Miniaturization and performance enhancement of super wide band four element MIMO antenna using DNG metamaterial for THz applications

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Abstract

A compact semi-hexagonal-shaped MIMO antenna loaded with a planar SRR (split-ring resonator) structure is presented for Terahertz applications. The single radiating element consists of a semi-hexagonal shape metallic patch loaded with SRR-CC (Split ring Resonator-Connected C shape) metamaterial unit cell to enhance the impedance bandwidth as well as gain of the proposed antenna. The proposed antenna element can be easily extended into two-port and four-port MIMO antenna configurations. Four radiating elements of the proposed antenna are printed on 122.4*122.4 μm² quartz substrate having a thickness of 10 μm. The radiating elements are placed orthogonally to achieve high isolation and miniaturization in the MIMO system. The proposed antenna exhibits super-wide impedance bandwidth ($S_{11} \leq -10$ dB) in the range of 0.9–10.1 THz (with fractional bandwidth of 168% at $f_0 = 5.5$ THz) while isolation of antenna is more than 20 dB in the whole operating band. The peak gain of the antenna is 7.51 dBi with more than 95% radiation efficiency in the entire band. The stable radiation pattern, high gain, high radiation efficiency, and good diversity performance of the proposed antenna make it suitable for many THz applications such as breast cancer detection, sugar measurement, drug detection.

Keywords Super wide band · THz application · Four-port MIMO antenna · Envelope correlation coefficient (ECC) · Channel capacity loss (CCL) · SRR-CC unit cell

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1 Introduction

Because of high spectral efficiency, wide bandwidth, high penetration power, and low interference noise Terahertz spectrum have attracted a lot of researchers’ interests to design application based antennas in Jamshed et al. (2020). Nowadays, researchers have focused to design antennas for terahertz applications such as biomedical imaging (Zhang et al. 2021), cancer detection (Thakur and Singh 2021), material characterization (Koenig et al. 2013), THz sensing (Vafapour et al. 2020), space and earth applications (Maagt 2007). Further, to utilize the THz regime because of simple features and low manufacturing cost, various planar microstrip geometries-based antennas are designed in Keshwala et al. (2021) and Davoudabadifarahani and Ghalamkari (2019) for different applications. However, planar microstrip antennas have low bandwidth and low radius of radiation. To enhance the performance of microstrip antenna, photonic crystal is utilised as substate in Kushwaha et al. (2018). However, this antenna suffers from high radiation losses in THz regime. The researchers in Kumud and Singh (2010), a microstrip patch antenna has been designed for dual-band operation. However, its size is not compact and resonates at only dual frequencies for surveillance system and not able to cover multiple applications. Therefore, it is necessary to design an ultra-wide band (UWB) antenna to cover many applications. Therefore, In Singhal (2019a, b) have utilized elliptical shape in a single element to achieve wideband and high gain for THz spectrum. However, it has been observed that the gain, as well as radiation efficiency, are very poor at lower THz frequencies. In the literature review, many researchers (Keshwala et al. 2021; Davoudabadifarahani and Ghalamkari 2019; Kushwaha et al. 2018; Kumud and Singh 2010; Singhal 2019a, b) have focussed only on designing single element antenna for THz regime. However, to enhance the channel capacity of the THz system, MIMO antennas are employed. Author in King (2014) explains the usages of MIMO antennas which helps to increase data rate, channel capacity without increasing the antenna’s transmitting power and spectrum resources in the THz communication system.

