100 | 90  | 60  | 240 | 60  | 240 | 60  |
Figure 2b shows the second step of the design process. In stage 2 of the design evolution process, the structure of the radiating patches has been modified to form a new front plane geometry by adding three ellipses within the rectangular patches to improve the reflection and transmission coefficient parameters. The ground plane remains the same as observed in stage 1. In stage 2, the designed antenna resonates at 0.698 THz with $S_{11}$ of $-32.43$ dB and $S_{21}$ of $-24.23$ dB. So, significant improvement is noticed in terms of return loss and isolation compared to stage 1. But the operating bandwidth of the antenna is not enhanced as per expectations with the suggested change in antenna geometry as presented in Stage 2 of the design process. In stage 2, the overall bandwidth is enhanced by 25 GHz and the new operating bandwidth is 291 GHz ranging from 0.461 to 0.752 THz. Finally, to bring further improvement in operating bandwidth, reflection coefficient and isolation, the structure of the antenna has been further modified in stage 3 (proposed MIMO antenna) of the design process as indicated in Fig. 2c. In the front plane of the geometry, another three ellipses are introduced within the patches which resemble a tree-shaped and in the backplane, individual monopole ground planes are used to provide major improvements in bandwidth, reflection coefficient and isolation values. The incorporation of the ellipse slots excites additional resonances. Due to the introduction of ellipse-shaped slots in the patch, the electrical dimensions of the antenna increases due to the circular of surface current around the corner edges of the ellipses; hence, it lengthened the path of surface current on the patch which in turn lowers the values of $S_{11}$ at lower edge of the spectrum and shifts the resonance to a lower value. However, the physical dimensions of the antenna remain the same. Consequently, at this final stage, the resonant frequency is shifted to a lower size and the proposed antenna resonates at 0.472 THz with $S_{11}$ of $-38.43$ dB and $S_{21}$ of $-52.86$ dB. Due to the suggested changes in the final antenna geometry, the operating bandwidth is enhanced by an amount of 144 GHz as compared with the previous design step (stage-2). The proposed MIMO antenna provides wide operating bandwidth of 0.435 THz (0.276–0.711 THz, fractional BW = 88.14%).

2.3 Characteristic analysis of graphene

The graphene material shows higher thermal and electrical conductivity compared to copper and silver. The graphene material offers high charge carrier mobilities which allow the electrons to move with minimal resistance in graphene material, and this enables a much faster speed of electricity than conventional metal. This property helps in the formation of unique electromagnetic radiation in the THz frequency of operation compared to conventional metal-based antennas. The quantum–mechanical based electron transport (quantum scattering) techniques have been adopted to understand graphene properties for probing enhanced transmission and THz properties of the graphene structures [40, 41]. In Ref. [40], the efficient terahertz electromagnetic response of graphene was explained with free background Dirac electrons to investigate the effective energy transfer between the THz field and graphene through a nonlinear intraband conductivity mechanism. In [41], the variation in conductivity of graphene under an applied voltage, barrier velocity, different numbers of barriers and carbon atoms was examined with an important conclusion that the shifting of threshold energy of the conductance is possible with an increase in the magnitude of applied voltage. On the other hand, it can be stated that the surface conductivity parameter of graphene material varies with temperature ($T$), radian frequency ($\omega$) chemical potential ($\mu_c$), bias magnetostatic field ($B_0$) and scattering rate ($\Gamma = 1/\tau$). The applied electrostatic field is expressed in terms of chemical potential. For the field $B_0=0$, the graphene Hall’s conductivity becomes zero. According to the kubo’s reports, $\sigma_g$ is a combination of diagonal and Hall’s conductivity. Thus, the component of $\sigma_g$ is occurred only due to the field component ($E_0$) which is called the diagonal conductivity. For graphene material, the diagonal conductivity is the combination of Intraband and interband transitions [42]. The real part of the interband conductivity
at lower frequencies remains negligible as reported in [43]. In this case of our designed MIMO structure, \( \sigma_{i} \) is obtained only by the intraband contribution as it works at terahertz frequency. According to Drude’s form representation, the intraband conductivity for graphene reported [44] can be represented as in Eq. (1)

\[
\sigma_{\text{intraband}}(\omega, \mu_{c}, \Gamma, T) = -\frac{e^{2}K_{B}T}{\pi\hbar^{2}(\omega - j2\Gamma)} \times \left( \frac{\mu_{c}}{K_{B}T} + 2\ln \left( \frac{\omega}{2\pi e^{2}} + 1 \right) \right)
\]

