Tunable four-port MIMO/self-multiplexing THz graphene patch antenna with high isolation

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Abstract
A tunable terahertz four-port multiple-input-multiple-output (MIMO) graphene-based microstrip patch antenna with self-multiplexing ability is designed and numerically studied. Insertion of cross-slot in the graphene patch improved the isolation level to the order of $50\text{–}70\text{ dB}$ in the four-port MIMO mode operation. Four separate biasing pads are used to obtain independent frequency tunability, which gives rise to MIMO and/or self-diplexing, self-triplexing, and self-quadruplexing operation, by using different combinations of dc bias voltages. The MIMO and self-multiplexing actions are attained while using common ground plane and continuous graphene patch. The MIMO performance parameters like envelope correlation coefficient (ECC), diversity gain, mean effective gain, port-to-port isolation, etc. are found to be within the acceptable limits. A four-port equivalent circuit model of the MIMO antenna is presented to provide insight into the radiation mechanism and to validate the simulation results. The designed four port antenna is found to provide ECC in the order of 0.0073 and isolation in the range of 35–43 dB while it is operated in the self-diplexing with two-port MIMO mode operation.

Keywords Graphene · MIMO · Self-multiplexing · Terahertz · Patch antenna

1 Introduction
The terahertz (THz) frequency ranging from 0.1 to 10 THz with wavelength ranging from 3mm to 30μm is being explored owing to its capability in providing the wide bandwidth, high data rates, and high-speed miniaturized processing for future communication systems (Akyildiz et al. 2014). In this context, antennas design for THz communication is under consideration for quite some time (Abadal et al. 2019; Akyildiz and Jornet 2016; Dash et al. 2022; Hosseininejad et al. 2019, 2017; Sarieddeen et al. 2019; Tamagnone and
Perruisseau-Carrier 2014; Xu et al. 2014) The multiple-input-multiple-output (MIMO) communication and antenna design for the same is being emphasized for increasing the data rate since inception of the massive MIMO and millimeter wave (mm-wave) beamforming concepts, which is extended to the THz frequency range as well (Akyildiz and Jornet 2016; Ali et al. 2020, 2021; Babu et al. 2022; Das et al. 2021, 2022; Esfandiyari et al. 2019; Faisal et al. 2020; Luo et al. 2019; Malhat et al. 2022; Sarieddeen et al. 2019; Shamim et al. 2021; Temmar et al. 2021; Varshney et al. 2019; Vasu Babu et al. 2022; Vijayalakshmi et al. 2021; Zhang et al. 2019). In many of these works, the massive MIMO antenna system is implemented with separate excitation of each radiator indicating implementation of fully digital beamforming (Akyildiz and Jornet 2016; Faisal et al. 2020; Sarieddeen et al. 2019). A single unit multi-beam MIMO antenna with beam-reconfigurable is introduced in (Luo et al. 2019) for 5G and beyond applications. It is worth noting that the antennas reported in Das et al. (2021), Temmar et al. (2021), Vijayalakshmi et al. (2021) do not offer tunability, which could be attended in micro/nano-scale devices if attempted with proper use of reconfigurable materials (Abdollahramezani et al. 2021; Dash et al. 2021; Kiani et al. 2021; Pascual et al. 2022; Sharma et al. 2020).

The problem of mutual coupling reduction in THz graphene MIMO antennas is addressed in Ali et al. (2021), Das et al. (2022), Vijayalakshmi et al. (2021), Zhang et al. (2019). A graphene-based frequency selective surface (FSS) is used in Zhang et al. (2019), and a metamaterial used in Das et al. (2022) where the structure becomes 3D and its fabrication becomes challenging, and a meandered line decoupling structure is used in Vijayalakshmi et al. (2021) for enhancement of isolation. Recently, a tunable two-port THz MIMO antenna with the option of self-diplexing is reported in Ali et al. (2021), where the isolation is achieved by inserting a slot on the graphene patch. A MIMO antenna with multiplexing ability makes it more useful especially in the present-day multi-standard communication scenario. It is well known that usage of multiple transceivers often leads to undesired higher-order effects like intermodulation distortion (Kumar et al. 2020; Mukherjee and Biswas 2016). Multiplexer circuits such as diplexer, quadruplexer, etc. are used to do away with these problems by improving the isolation (Chuang and Wu 2011). The usage of a separate multiplexer circuit increases the overall size, complexity, and cost of the RF front-end. Therefore, a substantial amount of research is being carried out in designing compact ferrite-free antenna structures having self-multiplexing ability in the RF frequency range: self-diplexing antenna $\left| S_{ij} \right| \approx -25\text{dB}$ (Mukherjee and Biswas 2016), self-quadruplexing antenna $\left| S_{ij} \right| \approx -25\text{dB}$ (Kumar et al. 2020), and self-quadruplexing/MIMO antenna $\left| S_{ij} \right| \approx -20\text{dB}$ (Boukarkar and Lin 2020). To the best of the author’s knowledge, no reconfigurable MIMO/self-quadruplexing antenna, working in the THz band, is available in the literature.