To acquire these demands, many researchers (Varshney et al. 2019; Luo et al. 2019a, b; Babu et al. 2022; Okan 2021; Saxena et al. 2020; Singhal 2020a, b, c) have been focused to design MIMO antenna systems for THz applications. To ensure the functioning of MIMO communication system, self-interference between radiating elements must be minimum. Therefore, a graphene-based MIMO antenna with pattern diversity has been designed in Varshney et al. (2019) for narrow THz spectrum (1.76–1.87 THz) with good mutual coupling between elements. In Luo et al. (2019a, b), a graphene tunable FSS structure has been implemented between radiating elements to achieve high isolation for narrow THz frequency spectrum. In (Babu et al. 2022; Okan 2021), mutual coupling between two radiating elements has been achieved by employing spatial and pattern diversity techniques. Apart from this, numerous two-port MIMO antenna systems with wide spectrum for SWB operation have been designed in (Saxena et al. 2020; Singhal 2020a, b, c). A super wideband MIMO antenna has been designed with impedance bandwidth (0.33–10 THz) for high-speed THz applications in Saxena et al. (2020). However, the designed antenna is not compact with low gain as well as radiation efficiency at sub-THz frequencies as compared to higher THz frequencies. A spatial diversity-based MIMO antenna is discussed in Singhal (2020a) having isolation of more than 23 dB and the footprint of antenna configuration is printed on polyimide substrate having size 820*1000*81.29 μm³. In (Singhal 2020b, c), tetradecagonal ring and windmill shapes are utilized to design the MIMO antenna for super wideband operation. Furthermore, many existing two-port MIMO antennas have been reported for super wideband (SWB) operation and also observed to have low peak
gain (dBi) and radiation efficiency (%) in sub-THz frequency range as compared to higher frequency spectrum.

Therefore, in this article, planar SRR-CC metamaterial loaded semi hexagonal MIMO antenna is proposed to enhance gain as well as impedance bandwidth, and minimize self-interference among radiating elements. The key contributions of the proposed antenna are (1) compact size of 0.37 λ * 0.37 λ * 0.03 λ; (2) fractional impedance bandwidth of 168%; (3) number of ports are four with good isolation; (4) overall low profile with high efficiency and omnidirectional patterns with maximum peak gain 7.51 dBi. This paper is divided into different sections. Evolution steps of the single radiating element with analysis of SRR-CC unit cell, formation of two and four-port MIMO antenna and equivalent diagram of proposed four port MIMO antenna are discussed in Sect. 2. Results and discussions of the proposed antenna are discussed in Sect. 3. In Sect. 4, the conclusions of the proposed antenna are drawn.

2 Designing of proposed MIMO antenna

The proposed antenna is designed on a 10 μm thick quartz substrate with dielectric constant (Ɛr) 3.75 and tangent loss of 0.0001. Quartz substrate has been characterized by low loss factor over a wide frequency spectrum in Davies et al. (2018) and Miao et al. (2019). The design of a four-port MIMO antenna is divided into three sub-sections.

2.1 Evolution of SRR-CC unit cell loaded single element

Figure 1 elucidates the evolution stages of single radiating element loaded with SRR-CC. The evolution procedure is divided into four stages. Each stage has been designed and simulated by CST microwave studio.

In Fig. 1a, stage 1 is initial stage of proposed antenna which illustrates the physical dimensions of rectangle patch antenna with Lp = 35.6 μm and Wp = 40.4 μm. It has been designed by connecting 50Ω microstrip feed line with Lf = 19.8 μm and Wp = 5 μm. The patch antenna with partial ground dimensions Lg = 18.5 μm and Wg = 51.3 μm is implanted on 61 × 61.3 × 10 μm3 quartz substrate for achieving wider impedance bandwidth as

![Fig. 1 Evolution stages of single radiating element. a Stage 1, b Stage 2, c Stage 3 d Stage 4 (Final), e RAT with dimensions, f Semicircle with chord, g Zoom view of SRR-CC](image-url)
containing the range of operating frequencies in stage 1. The resonant frequency of antenna is depended on selection of width, length, substrate thickness, and dielectric constant Sharma et al. (2022). After simulation, result of the stage 1 has been depicted in terms of reflection coefficient/S11 (dB) in Fig. 3a. The reflection coefficient (S11) specifies the amount of reflected power to the antenna when the antenna's port is excited. To obtain less reflected power and better impedance matching, S11 (dB) should be minimum. The value