(1)

where \( h \) is Planck’s constant, \( K_{B} \) represents Boltzmann’s constant and \( e \) is the charge of an electron.

\[
\sigma_{\text{intraband}}(\omega, \mu_{c}, \Gamma, T) \approx -\frac{je^{2}}{4\pi\hbar} \ln \left( \frac{2|\mu_{c}| - (\omega - j\Gamma)h}{2|\mu_{c}| + (\omega - j\Gamma)h} \right)
\]

(2)

The approximated interband conductivity of graphene is expressed in Eq. (2). It is approximated by the condition \( K_{B}T \approx |\mu_{c}| \) and \( K_{B}T \approx \hbar\omega \). From Eq. (2), it can be observed that \( \sigma_{\text{intraband}} \) is imaginary with a corresponding negative magnitude at the lower frequency range. At higher frequency, it becomes complex with real part value \( \pi\varepsilon^{2}/2\hbar \) and the corresponding imaginary part value is negative. Here \( K_{B}T \approx |\mu_{c}|; K_{B}T \approx \hbar\omega; h\omega = 2|\mu_{c}| \).

The characterization of graphene material is done by its displacement vector \((D_{n})\) which is normal to the surface of the graphene patch. For homogenous dielectric material, the displacement vector of the graphene patch is \( D_{n} = \varepsilon_{r}\varepsilon_{0} \). Here \( \varepsilon_{r} \) is the permittivity of the homogenous dielectric, \( \varepsilon_{0} \) is the two-sided graphene surface charge density [45]. The surface charge density can be evaluated by using Eq. (3).

\[
n_{s} = \frac{2}{\pi\hbar^{2}v_{f}^{2}} \int_{0}^{\infty} E(f_{d}(E) - f_{d}(E + 2\mu_{c})) \, dE
\]

(3)

Here, \( f_{d}(E) \) represents the Fermi–Dirac distribution function which is interms of energy, \( f_{d}(E) = \left( e^{\frac{E - \mu_{c}}{k_{B}T}} + 1 \right)^{-1} \).

The parametric investigation has been carried out to observe the effect of various major structural parameters on the reflection coefficient and isolation characteristics of the suggested MIMO design. The dimension of feed line width ‘g’ and inter-element spacing of two patches ‘k’ play a vital role in achieving the desired resonance responses. All the parametric studies have been performed and analyzed by varying only one structural parameter at a time while keeping all other parameters fixed to their optimized dimensions. The variations in \( S_{11} \) and \( S_{22} \) parameters as a function of geometrical parameter ‘g’ are shown in Fig. 5a, b. The variations in the response of reflection coefficient \((S_{11})\) and isolation \((S_{22})\) are observed by setting the dimension of the parameter \( g = 50 \mu m, 55 \mu m \) and \( 60 \mu m \). It is clearly presented in Fig. 5a that best impedance matching is obtained for the proposed value of \( g = 60 \mu m \), and thus, the reflection coefficient reaches a maximum level of \(-39\) dB at 0.472 THz for the proposed dimension of ‘g’. Also, from the expression of the nonlinear equation, it can be concluded that the conductivity of graphene completely depends on its chemical potential \( (\mu_{c}) \). The value of \( V_{0} \) provides that voltage-dependent parameter compensation to the chemical potential \( (\mu_{c}) \). In this DC bias voltage, expression ‘t’ indicates thickness and \( \varepsilon_{r} \) indicate permittivity of a dielectric substrate. Here \( V_{0} \) is considered as zero. Figure 4 represents the real and imaginary parts of the intraband conductivity of the graphene at 0.16 eV.