In this era of increased cognitive ability in communication systems, frequency agility would be another desirable characteristic of THz MIMO self-multiplexing antennas (Kumar et al. 2018; Rajo-Iglesias et al. 2014; Ridwan et al. 2021). The tunability is possible at the millimeter scale dimension or the microwave frequency by using the varactor-diode, PIN-diode, and MEMS switches (Dai et al. 2020; Rajo-Iglesias et al. 2014). The THz developments are possible with the micro/nanoscale dimensions which do not allow the usage of these devices for obtaining tunability. In recent investigations, the advent of tunable bandgap materials is paving the way for the implementation of tunable THz devices. Graphene is one of the most promising 2D materials used in THz and mid-infrared frequency bands due to its unique electronic and optical properties (Choudhury and Abou El-Nasr 2017). The application of
electrostatic field on the graphene material can tune its surface conductivity and hence the frequency response of graphene-based devices (Abadal et al. 2019).

In this work, a graphene-based tunable THz four-port proximity-coupled MIMO/self-multiplexing patch antenna is designed. A cross-shaped slot is introduced in the graphene-based radiator which improves the isolation, and it increases the port-to-port isolation by 25−30 dB. The proposed antenna is also studied by engraving the different shape of slot like, circular and square. The proposed antenna provides pattern diversity and can offer multi-directional coverage. The response of each radiating element through the individual port of the antenna can be tuned independently by applying dc bias voltage on the bias pad underneath the graphene patch. Thus, the designed antenna can offer the capability of MIMO with self-diplexing, MIMO with self-triplexing and self-quadruplexing depending upon the value of the applied dc voltage on each radiator. Furthermore, an electrical equivalent circuit model of the proposed antenna is presented to provide insight into the radiation mechanism and validate the results.

2 Antenna design and its evolution

The 3D view of the proposed tunable four-port MIMO/self-multiplexing graphene patch antenna are shown in Fig. 1. The proposed MIMO antenna consists of two silicon dioxide (SiO2) substrates of heights $h_1$ and $h_2$, respectively, and it is being fed by proximity-coupled (see Fig. 1a). A cross-shaped patch of monolayer graphene of thickness 0.34 nm is placed on the top of the upper substrate. Here, the intraband term of the surface conductivity of graphene $(\sigma_{\text{graphene}})$ remains dominant over the interband term as the proposed antenna is designed to work in the lower THz frequency regime (Hanson 2008). According to Kubo formalism, $\sigma_{\text{graphene}}$ is given by:

$$\sigma_{\text{graphene}}^{\text{intraband}} = \frac{q_e^2 k_B T}{\pi \hbar (j\hbar \omega + \frac{\hbar}{\tau})} \left[ \frac{\mu_c}{k_B T} + 2 \ln \left( 1 + \exp \left( -\frac{\mu_c}{k_B T} \right) \right) \right]$$

(1)

where $q_e$, $\omega$, $\hbar$, $k_B$, $\mu_c$, $T$ are the electronic charge, frequency of operation, reduced Planck’s constant, Boltzmann’s constant, chemical potential, and temperature, respectively. Here, $\tau$ is the relaxation time, which generally varies in the range of 0.1−1 ps (Fardoost et al. 2017; 2019).

Fig. 1 Antenna structure (a) perspective separated 3D view (b) zoomed view of the antenna showing polysilicon pads and (c) side view electrostatic biasing mechanism of the radiator ($L_{s1} = 56, L_{s2} = a = 36, h_1 = h_2 = 1.6, b = 14.5, l_p = 18.5, w_p = 4, l_f = 18, w_f = 2$ all the dimensions are in $\mu m$). The structure of this 4-port antenna is fully symmetric with respect to all the ports.
Khan et al. 2021; Li et al. 2017; Ma et al. 2021; Rodrigues et al. 2018; Vasu Babu et al. 2022). Figure 1a shows that all the four ports of the proposed antenna are placed symmetrically. The length of the transmission line that goes under the patches and the height of the upper substrate ($h_2$) are decided such that the antenna remains low-profile while maintaining the impedance matching. One of the main advantages of graphene-based antennas lies in the ease of varying the Fermi energy level or $\mu_c$ of the graphene patch by applying a dc bias voltage. As stated in the Eq. (1), such variation of $\mu_c$ results in easy manipulation of $\sigma_{\text{graphene}}$. In general, the transverse magnetic (TM) surface plasmon polaritons (SPP) mode propagates in graphene at lower THz frequency and the standard dispersion relation relating $k_{\text{spp}}$ and $\omega$ is given by (2) (Gonçalves and Peres 2016):

$$\frac{\epsilon_{r_1}}{\sqrt{k_{\text{spp}}^2 - \epsilon_{r_1} k_0^2}} + \frac{\epsilon_{r_2}}{\sqrt{k_{\text{spp}}^2 - \epsilon_{r_2} k_0^2}} = -\frac{j\sigma_{\text{graphene}}}{\omega \epsilon_0}$$

(2)

$$k_{\text{spp}} = \frac{j2\omega \epsilon_{r,\text{eff}} \epsilon_0}{\sigma_{\text{graphene}}}$$