![Figure 2](image2.png)

**Fig. 2** Iterations of stage 4 (final stage). a Iteration 1, b Iteration 2, c Iteration 3 (Stage 4)

![Figure 3a](image3a.png)

![Figure 3b](image3b.png)

![Figure 3c](image3c.png)

**Fig. 3** a Simulated results of reflection coefficient/S11 (dB) for evolution stages (single element), b reflection coefficient (dB) of stage 4 iterations, c comparative gain (dBi) of three iteration of stage 4
of $S11 \leq -10 \text{ dB}$ specifies the impedance bandwidth of radiating element as containing the operating frequency range. According to observation, stage 1 offers dual resonance having the $-10 \text{ dB}$ impedance bandwidth 1.25–2.2 THz and 4.7–5.8 THz, respectively. The stage 1 is only able to produce narrow impedance bandwidth. Therefore, to improve impedance bandwidth, later alterations have been done in stage 2–stage 4 by CST microwave studio.

To achieve wider bandwidth or increased the fractional bandwidth (%), two right-angle triangles (RAT) with $Lp1 = 21.2 \mu m$ have been etched out from the lower edge of the patch antenna in stage 2 which converts the geometry of the rectangle patch into a hexagonal patch as depicted in Fig. 1b and the better insight geometry of RAT is illustrated in Fig. 1e. Because of the reduction in the area of hexagonal shape radiator, $-10 \text{ dB}$ impedance bandwidth has been extended from 1.2 to 4.8 THz as illustrated in Fig. 3a. Therefore, stage 2 is only able to improve the fractional bandwidth by 65% but the objective of the designed antenna is to achieve 0.9–10 THz.

In Fig. 1c, a circle with $R = 14 \mu m$ radius and chord length $C1 = 23.4$ has been etched out from the upper edge of the hexagonal radiating element to improve radiation characteristics and operating frequency range of stage 3. To validate the enhanced impedance bandwidth, the simulated result of the stage 3 is illustrated in terms of reflection coefficient (dB) in Fig. 3a. As per observation, the impedance bandwidth has been achieved from 1.8 to 7.9 THz with fractional bandwidth of 126% at 4.85 THz. In Fig. 1d, the SRR-CC is implanted on the upper edge of radiating element to design stage 4 (final stage) for further improvement of impedance bandwidth. Better physical insight, SRR-CC is shown in Fig. 1g which is the amalgamation of three opposite concentric C-shape split metallic rectangle rings.

In Fig. 2a–c, the three iterations of stage 4 have been designed to validate the effect of opposite concentric C-shape split metallic rectangle rings on reflection coefficient (dB) and gain (dB). In Fig. 2a, Iteration-1 is shown in which the outermost ring has been printed with length $U2 = 18 \mu m$, width $U1 = 13 \mu m$, and a split gap $U3 = 10 \mu m$ at the bottom arm. The thickness is $t1 = 1.5 \mu m$ and $t2 = 1 \mu m$ respectively. Figure 2b shows the iteration 2, only the adjacent ring has been inserted with length $U4 = 9 \mu m$, width $U6 = 7.8 \mu m$, and a split gap $U5 = 3.6 \mu m$ at the top arm without altering the previous iteration. The thickness is $t3 = 1 \mu m$ and $t4 = 0.6 \mu m$ respectively. Figure 2c illustrates the iteration 3, one innermost metallic ring has been printed with length $U7 = 5.4 \mu m$, width $U8 = 3.3 \mu m$, and split gap $U11 = 1.8 \mu m$ at the bottom arm. The thickness is $t5 = 0.4 \mu m$ and $t6 = 0.3 \mu m$ respectively. Furthermore, two rectangle strips with lengths $U9 = 1.9 \mu m$, $U10 = 2 \mu m$ and both with thickness 0.6 μm are utilized to connect the outermost and the innermost ring to the middle ring. The metal rings with split gaps are accountable for producing the effect of capacitance and inductance simultaneously which shift the reflection coefficient ($S11$ in dB) in lower side of intended spectrum. After simulation of iteration 1–iteration 3, the effect of iterations have been illustrated in Fig. 3b in terms of reflection coefficients (dB) and gain (dBi). According to observation, the impedance bandwidth has been acquired from 1.65 to 10.1 THz in iteration-1, 1.5 to 10.1 THz in iteration 2 and, 0.9 THz to 10.1 THz in iteration-3 respectively. Therefore, the factional bandwidth of iteration 3 is 25% wider than iteration-1. The comparative gain of iterations has been discussed in Fig. 3c, according to observation gain in iteration 3 is 1.5 dBi higher than iteration 1. After optimizing the iteration 3 in terms of impedance bandwidth and gain (dBi), iteration 3 is the stage 4 (final stage).