### 3 Parametric variations of the MIMO design

#### 3.1 Effect of structural parameters on reflection coefficient \((S_{11})\) and transmission coefficient \((S_{21})\) characteristics

The parametric investigation has been carried out to observe the effect of various major structural parameters on the reflection coefficient and isolation characteristics of the suggested MIMO design. The dimension of feed line width ‘g’ and inter-element spacing of two patches ‘k’ play a vital role in achieving the desired resonance responses. All the parametric studies have been performed and analyzed by varying only one structural parameter at a time while keeping all other parameters fixed to their optimized dimensions. The variations in \( S_{11} \) and \( S_{22} \) parameters as a function of geometrical parameter ‘g’ are shown in Fig. 5a, b. The variations in the response of reflection coefficient \((S_{11})\) and isolation \((S_{22})\) are observed by setting the dimension of the parameter \( g = 50 \mu m, 55 \mu m \) and \( 60 \mu m \). It is clearly presented in Fig. 5a that best impedance matching is obtained for the proposed value of \( g = 60 \mu m \), and thus, the reflection coefficient reaches a maximum level of \(-39\) dB at 0.472 THz for the proposed dimension of ‘g’. Also,
maximum − 10 dB bandwidth is attained when the parameter \( g \) is set to an optimized value of 60 \( \mu m \). Similarly, the variations in transmission coefficient \( (S_{21}) \) versus frequency due to change in parameter ‘\( g \)’ is plotted in Fig. 5b. The isolation of the designed MIMO structure reaches its best value of − 52 dB at 0.472 THz and also the isolation below − 20 dB is maintained across the whole operating band for the proposed value of \( g = 60 \mu m \). When the parameter ‘\( g \)’ is changed from the optimized value to 50 and 55 \( \mu m \), the isolation value decreases to − 19, and − 21 dB at the resonant frequency of 0.472 THz and also the overall isolation value is degraded across the entire operating band. The influence of design parameter ‘\( k \)’ on \( S_{11} \) and \( S_{21} \) characteristics is demonstrated in Fig. 5c, d. Significant variations are observed in terms of reflection coefficient and isolation characteristics due to a change in parameter \( k \) that specifies the spacing between the patch elements. The changes in reflection coefficient and isolation are recorded by varying the distance between the patches ‘\( k \)’ with 180 \( \mu m \), 170 \( \mu m \) and 160 \( \mu m \). It can be noticed that the values of \( S_{11} \) and \( S_{12} \) parameters get improved with an increase in parameter \( k \). As indicated in Fig. 5c, the maximum reflection coefficient of − 39 dB at the resonant frequency of 0.472 THz is obtained for the proposed value of \( k = 180 \mu m \). Any further changes in parameter \( k \) (170 \( \mu m \) and 160 \( \mu m \)) lead to degradation in the \( S_{11} \) parameter and also shift in resonant frequency. Similarly, Fig. 5d represents as per expectation that the maximum isolation \( (S_{21}) \) at the resonant frequency along with best isolation characteristics across the entire operating band are obtained for the suggested value of \( k = 180 \mu m \). So, the selection of optimized values of these design parameters \( (g \) and \( k \)) are justified according to their \( S_{11} \) and \( S_{21} \) responses.

### 3.2 Effect of chemical potential \( (\mu_c) \) on reflection coefficient \( (S_{11}) \) and transmission coefficient \( (S_{21}) \) characteristics

The tuning of the chemical potential of graphene material can affect the resonance characteristics of the MIMO antenna. In fact, the resonant frequency of the antenna can be tuned based on the variations of chemical potential \( (\mu_c) \) which leads to flexible control of the resonance of the designed antenna. The tunability of resonance response by varying various chemical potentials of the graphene is shown in Fig. 6. Figure 6a shows the variation of frequency with TM02 mode of operation. It can be identified that the resonant frequency varies almost linearly with respect to the change in chemical potential \( (\mu_c) \). The variations in S-parameters \( (S_{11} \) and \( S_{21} \)) as a function of uniform change in \( \mu_c \) are depicted in Fig. 6b, c, respectively. The resonant frequency shifts toward higher resonance with an increment in the value of chemical potential.
4 Result analysis and discussions

4.1 S-Parameters

Figure 7 shows the S-parameter response of the proposed MIMO antenna obtained using the CST simulation and electrical equivalent circuit model (ECM). The value of electrical component is calculated, and the electric circuit model of antenna is developed using the circuit theory approach [37]. The calculated value of the circuit parameters is as \( R = 50\Omega, L = 5.3pF \) and \( C = 9.38fF \). Figure 7a shows the ECM of the proposed antenna. The results obtained from the circuit theory approach are in good agreement with those obtained from the simulation validating the antenna operation. Due to the symmetry of the antenna structure, the reflection coefficients of the designed MIMO system at the dual ports are the same (\( S_{11} = S_{22} \)). It is indicated that the designed MIMO structure shows an attractive wideband resonance characteristic covering 0.276 to 0.711 THz with an impedance bandwidth of 435 GHz for \( S_{11} \leq -10 \) dB which is 88.14% fractional bandwidth with respect to the center frequency at 0.4935 THz. The transmission coefficient (\( S_{21} \)) is maintained below \(-20 \) dB over the entire operating band for the proposed MIMO design. A maximum transmission coefficient of about \(-52 \) dB is obtained at 0.472 THz. It indicates very high isolation between the antenna elements which is very essential for an efficient MIMO antenna design.
4.2 Surface current distribution