(3)

$$\lambda_{\text{spp}} = \frac{2\pi}{(k_{\text{spp}})_{\text{Re}}}$$

(4)

with $\epsilon_{r_1} = 1$ and $\epsilon_{r_2} = \epsilon_{r,\text{SiO}_2} = 3.9$. The value of $\sigma_{\text{graphene}}$ comes from the famous Kubo formula, given in Eq. (1). The exact value of $k_{\text{spp}}$ is to be obtained by numerically solving the transcendental Eq. (2). However, an estimate of $k_{\text{spp}}$ could be obtained from the asymptotic value of $k_{\text{spp}}$ given by the closed-form expression of Eq. (3), valid under the approximation $k_{\text{spp}} \gg k_0 \sqrt{\epsilon_{r,\text{eff}}}$. Here, the effective relative permittivity, $\epsilon_{r,\text{eff}}$, is defined as $\epsilon_{r,\text{eff}} = (\epsilon_{r_2} + 1)/2$ (Gonçalves and Peres 2016; Koppens et al. 2011). Finally, Eq. (4) is used to obtain the SPP wavelength from the real part of $k_{\text{spp}}$. For $\mu_c = 0.16$ eV, the operating frequency of the antenna is 1.76 THz, and Eqs. (3) and (4) gives $\lambda_{\text{spp}} \approx 22\mu$m. The electric field distribution of the designed antenna is shown in Fig. 2b. The presence of magnetic-wall boundary condition makes field distribution along Y-axis bit complicated. However, it is evident that the $\lambda_{\text{spp}}$ is about 22–25 $\mu$m, which is in good agreement with the theoretically predicted value of 22$\mu$m.

Fig. 2 (a) Top view of Ant-1, (b) The absolute electric field in the $XY$ plane on the top surface of Ant-1 when the port-1 is excited at frequency 1.76 THz and all other ports are terminated at matched load [with $\mu_c = 0.16$eV, $\tau = 1$ps, $T = 300$K]
In the designed antenna, frequency tunability is obtained by using the said electrostatic biasing approach. Towards this aim, four isolated polysilicon bias-pads of thickness $t_p = 100$ nm are placed below the graphene patches as illustrated in Fig. 1b. The biasing mechanism is elaborated in Fig. 1c (Cheng et al. 2017). The gap between the graphene patch and the polysilicon bias-pad is $t = 20$ nm (Cheng et al. 2017). In this case, $\mu_{c,i}$ (chemical potential of the $i-th$ patch) is related to the electrostatic dc bias voltage of graphene patches ($V_{bi}$ for the $i-th$ graphene patch) given by (5) (Ali et al. 2021). Here, $\varepsilon_{r-SiO_2}$ is the relative permittivity of SiO$_2$ and $t$ is the thickness of the insulating layer between graphene and polysilicon bias-pad.

$$V_{bi} = \frac{qe^2 \mu_{c,i} t}{\pi \hbar^2 v_f^2 \varepsilon_0 \varepsilon_{r-SiO_2}}, \ i = 1, 2, 3, 4 \tag{5}$$

It is worth mentioning that the value of all the dimensions of the final design is given in the caption of Fig. 1. The full-wave simulation of the graphene antennas is performed using CST microwave studio in the time domain. The monolayer graphene material is selected from the CST macros library. For the simulation, the parameters are considered as temperature, $T = 300$ K, $\tau = 1$ ps and the value of $\mu_c$ can be selected in the range from 0 to 1 eV. In this paper, $\mu_c$ is taken as 0.16 eV if not otherwise mentioned. Next, the design and analysis of basic antenna structure i.e., Ant-1, and the isolation enhancement through engraving the different shape of slots are dealt with in detail in the following two subsections.

2.1 Design of basic antenna structure

The top view of basic antenna structure (Ant-1) is shown in Fig. 2a. Notably, the cross-shaped graphene patch is continuous and there is not any slot. While designing Ant-1, the main focus is given on impedance matching and modal configuration. It is shown in detail (Ali et al. 2021) that this kind of graphene patch antenna works as a cavity-backed SPP radiator, where the TM SPP modes propagate along the graphene patch (Koppens et al. 2011; Llatser et al. 2012). The distribution of the magnitude of the electric field on Ant-1, shown in Fig. 2b, depicts that the SPP can propagate in a relatively unperturbed manner when it reaches the central section of the cross-shaped graphene patch. Interestingly, the SPP leaky wave loses its energy over a short distance despite being successfully excited at the feed. The reflection coefficient of this symmetric MIMO antenna is shown in Fig. 4a. This decay of the SPP is evident in Fig. 2b and its effect on the mutual coupling is shown in Fig. 4b and c. Though no special care is taken in designing Ant-1 to reduce the mutual coupling, the isolation remains on the order of 35–38 dB. Notably, the mutual coupling to the nearer ports is around 5 dB higher compared to the coupling to the port, lying on the opposite side.