Figure 3a, show the combine simulated results of stage 1–stage 4 and as per observation fractional bandwidth of stage 4 is 48% wider than stage 3. Finally, construction of single element configuration is designed in final stage having fractional bandwidth 168% at
operating frequency 5.5 THz. It is clear from Fig. 2 that SRR based metamaterial (MTM) unit improves the overall impedance bandwidth of the antenna specifically in the lower band.

Authors in (Ali et al. 2019; He et al. 2011), metamaterial with negative (permittivity, permeability, and refractive index) characteristics are designed to enhance the antenna’s bandwidth, efficiency, and gain. Therefore, to improve the impedance bandwidth and isolation of antenna, Pan (2016) has been designed a DNG (Double negative) MTM. According authors in Balmaz and Martin (2002), SRR is a common MTM that is artificially produced to generate anticipated magnetic field in various meta surface. In order to obtain the negative refractive index regime, abnormal phase dispersions also specify the region of a negative refractive index regime Luo et al. (2019a, b). The sharp phase dispersion is accountable for the sharp changes in the refractive index. Authors Tung et al. (2009) has also been analyzed that a negative refractive index in planar structure could be attained when permittivity and permeability are negative. To produce triple-band resonance with negative (permittivity, permeability, and refractive index) in intended spectrum (0.9–10.1 THz), three opposite concentric rectangle rings are printed on the top layer of quartz substrate which creates magnetic resonance on excitation and produce a vertical magnetic field. This vertical magnetic field retains negative permittivity values with respect to frequency. The split gaps among metallic rings produce capacitances that are efficient to control the resonance of planar structure. The optimized physical dimensions of SRR-CC unit cell have been illustrated in Fig. 4a and physical dimensions are shown in Table 1. To evaluate the effective parameters of unit cell to understand the working mechanism, a finite integration technique (FIT) based on electromagnetic simulation.

Fig. 4  a Geometric layout, b boundary conditions arrangement of planar SRR-CC unit cell, c reflection and transmission coefficients of unit cell, d equivalent circuit
CST microwave studio has been used. A unit cell has been placed between two ports of positive Z-axis and negative Z-axis. To energize the unit cell electromagnetic wave is applied towards Z axis. The perfect electric (PE) and perfect magnetic (PM) boundary conditions are applied along the x-axis and y-axis as illustrated in Fig. 4b.

After simulation, analysis of SRR-CC is done by reflection coefficient (S11) and transmission coefficients (S21) as illustrated in Fig. 4c. The reflection coefficient (S11) of unit cell is ratio of the amplitude of reflected wave to that of the incident wave. The transmission coefficient (S21) is the ratio of amplitude of transmission wave to that of the incident wave. According to the simulated result of S11 (dB), unit cell is resonating at three resonant frequencies 2 THz, 3.6 THz and 5.6 THz to cover intended spectrum 0.9 to 10.1 THz and the maximum value of reflection coefficient (S11 in dB) is observed at 3.6 THz.