The distribution of surface currents of the proposed THz MIMO design at the resonant frequency of 0.472 THz is shown in Fig. 8. Figure 8a shows the distribution of surface currents when port # 1 of the device is excited. There is a null of the current at the center of feedline and radiating patch. Figure 8b also shows the ground plane contains the current vectors in the anti-parallel direction to that of at the patch, as expected. However, for the proposed MIMO structure, distributions of surface currents are more prominent and stronger at the higher operating frequency for the purpose of characteristics improvement at a higher resonance.

4.3 Radiation characteristics

Figure 9 shows the representation of far-field radiation patterns in E and H planes at 0.472 THz with excitation of port #1 and port #2. The E and H plane radiation patterns are represented in terms of co-pol and cross-pol components. The proposed monopole MIMO configuration exhibits almost identical radiation patterns for the excitation of port 1 and port 2 except slight variation in the cross-pol pattern of the H plane for the port#2 excitation. In the E plane, the co-polarization radiation patterns resemble bi-directional and cross-polarization patterns are omnidirectional for the excitation of port #1 and port #2. Similarly, the H plane patterns are observed with separate excitations at dual ports. The proposed MIMO antenna maintains the desired monopole like omnidirectional co-polarization radiation patterns in the H plane. Relatively low cross-polarization levels of below − 20 dB are attained for both the principal planes, which is quite acceptable. The radiation efficiency and gain of the proposed MIMO structure are also evaluated and presented in Fig. 10. The variations of the radiation efficiency are presented in Fig. 10a. The radiation efficiency of the proposed antenna remains around 7% to 15% over the entire operating band. Furthermore, the graphene antennas are not so much efficient in terms of gain, hence, the directivity is reported here which remains around 4.27 dBi at the resonant frequency of the antenna.

5 Analysis of MIMO parameters

The benefit of the MIMO system is that it supports the data rate enhancement for the system even which is under the conditions of signal fading, multipath fading and interference. The demand for the higher amount of data rates for transmitting longer distances is the one of major motivation behind the MIMO system for satisfying the acceptable values of MIMO parameters. In order to ensure the compatibility of the designed wideband THz antenna in MIMO applications, the envelope correlation coefficient (ECC) and diversity gain (DG), total active reflection coefficient (TARC), channel capacity loss (CCL) and mean effective gain (MEG) parameters are evaluated and discussed [47].
These MIMO performance evaluation parameters are shown in Fig. 11.

5.1 Envelope correlation coefficient (ECC)

The parameter ECC defines the amount of correlation of far-field radiation pattern excited at different ports of the MIMO structure. ECC of any MIMO design must be as small as < 0.5. [48]. It is evaluated by far-field parameters at the corresponding resonant frequency using Eq. (6) reported [44].

$$\rho_{ij} = \left[ \frac{\iint (E_{\theta_1}E_{\theta_1}^* + E_{\phi_1}E_{\phi_1}^*)d\Omega}{\iint (E_{\theta_1}E_{\theta_1}^* + E_{\phi_1}E_{\phi_1}^*)d\Omega} \right]^2$$

Here $\rho_{ij}$ is the Envelope Correlation Coefficient (ECC) of antenna $i$th and $j$th elements of the system and $\Omega$. 

Fig. 9 Radiation patterns of THz MIMO antenna at 0.472 THz a Port 1 excited, b Port 2 excited

Fig. 10 Radiation efficiency and directivity characteristics of THz MIMO design. a Radiation efficiency, b directivity

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Fig. 11. MIMO parameters a ECC, b diversity gain, c MEG, d total active reflection coefficient (TARC), e channel capacity loss (CCL)

represents the solid angle. The evaluation of ECC using far-field radiation parameters is a complex procedure. Another way of measuring ECC using the S-parameters method by Eq. (7) reported in [49].