2.2 Isolation enhancement through slot engraving

Three different types of slots like, circular, square, and a cross are engraved in the Ant-1, depicted in Fig. 3, to reduce the mutual coupling between the ports. The four different configurations of the antennas are shown in Fig. 3a, b, c and d respectively. The dimension of each slot is selected such that (i) the port-level impedance matching is not compromised and (ii) mutual coupling to both the near and far ports are minimized. The purpose of this study is to investigate the significance of slot shape in improving
the isolation between the ports. Figure 4 shows the S-parameters of antenna without and with the different shapes of the slot engraved in it. Evidently, the impedance matching, shown in Fig. 4a, is quite resilient to the perturbation caused by engraving slots of different shape. Figure 4b and c reveals that the isolation is better in case of the cross-slotted antenna, i.e., the Ant-4. The reason behind it can be understood by analyzing the electric field distribution on the slot geometries as shown in Fig. 5, which shows the vectored field distribution on antenna at center of the graphene radiator of Ant-1−4. The vectored field on the graphene radiator without slot shown in Fig. 5a follows the boundary conditions as \( \hat{n} \times \vec{E} \approx 0 \), as expected. The electric field are dispersed in the form of field fringes in the case of usage of circular and rectangular slot i.e., Ant-2 and
Ant-3. The field vectors make a symmetrical arrangement over the assumed magnetic current in edges of these slots. These slots enhance the power coupling between the ports hence the isolation is less near the resonant frequency and operating passband. The vectored field in the Ant-4 with the cross-shaped slot shows the out of phase field components. The direction of the magnetic current in the cross slot can be assumed as in opposite direction in each arm of the slot due to which the field components cancel each other. Consequently, the resultant field at the center of radiator creates a null which drastically reduces the mutual coupling between the ports. The similar is being verified with the absolute field shown in Fig. 5d. The comparative study of Fig. 4 shows that the antenna with cross-slot provides best port-to-port isolation without affecting the impedance matching. The isolation levels in the passband at resonant frequency 1.76 THz and the envelop correlation coefficients (ECC) obtained from the far-filed for the different antenna configurations are summarized in Table 1. Moreover, the magnitude of electric field distribution of the proposed antenna i.e., Ant-4 is depicted in Fig. 6.

3 Multiple functionalities of designed four-port antenna

Based on the applied electrostatic bias voltage of the different bias pads to the graphene patch, the proposed antenna offers multiple functionalities. The multi-functionality of the designed antenna can be understood from Table 2. It can offer multifunctionality as (i) tunable 4-port MIMO antenna, (ii) Tunable self-Multiplexing. In self-multiplexing, self-diplexing, self-triplexing, and self-quadruplexing antenna depending upon the value of the applied gate bias voltage on the antenna structure (Fig. 1b). The multi-functionalities of the proposed antenna are defined in the following sub-sections.

3.1 Four-port MIMO operation

For using the proposed antenna as a 4-port MIMO antenna, all the patches must resonate at the same frequency. Hence, the applied gate voltage at each port must be set at equal values as \( V_{b1} = V_{b2} = V_{b3} = V_{b4} \). In this subsection first, an electrical circuit model (ECM) of this MIMO antenna is presented to obtain further insight into its working principle (Fig. 7a and b). Subsequently, the tunability of the designed antenna and its MIMO performance are discussed. The radiators are modelled as parallel R-L-C resonators with feed capacitance \( C_f \). All the equivalent circuit parameters, their physical significance, and their values are summarized in Table 3. As per the E-field distribution shown in Fig. 6, the cross-slot, used here to reduce mutual coupling, is non-radiating in nature. Therefore, this slot is modelled as a coupling network having mutual inductance and capacitance between each radiator of the antenna as shown in Fig. 7b. The mutual coupling between two near-patches can be obtained by an inductance of \( L_{ij} \) with parallel to the cross-slot capacitance \( C_{mij}^{N-P} \). The mutual coupling between the far-patches, is modelled as coupling capacitance \( C_{mij}^{F-P} \). The values of the feeding capacitance \( c_f \) and parallel R-L-C resonators parameters are estimated at the resonant frequency in the technique given in (Garg et al. 2000). Moreover, the circuit element’s values of the coupling network can be obtained by observing the behavior of isolation between the ports (see Fig. 4b and c). The obtained ECM parameters are
Table 1  MIMO performance for different antenna configurations

| Antenna configuration | Resonant Frequency at $\mu_c = 0.16$eV | Max. of $|S_{ij}| = |S_{ji}| dB$ (Between two antennas at the opposite sides) | Max. of $|S_{ij}| = |S_{ji}| dB$ (Between placed antennas side-by-side) | Max ECC Between two antennas at the opposite sides | Max ECC Between placed antennas side-by-side |
|-----------------------|----------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Ant-1 (no slot)       | 1.76THz                                | $i = 1$ $j = 2$ $-39.1$ $i = 1or2$ $j = 3or4$ $-36.8$                           | $i = 1or2$ $j = 3or4$ $-36.8$                                                      | 0.46                                           | 0.0047                                        |
| Ant-2 (circular slot) | 1.76 THz                               | $i = 1$ $j = 2$ $-27.6$ $i = 3or4$ $j = 1or2$ $-20.8$                           | $i = 3or4$ $j = 1or2$ $-20.8$                                                     | 0.58                                           | 0.0014                                        |
| Ant-3 (rectangular slot) | 1.76 THz                             | $i = 1$ $j = 2$ $-31.2$ $i = 3or4$ $j = 1or2$ $-36.4$                           | $i = 3or4$ $j = 1or2$ $-36.4$                                                     | 0.55                                           | 0.0018                                        |
| Ant-4 (cross slot)    | 1.76 THz                               | $i = 1$ $j = 2$ $-54.8$ $i = 3or4$ $j = 1or2$ $-56.7$                           | $i = 3or4$ $j = 1or2$ $-56.7$                                                     | **0.36**                                       | **0.0073**                                   |

Bold signify the final antenna results
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enlisted in Table 3. Figure 8 shows that the S-parameters, computed using the proposed ECM, and the same, obtained from CST microwave studio time-domain simulation, are in good agreement. Hence, the behavior of electromagnetic field in radiation and mutual coupling, considered during equivalent circuit modelling are consistent.