To validate the simulated results of the SRR-CC, the Nicolson–Ross–Wier (NRW) approach has been utilized to compute the relative permeability ($\mu_r$), relative permittivity ($\varepsilon_r$), and relative refractive index ($\eta_r$). This approach initially calculate $v_1$ and $v_2$ from addition and subtraction of S11 (dB) and S21 (dB) in Smith et al. (2002). The $v_1$ and $v_2$ is calculated by Eqs. (1) and (2) and the computation of permittivity, permeability and, refractive index is done by following the Eq. (3)–(5).

\[
v_1 = S_{21} + S_{11}
\]

\[
v_2 = S_{21} - S_{11}
\]

\[
\mu_r = \frac{2}{jk_0t} \times \frac{1 - v_2}{1 + v_2}
\]

\[
\varepsilon_r = \frac{2}{jk_0t} \times \frac{1 - v_1}{1 + v_1}
\]

\[
\eta_r = \frac{2}{jk_0t} \sqrt{\frac{(S_{21} - 1)^2 - S_{11}^2}{(S_{21} + 1)^2 - S_{11}^2}}
\]

| Parameters | Dimensions (µm) | Parameters | Dimensions (µm) |
|------------|-----------------|------------|-----------------|
| U1         | 13              | U2         | 18              |
| U3         | 10              | U6         | 7.8             |
| U4         | 9               | U5         | 3.6             |
| U8         | 3.3             | U7         | 5.4             |
| U11        | 1.8             | U9         | 1.9             |
| U10        | 2               | t1         | 1.5             |
| t2         | 1               | t3         | 1               |
| t4         | 0.6             | t5         | 0.4             |
| t6         | 0.3             | T          | 10              |
In Eqs. (3)–(5), $t$ is thickness of substrate, $k_0$ is wave number, $v_1$ and $v_2$ are scattering parameters.

Figure 5a exhibits the corresponding phase curve of S11 (dB) for SRR-CC unit cell. Because of the maximum peak value of S11 (dB) at 3.67 THz, the abnormal phase variation has been observed which produces the enormously strident changes in the refractive index of unit cell as shown in Fig. 5d. The simulated results of effective permittivity ($\varepsilon_r$), effective permeability ($\mu_r$), and refractive index ($\eta_r$) of a SRR unit cell are illustrated in Fig. 5b–d. The frequency range of permittivity, permeability, refractive index, and the double negative region has been shown in Table 2. The double negative regions are 2.0–3.0 THz, 3.9–4.4 THz, 5.3–6.4 THz, and 7.3–7.5 THz respectively. The double negative regions (DNG) exhibit that a unit cell can be utilized for sensing and detecting THz applications in Smith et al. (2002).

To investigate the original place of such low absorption in that frequency regime, the electric field is inspected at 5.5 THz. Figure 5e shows that the right half of the resonator has a large concentration of electric field. This field is connecting three rings which intensify the total electric field and exhibit high reflection and low absorption at a particular frequency. This produces magnetic field resonance along electric field resonance which is needed to raise absorption levels.

According to geometric layout of SRR-CC, a split gap of the ring resonator produces the capacitance which help to control resonance and metal loop of ring produce inductance its value introduces the vertical magnetic field. The vertical magnetics field employ the negative permittivity values. The equivalent diagram of SRR-CC is illustrated in Fig. 4d. The equivalent capacitance of split gaps and inductance of metal loops are calculated by Eqs. (6)–(7).