\[
\rho_{ij} = \frac{\left| S_{11}^* + S_{12} S_{22}^* \right|^2}{\left( 1 - \left| S_{11} \right|^2 + \left| S_{21} \right|^2 \right) \left( 1 - \left| S_{22} \right|^2 + \left| S_{12} \right|^2 \right)} \tag{7}
\]

The ECC versus frequency result of the proposed design is shown in Fig. 11a. It can be observed that ECC remains less than 0.001 across the entire wide operating bandwidth (0.276–0.711 THz) of the antenna. Furthermore, the ECC is recorded as 0.0458 at the resonant frequency of 0.472 THz. The lower value of the obtained ECC indicates a lower correlation between antenna elements. The values are well below the acceptable limit of 0.5 that guarantees good MIMO performance of the proposed antenna.

5.2 Diversity gain (DG)

Diversity techniques are used to reduce the impact of fading by combining antenna elements that experience different fading. The diversity gain is defined as the time-averaged difference between signal-to-noise ratio combined within diversity antenna system and its corresponding single antenna system within single diversity of the channel. The parameter DG can be evaluated in terms of maximum theoretical diversity gain (10 dB) and envelope correlation coefficient by using Eq. (8) reported in [50]. The higher value of diversity gain means better isolation between the
patch elements of the MIMO antenna. The DG should be greater than 9.95 dB. As drawn in Fig. 11b, the approximate values of DG are greater than 9.99 dB throughout the entire operating band of the antenna. This ensures very good diversity performance of the proposed MIMO structure.

\[
DG = 10\sqrt{1 - |ECC|^2}. \quad (8)
\]

5.3 Mean effective gain (MEG)

The Mean Effective Gain (MEG) is a measure of the amount of average power received by the diversity antenna in the fading environment relative to the sum of average powers that would have been received by two isotropic antennas. It illustrates the performance gain of the MIMO antenna with consideration of their environmental effects. The MEG is evaluated at both ports of the designed structure using Eq. (9) as indicated in [51].

\[
MEG_i = 0.5\eta_{i,\text{rad}} = 0.5 \left[ 1 - \sum_{j=1}^{M} |S_{ij}|^2 \right] \quad (9)
\]

Here, \( M \) indicates the total number of ports in MIMO design and radiation efficiency (\( \eta_{i,\text{rad}} \)) of the current MIMO design structure. The value of MEG should be \(-3\) dB at each port of the device and the difference between both ports must be approximately 0 dB to ensure better diversity performance. The current MIMO structure design follows the limits in acceptable ranges. Figure 11c shows the frequency versus MEG which is remaining around \(-3\) dB and also identified that the variation among MEG 1 and MEG 2 is almost 0 dB.

5.4 Total active reflection coefficient (TARC)

When using multiple ports Total Active Reflection Coefficient (TARC) is the best parameter to represent the radiation performance and frequency response [52]. Total Active Reflection Coefficient (TARC) is defined as the ratio of the square root of the total reflected power divided by the square root of the total incident power in a MIMO system. TARC accounts for mutual coupling along with random signal combinations between ports. It is represented by Eq. (10) using reflected and incident waves. It can also be evaluated by using Eq. (11) in terms of S-parameters as reported in [51]. The TARC of the proposed MIMO antenna is shown in Fig. 11d. The obtained result is suitable for the intended applications for the best MIMO performance in the THz band.

\[
\Gamma_a = \sqrt{\frac{\sum_j |b_j|^2}{\sum_j |a_j|^2}} \quad (10)
\]

Here, \( a_j \) and \( b_j \) indicate the incident and reflected waves.

\[
\Gamma_a = \sqrt{\frac{(S_{11} + S_{12}\exp^{\jmath\theta})^2 + (S_{21} + S_{22}\exp^{\jmath\theta})^2}{2}} \quad (11)
\]

where ‘\( \theta \)’ represents the phase of the signal input.

5.5 Channel Capacity Loss (CCL)

Another important parameter is Channel Capacity Loss (CCL) to evaluate the MIMO performance of the designed THz antenna. The channel capacity loss defines the maximum limit of the information transmission rate without significant loss. It should be <0.5 bits/s/Hz for a well-designed MIMO system to indicate lossless information transmission. The CCL parameter can be obtained by using Eq. (12) reported in [53].

\[
C_{\text{loss}} = -\log_2 \det(a^R) \quad (12)
\]

\[
a^R = \begin{pmatrix}
\rho_{11} & \rho_{12} \\
\rho_{21} & \rho_{22}
\end{pmatrix} \quad (13)
\]

where \( i, j = 1 \) or 2 (14).

where \( a^R \) indicates the correlation matrix at the receiving antenna.