Regarding the tunability of the designed MIMO antenna, the graphene conductivity can be tuned by the given relation in (1–5). Figure 9 depicts that impedance matching is obtained in the range of 1.65–2.1 THz by varying $\mu_c$. Figure 10 shows the simulated 3D directivity radiation pattern of the proposed MIMO antenna for two different values of chemical potentials the radiation pattern in Fig. 10a at 1.76 THz ($\mu_c = 0.16$ eV) and (b) at 2.36 THz ($\mu_c = 0.28$ eV). The beam-tilting is known to be due to the leaky nature of SPP (Ali et al. 2020; Correas-Serrano et al. 2014; Esquius-Morote et al. 2014).

The ECC, denoted by $\rho$, is an important parameter for MIMO antenna design. The value of ECC is measured from the 3D far-field radiation pattern in the receiving mode of antenna operation (Ali et al. 2021). The proposed antenna gives better-simulated results on certain conditions like XPR = 2, uniform Gaussian distribution with 0° mean and 10° variance. For ports-1 and 2, the ECC $\rho_{12} > 0.36$ because there is no polarization diversity, and ports-1 and 3 the $\rho_{13} > 0.0073$ (Maurya and Bhattacharya 2020). Another parameter is diversity gain (DG) which also relates to ECC (Babu et al. 2022). The DG for ports-1 and 2, DG > 9.985 and for ports-3 and 4 DG > 9.999. Also, the mean effective gain of the proposed antenna at each port remains around $-3$ dB.

Figure 11 shows the 2D radiation pattern of the proposed antenna in the principal planes at 1.76 THz frequency with excitation of different ports. The X-pol level of the proposed antenna is $-65$ dB in the $\phi = 0^\circ$ plane and $-13$ dB in the $\phi = 90^\circ$ plane. The antenna radiation efficiency ($\eta_r$) and gain are also evaluated with CST simulator, and it is found that the graphene antenna is not good in terms of gain. The radiation efficiency of the proposed MIMO antenna remains around 4–8% in the operating passband. For practical application of such graphene antennas, lack of efficiency is often compensated by using high gain large arrays, say 1024×1024 elements (Akyildiz and Jornet 2016; Singh et al. 2020). The detailed analysis of radiation efficiency and effect of varying graphene $\mu_c$ and $\tau$ are reported in (Abadal et al. 2019; Ali et al. 2021). Moreover, the 3D directivity of the antenna is shown in Fig. 10 with excitation of different ports, the directivity is reported here which remains around 4.76 dBi at the resonant frequency 1.76 THz and 5.67 dBi at 2.36 THz of the antenna.
Table 2  Summary of antenna functionalities with details of the naming convention along with the dc bias voltages and chemical potentials

| S.N | Applied bias voltage | Chemical potential on the graphene patches | Configuration Name | Antenna Functionalities |
|-----|-----------------------|---------------------------------------------|--------------------|-------------------------|
| 1   | \( V_{b1} = V_{b2} = V_{b3} = V_{b4} \) | \( \mu_{c1} = \mu_{c2} = \mu_{c3} = \mu_{c4} = \mu_c \) | 4-Port MIMO | 4-Port MIMO operation (All ports work at Same frequency band of operation) **No self-multiplexing |
| 2   | \( (V_{b1} = V_{b3}) \neq (V_{b2} = V_{b4}) \) | \( \mu_{c1} = \mu_{c3} \neq \mu_{c2} = \mu_{c4} \) | 2-Port MIMO (Two bands of operation) with 2-Port self-diplexing ability | MIMO Unit-1: Port 1 & 3 (to be diversity combined) @ Band-1 MIMO Unit-2: Port 2 & 4 (to be diversity combined) @ Band-2 |
| (i)3 | \( (V_{b1} = V_{b3}) \neq V_{b2} \neq V_{b4} \) | \( \mu_{c1} = \mu_{c3} \neq \mu_{c2} \neq \mu_{c4} \) | (iv)2-Port MIMO with self-triplexing in 3-Ports | (v)Port-1, Port-3 (diversity combined) @ Band-1 (vi)Port-2 @ Band-2 (vii)Port-4 @ Band-3 |
| 4   | \( V_{b1} \neq V_{b2} \neq V_{b3} \neq V_{b4} \) | \( \mu_{c1} \neq \mu_{c2} \neq \mu_{c3} \neq \mu_{c4} \) | Four-port Self-quadruplexing | 4 different frequency Bands of operation at 4 Ports **No MIMO ability |
3.2 Self-multiplexing operation

Table 2 shows that apart from being used as a 4-port MIMO antenna, the designed quad-port antenna could also be used as a self-multiplexing antenna, where a good amount of...
Fig. 9 Tunability in $|S_{ii}|$, $i = 1, 2, 3, \text{ and } 4$ of the symmetric MIMO antenna for different values of the $\mu_c$.