2.2 Formation of diversity based two-port MIMO antenna

In this section, the optimized SRR-CC based single-element antenna has been transformed into a two-port MIMO antenna, and further, two-port antenna has also been investigated utilizing spatial and pattern diversity techniques. The optimized spatial diversity-based two-element MIMO antenna with physical dimensions is illustrated in Fig. 6a. The dual port proposed antenna is printed on substrate with $W_{\text{sub\_spatial}} = 122.4 \ \mu\text{m}$, $L_{\text{sub\_spatial}} = 61.2 \ \mu\text{m}$ dimensions and the distance between radiating elements is $L_g1 = 17 \ \mu\text{m}$. After simulation, the Fig. 6b show the combine view of reflection coefficients and transmission coefficients. As per observation, the reflection coefficients (S11/S22) show the impedance bandwidth from 0.9 to 10.1 THz and the transmission coefficient (S21) shows the power received at port 2 relative to power input at port 1. $L_g1$ is minimum distance between radiating elements which provide the acceptable range of isolation (S21 in dB) between radiating elements. The impact of $L_g1$ (µm) is also discussed in terms of transmission coefficient/S21 (dB) in this section.

In MIMO system, isolation among radiating elements should be less than $-15\text{db}$ and due to the closeness of radiating elements, isolation (S12/S21) of the proposed antenna without SRR-CC is poor in frequency range from 1.0 to 1.7 THz as well as 7 to 7.7 THz as illustrated in Fig. 6b. Therefore, to improve the isolation in these frequency ranges, SRR-CC is implanted on top of radiating elements. According to simulated results, the mutual coupling between two elements has been improved in frequency range 3.0 THz to 10.1 THz. Isolation is highest at 8.3 THz and at 2.5 THz, isolation is acquired 16 dB which is acceptable range only. To validate the isolation between elements, the impact
of Lg1 has been illustrated in terms of the transmission coefficient (dB) in Fig. 6c. When the distance between radiating elements reduces from 17 to 15.5 µm, the interference between elements increases in frequency range 0.9–1.5 THz which reduce the diversity performance of proposed antenna in intended spectrum. Therefore, Lg1 = 17 µm is
optimum distance which improve the transmission coefficient (dB) in frequency ranges from 0.9 to 1.5 THz.

Therefore, for further the isolation/S21 (dB) improvement between radiating elements, a pattern diversity-based MIMO antenna is printed on substrate with Wsub_pattern = 122.4 µm, Lsub_pattern = 61.2 µm and, L3 = 20.3 µm dimensions. The SRR-CC loaded two radiating elements are placed orthogonally at the minimum allowable space L3 = 20.3 µm between elements. The top and bottom view of the antenna is illustrated in Fig. 7a, b.

The simulated results of reflection and transmission coefficients at both ports are demonstrated in Fig. 7b. As per demonstration, the proposed antenna is operating from

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**Table 2** Negative effective parameters vs frequency region of a unit cell

| Parameters                        | Frequency region of negative index in THz |
|-----------------------------------|------------------------------------------|
| Effective permittivity            | 2.0–3.2, 3.4–5.0, 5.3–7.5                |
| Effective permeability            | 2.0–3.0, 3.9–4.4, 5.0–6.4, 7.3–7.5       |
| Effective refractive index        | 1.5–3.45, 4.0–5.5                         |
| Effective double negative region (DNG) | 2.0–3.0, 3.9–4.4, 5.3–6.4, 7.3–7.5     |

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**Fig. 6** a Two port MIMO antenna design with spatial diversity, b combine simulated results of Scattering parameters with and without SRR-CC, c impact of Lg1 on isolation/transmission coefficients (dB)
0.9 to 10.1 THz and the mutual coupling effect between elements are analysed by transmission coefficient (S21/S12 in dB) which is more than 25 dB in the intended frequency spectrum. So, the proposed antenna exhibits good diversity performance in the super wideband frequency spectrum. Isolation among radiating elements is also explained by surface current density (A/m) in next section.

2.3 Formation of four-port MIMO antenna

After optimizing the design of a two-port MIMO antenna with the pattern diversity technique, a four-element MIMO antenna is proposed to increase the data rate and channel capacity of the system. The quartz substrate with Ws = 122.4 µm, Ls = 122.4 µm, and t = 10 µm dimensions is utilized to print four radiating elements on top of the substrate as portrayed in Fig. 8a and the ground of proposed antenna is printed on the backside of the substrate as depicted in Fig. 8b. The physical dimensions of the proposed four-port MIMO antenna are given in Table 3.