The simulated CCL is presented in Fig. 11e. It is recorded below the specified limit for the proposed THz MIMO antenna. Its value is only 0.00018 bits/s/Hz at the resonant frequency of 0.472 THz for the proposed MIMO design. So, with the available CCL, it can be confirmed that the proposed antenna delivers more transmission data rate in any scattering environment.

6 Performance analysis with some other printed THz antennas

The performance of the proposed terahertz MIMO antenna is compared with some other microstrip THz antennas. The analyzed performance comparison is summarized in Table 2. It is clear from the comparison table that the proposed antenna offers broader impedance bandwidth and requires the smallest dimension as compared with reported single element THz antenna structures [25–32], multi-layered THz array antenna structure [33] and recently reported MIMO
antenna structures [34, 35]. So, the novelty of the proposed design is wider impedance bandwidth in relatively smaller antenna size along with good impedance, radiation and diversity characteristics as discussed in the preceding sections of the manuscript.

7 Conclusion

In this paper, a graphene-based wideband microstrip MIMO antenna for terahertz wireless communication applications is proposed. The performance of the proposed design has been analyzed and discussed in terms of its various antenna characteristics parameters like impedance bandwidth, surface current distribution, reflection coefficient, gain, efficiency, radiation characteristics. Furthermore, different diversity parameters like ECC, DG, TARC, MEG and CCL are also investigated and presented to confirm the suitability of the proposed antenna for MIMO applications. The proposed THz MIMO antenna resonates at 0.472 THz with a return loss of −39 dB and exhibits a wide impedance bandwidth characteristics covering 0.276 to 0.711 frequency spectrum in the terahertz regime. The designed antenna maintains isolation < −20 dB over the entire operating range with maximum isolation of −52 dB at resonant frequency 0.472 THz. The good MIMO performance is ensured by attaining the MIMO performance parameters [ECC (< 0.01), CCL (< 0.5), MEG (≤ −3 dB), DG (∼ 10 dB), and TARC (≤ 10 dB)] within acceptable limits. The proposed MIMO antenna is suitable for high-speed short-distance indoor communication applications, video-rate imaging, biomedical imaging, sensing and security scanning in the terahertz frequency band.

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Table 2 Comparison table with existing THz designs

| References | Size of the antenna structure (μm²) | Substrate | Operating center frequency (THz) | −10 dB bandwidth (THz) | Bandwidth (%) | Antenna configuration |
|------------|-----------------------------------|-----------|---------------------------------|------------------------|---------------|----------------------|
| [25]       | 800×600×191.29                    | Polyimide | 0.632                           | 0.615–0.6514           | 5.75          | Single element       |
| [26]       | 600×600×90                        | Polyimide | 0.65                            | 0.5–0.8                | 46.15         | Single element       |
| [27]       | 500×50                            | Pyrex     | Narrowband (value not reported) | Not reported           |               | Single element       |
| [28]       | 1000×1000                          | 2D Electromagnetic crystal substrate | 0.775                     | 0.6–0.95              | 34.3          | Single element       |
| [29]       | 1000×1000                          | RT/Duroid 6006 | 0.775 | 0.7–0.85              | 19.35         | Single element       |
| [30]       | 700×600                            | RT/Duroid 6006 | 0.775                     | 0.7–0.85              | 19.35         | Single element       |
| [31]       | 1000×1000                          | RT/Duroid 6006 | 0.7                      | 0.6–0.8               | 22.47         | Single element       |
| [32]       | 1200×460                          | RT/Duroid 6006 | 0.3065                     | 0.258–0.355           |               | Single element       |
| [33]       | 1122×280                           | Indium phosphide (InP) and benzocyclobutene (BCB) | 0.335                   | 0.294–0.376          | 27.3          | Multi-layer array    |
| [34]       | 2000×1000                          | Rogers RO4835-T | 0.15                     | 0.093–0.207           | 76            | MIMO                 |
| [35]       | 1600×800                           | Polyimide          | 0.809                       | 0.618–1.0             | 57.96         | MIMO                 |
| Proposed structure | 600×300                            | Polyimide          | 0.4935                     | 0.276–0.711          | 88.14         | MIMO                 |
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