Fig. 10 3D radiation pattern directivity of the proposed MIMO antenna (a) at frequency 1.76 THz with $\mu_c = 0.16\text{ eV}$, and (b) at frequency 2.36 THz with $\mu_c = 0.28\text{ eV}$ with the excitation of different ports.

Fig. 11 2D E-field radiation pattern of the proposed antenna for excitation of different ports at 1.76 THz with $\mu_c = 0.16\text{ eV}$. 

Co-polarization

Cross-polarization

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hardware could be avoided. The independent tunability, elaborated in (Ali et al. 2020) for two-port graphene patch antenna, of the proposed MIMO antenna ports can be utilized to obtain the different types of self-multiplexing antenna characteristics. This antenna can offer (i) MIMO with the self-diplexing ability, (ii) MIMO with the self-triplexing ability, and (iii) self-quadruplexing ability antenna as detailed in the following three subsections.

### 3.2.1 MIMO antenna with self-diplexing ability

In the MIMO with self-diplexing mode of operation, the bias voltages of two antennas, placed side-by-side, are made equal with a possible combination of \( V_{b1} = V_{b3} \) ≠ \( V_{b2} = V_{b4} \) as mentioned in Table 2. In this configuration port-1, 3 and port-2, 4 are maintained at the same chemical potentials with \( \mu_{c1} = \mu_{c3} = 0.16 \text{eV} \) and \( \mu_{c2} = \mu_{c4} = 0.28 \text{eV} \). The corresponding S-parameters are shown in Fig. 12. Evidently, the designed 4-port antenna structure effectively offers 2-port MIMO operation at two different frequencies under this biasing configuration. Figure 12a shows that port-1 and 3 operate in the lower band at 1.76 THz, say \( B_1 \), and port-2 and 4 operate in the upper band at 2.35 THz, say \( B_2 \). Furthermore, self-diplexing mode of operation is achieved at these two bands with an isolation better than 38.3 dB at the operating passbands (see Fig. 12b).

The isolation levels in the two frequency bands are summarized in Table 4. A close observation of the tabulated data reveals that the isolation levels between the ports, working at different frequencies, i.e., working as self-diplexer, are better than 35 dB. Whereas the isolation levels between MIMO elements, i.e., between the ports 1 and 3, operating at 1.76 THz, and the ports 2 and 4, operating at 2.35 THz, are better than 43 dB. In this biasing voltage order, the orthogonality of the radiation patterns of the side-by-side placed antenna elements, depicted in Figs. 10 and 11, are utilized to obtain ECC better than 0.0073 in both the bands. Evidently, this ECC is better than the ECC of the 4-port MIMO operation, discussed in Sect. 3.1.

### 3.2.2 MIMO antenna with self-triplexing ability

For the 2-port MIMO with self-triplexing mode of the antenna, three different bias voltages are applied such that \( V_{b1} = V_{b3} \) ≠ \( V_{b2} = V_{b4} \) as shown in the Table 2. Figure 13 depicts the S-parameters of the designed antenna, operating in self-triplexing mode. Since
the radiating elements of port-1 and 3 are at the same chemical potential, port-1 and 3 work 1.76 THz (see Fig. 13a) and provide MIMO operation with the ECC is better than 0.0073. The other two ports, i.e., port-2 and 4 are biased with the different voltages and the corresponding radiating elements work in 2.08 and 2.35 THz, respectively resulting in self-triplexing operation. Figure 13b shows the isolation between the ports which is better than 37.2 dB in the operating passbands. The isolation levels for this configuration are summarized in Table 5.

### 3.2.3 Self-quadruplexing antenna

For the self-quadruplexing mode of operation, all the applied bias voltages are required to be set at different values $V_{b1} \neq V_{b2} \neq V_{b3} \neq V_{b4}$ so that the corresponding antennas work at different frequencies. Figure 14 shows the S-parameters and the input impedance of the antenna with its functionality as a self-quadruplexing antenna. With chemical potential values of $\mu_{c1} = 0.16\text{eV}$, $\mu_{c2} = 0.22\text{eV}$, $\mu_{c3} = 0.28\text{eV}$, and $\mu_{c4} = 0.34\text{eV}$, the corresponding antenna elements operate at the resonant frequencies 1.76, 2.08, 2.35, and 2.60 THz. Notably, there is no MIMO functionality in this self-quadruplexing mode of operation as all the ports operate at different frequency bands in this case. The isolation between the ports remains more than 28.5 dB in the case of antenna function as a self-quadruplexing

| Frequency Band (B) | Max. of $|S_{ij}| = |S_{ji}|$ dB (Between two antennas at the opposite sides) | Max. of $|S_{ij}| = |S_{ji}|$ dB (Between placed antennas side-by-side) |
|--------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| $B_1$ (1.71 – 1.82THz) | $i = 1, j = 2$ or $i = 3, j = 4$ $-61.0$ $i = 1$ $j = 3, 4$ $-46.5, -41.0$ | $i = 3$ $j = 1, 2$ $-46.5, -40.5$ |
| $B_2$ (2.29 – 2.41THz) | $i = 2, j = 1$ or $i = 4, j = 3$ $-47.5$ $i = 2$ $j = 3, 4$ $-36.5, -43.5$ | $i = 4$ $j = 1, 2$ $-35.5, -43.5$ |

**Fig. 13** The frequency response of (a) reflection coefficients, (b) isolation, $|S_{23}| \approx |S_{41}|$, with the functionality of antennas as self-triplexing antenna with $\mu_{c1} = 0.16\text{eV}$, $\mu_{c2} = 0.22\text{eV}$, and $\mu_{c4} = 0.28\text{eV}$
Table 5 Summary of mutual coupling levels in the self-triplexing mode. (The \( |S_{13}| = |S_{31}| \) in MIMO at 1.76 THz is presented in boldface)

| Frequency Band (B) | Max. of \( |S_{ij}| dB \) (Between two antennas at the opposite sides) | Max. of \( |S_{ij}| dB \) (Between placed antennas side-by-side) |
|--------------------|-------------------------------------------------|-------------------------------------------------|
| \( B_1 \) \[(1.71 - 1.82THz)\] | \( i = 1 \) \( j = 2 \) \(-52.4 \) \( i = 1 \) \( j = 3, 4 \) \(-41.1, -38.5 \) | |
| \( B_2 \) \[(2.02 - 2.15THz)\] | \( i = 2 \) \( j = 1 \) \(-42.7 \) \( i = 2 \) \( j = 3, 4 \) \(-40.13, -40.13 \) | |
| \( B_3 \) \[(2.29 - 2.42THz)\] | \( i = 3 \) \( j = 4 \) \(-52.1 \) \( i = 4 \) \( j = 1, 2 \) \(-41.1, -37.0 \) | |

Fig. 14 The frequency response of (a) reflection coefficients and (b) isolation with the functionality of antennas as a self-quadruplexing antenna with \( \mu_{c1} = 0.16eV, \mu_{c2} = 0.22eV, \mu_{c3} = 0.28eV, \) and \( \mu_{c4} = 0.34eV \)

Table 6 Summary of mutual coupling levels in the self-quadruplexing mode

| Frequency Band (B) | Max. of \( |S_{ij}| dB \) (Between two antennas at the opposite sides) | Max. of \( |S_{ij}| dB \) (Between placed antennas side-by-side) |
|--------------------|-------------------------------------------------|-------------------------------------------------|
| \( B_1 \) \[(1.71 - 1.82THz)\] | \( i = 1 \) \( j = 2 \) \(-51.8 \) \( i = 1 \) \( j = 3, 4 \) \(-42, -41.8 \) | |
| \( B_2 \) \[(2.02 - 2.15THz)\] | \( i = 2 \) \( j = 1 \) \(-46.5 \) \( i = 2 \) \( j = 3, 4 \) \(-39.4, -43.9 \) | |
| \( B_3 \) \[(2.29 - 2.42THz)\] | \( i = 3 \) \( j = 4 \) \(-46 \) \( i = 3 \) \( j = 1, 2 \) \(-43.1, -45.8 \) | |
| \( B_4 \) \[(2.54 - 2.67THz)\] | \( i = 4 \) \( j = 3 \) \(-43.5 \) \( i = 4 \) \( j = 1, 2 \) \(-40.5, -28.5 \) | |

antenna. The isolation levels in the four frequency bands, mentioned above, are summarized in Table 6.

A comparative study of the proposed antenna with the others, available in the literature, in terms of MIMO performance, is reported in Table 7. It shows that the proposed antenna offers an increased number of ports with tunable frequency response. The designed antenna provides the smallest value of ECC and the highest value of the isolation between the ports. However, it is worth reiterating that the proposed four-port reconfigurable MIMO
| Ref. | No. of Ports | Material | Size of the antenna (μm × μm) | Resonance Frequency (THz) | Isolation Enhancement Techniques | Frequency Tunability | Max. ECC | $\eta_\text{r}$(%) | X-pol level (in the worst case) (dB) | Min. Isolation (dB) | Operating Mode |
|------|-------------|----------|-------------------------------|--------------------------|-------------------------------|---------------------|----------|----------------|--------------------------------|-------------------|----------------|
| Tamagnone and Perriusseau-Carrier (2014) | 1-port | Graphene on SiO$_2$ | 26 × 74 | 1.1 | – | Yes | – | 5 | – | – | Single band |
| Temmar et al. (2021) | 2-port | Graphene on Polyimide | 600 × 600 | 0.65 | – | No | – | – | – | 30 | MIMO |
| Vasu Babu et al. (2022) | 2-port | Graphene on Polyimide | 600 × 300 | Wide-band(0.27–0.71) | – | Yes | 0.01 | 7 | – 8 to −20 | 25 | MIMO |
| Babu et al. (2022) | 2-port | Graphene on Polyimide | 600 × 300 | 0.51 | – | Yes | 0.015 | – | 0 to −30 | 44 | MIMO |
| Varshney et al. (2019) | 2-port | Graphene on SiO$_2$ | 16 × 34 | 1.81 | – | Yes | 0.01 | – | – | 25 | MIMO |
| Das et al. (2022) | 2-port | Copper on SiO$_2$ | 180 × 90 | 2.44 | Metamaterial | Yes | 0.001 | – | – | 34 | MIMO |
| Zhang et al. (2019) | 4-port | Graphene on SiO$_2$ | 84 × 84 | 1.16, 1.41 | FSS | Yes | 0.01 | 2 | – | 25 | MIMO |
| Ali et al. (2021) | 2-port | Graphene on SiO$_2$ | 60 × 40 | 1.68 & 1.81 | Slot | Yes | 0.17 | 4 | – | 40 | Self-diplexing with MIMO |
| Vijayalakshmi et al. (2021) | 2-port | Graphene on Polyimide | 50 × 40 | 2.3, 3.2, & 4.5 | Decoupling Structure | No | 0.2 | – | – | 15 | MIMO |
| Das et al. (2021) | 4-port | Copper on polyimide | 125 × 125 | Wide-band(0.72–10) | – | No | 0.02 | – | 0 to −15 | 20 | MIMO |
Table 7 (continued)

| Ref.          | No. of Ports | Material                  | Size of the antenna | Resonance Frequency (THz) \(\mu m \times \mu m\) | Isolation Enhancement Techniques | Frequency Tunability | Max. ECC \(\eta(\%)\) | X-pol level (in the worst case) (dB) | Min. Isolation (dB) | Operating Mode                                      |
|---------------|--------------|---------------------------|---------------------|-------------------------------------------------|----------------------------------|----------------------|------------------------|-------------------------------------|---------------------|-----------------------------------------------|
| This work     | 4-port       | Graphene on SiO\(_2\)    | 56 \times 56        | 1.76                                            | Cros slot                        | Yes                  | 0.0073                 | −13 to −20                          | 50−70               | MIMO (with Self-multiplexing Ability)         |
antenna offers the capability of self-multiplexing as well. According to the results, summarized in Tables 4, 5 and 6, the isolation levels attained in the designed antenna are better than the ones reported in (Boukarkar and Lin 2020; Kumar et al. 2020; Mukherjee and Biswas 2016). Furthermore, it is evident from Table 7 that the X-pol performance of the proposed antenna is better to the reported THz antennas.

4 Fabrication process of the proposed antenna

The fabrication process of the proposed four-port antenna is illustrated in Fig. 15. The antenna can be implemented by growing a metal layer on a side of silicon dioxide substrate having relative permittivity \( \varepsilon_r = 3.9 \), of height \( h_1 \) and lateral dimensions \( L_{s1} \times L_{s1} \). Spin coating or sputtering can be used for growing the metal layer acting as the ground plane and the material like silver or gold can be used in ground plane (Kim et al. 2009; Varshney and Giri 2021). Another metal layer can be grown on another side of the same substrate and then electron beam lithography can be utilized for obtaining the elements which can act as the metallic feedline having width \( w_f \) and \( l_f \). An insulating layer can be placed at the top of the feedline structure by growing layer of material silicon dioxide with the lateral dimensions \( L_{s2} \times L_{s2} \) and height \( h_2 \). This insulating layer provides the separation between the graphene sheet which is grown at its top and the metallic feedlines. The polysilicon bias pads \( t_p = 100\) nm are engraved inside the substrate-2 just below the graphene of thickness \( t = 20\) nm. The chemical vapor deposition (CVD) technique can be utilized for growing the monolayer graphene and polysilicon bias pads then it can be transferred over insulating layer (Xu et al. 2019). After growing the graphene layer, the electron beam lithography can be utilized for patterning of the graphene layer and a cross-shaped slot can be engraved for obtaining the final antenna structure.

5 Conclusion

A tunable terahertz four-port multifunctional antenna has been designed and numerically studied. This antenna could be used either as a (i) four port MIMO or (ii) two-port MIMO with self-diplexing or (iii) two-port MIMO with self-triplexing or (iv) self-quadruplexing depending upon the combination of electrostatic dc bias voltages. The designed graphene patch antenna has been found to provide consistent impedance matching in the 1.5–3 THz frequency band with a bandwidth of about 120 GHz under all combinations of dc biasing voltages. A technique has been implemented for improving the isolation between the

Fig. 15 Shows the fabrication process of the proposed MIMO antenna using CVD techniques
ports of the THz MIMO antenna. The port-level isolation is better than 50 dB in the four port MIMO operation. In the other extreme case of self-quadruplexing mode of operation, the worst isolation value is in the order of 30 dB. The varied extent of pattern orthogonality between the antenna elements, placed face-to-face and side-by-side, has given rise to ECC values of 0.36 and 0.0073 in the former and later case, respectively. This MIMO and/or self-multiplexing performance has been attained while using not only a common ground plane for the MIMO antenna but also by using a continuous graphene patch radiator. Furthermore, an ECM has been proposed to provide further insight into the radiation mechanism of the designed antenna and to validate the results obtained from full-wave EM simulator.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Conflict of interest** The authors declare that there is no conflict of interest/competing interests related to this submission.

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