An inclined view of the proposed antenna with substrate thickness ‘t’ is depicted in Fig. 8c. According to Fig. 8c, antenna elements (A1–A4) are placed orthogonally to each other to achieve good isolation. Simulated results of S-parameters are illustrated in Fig. 8d. As per depiction, the S11/S22/S33/S44 shows the impedance bandwidth of the proposed antenna as containing the operating frequency range 0.9–10.1 THz. The transmission coefficients (S21/S12/S31/S41) show the mutual coupling among elements which is less than −20 dB in the entire frequency spectrum. These results exhibit good performance in the THz communication system.

2.4 Equivalent circuit model of proposed antenna

The equivalent circuit diagram of proposed four-port antenna loaded with SRR-CC is shown in Fig. 9. In Cao et al. (2012), each radiating element is represented by a parallel RLC circuit comprising resistance Rp, inductance Lp, and capacitance Cp. Each radiating element is excited by port with 50 Ω resistance. According to authors in Iqbal et al. (2018, 2019), always some coupling associated with nearby antennas in MIMO system and coupling between antennas is modeled by LcCc series lumped components in Fig. 9. In the circuit diagram of SRR-CC, split gap of the inner ring is represented by capacitance, and

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**Fig. 7**  
(a) Top and bottom view, (b) Scattering parameters of SRR-CC based two-port MIMO antenna
Fig. 8  a Front view,  b back view,  c Inclined view of proposed MIMO antenna,  d Simulated S-parameters characteristics of four proposed antenna

### Table 3  Dimensions of the proposed antenna

| Parameters                  | Dimensions (µm) | Parameters                  | Dimensions (µm) |
|-----------------------------|-----------------|-----------------------------|-----------------|
| \(L_s\)                     | 122.4           | \(W_p\)                     | 40.4            |
| \(W_s\)                     | 122.4           | \(L_p\)                     | 35.6            |
| \(W_f\)                     | 5               | \(L_p1\)                    | 22.19           |
| \(L_f\)                     | 19.8            | \(R\)                       | 14              |
| \(L_2\)                     | 23              | \(L_3\)                     | 20.3            |
| \(D_g\)                     | 52.8            | \(L_g\)                     | 18.5            |
| \(W_g\)                     | 51.3            | \(W_p1\)                    | 9.6             |
| \(L_p2\)                    | 19.26           | \(W_p2\)                    | 11.02           |
| \(t\)                       | 10              | \(L_{sub\_spatial/pattern}\) | 61.2            |
| \(W_{sub\_spatial/pattern}\) | 122.4         | \(L_g1\)                    | 17              |
metal loop of ring represented by inductance as shown in Fig. 4d. The electric resonance is generated by combination of splits. Magnetic field resonance is generated by the combination of metal loops when electromagnetic signal is applied at both side of planar SRR-CC unit cell structure. The formation of capacitances between split is represented by the following Eq. (6).

\[ C_{\text{split}}(FF) = \varepsilon_0 \varepsilon_r \frac{A}{d} \]  

(6)

In Eq. (7), \( \varepsilon_0 \), \( \varepsilon_r \) are free space permittivity and relative permittivity, \( A \) is area of split and \( d \) is distance between split. According to transmission line theory in Cao et al. (2012), inductance can be computed by following Eq. (8).

\[ L_s(pH) = 2 \times 10^5 l \left[ \ln \left( \frac{l}{w + t_f} \right) + 1.193 + 0.02235 \frac{w + t_f}{l} \right] C_g \]  

(7)

In equation \( C_g \) is correction factor 0.54–0.17, \( l \) (length of microstrip feedline), \( w \) (width of microstrip line), \( t_f \) (thickness of microstrip line).

### 3 Result and discussions

The proposed antenna is designed and simulated using CST Microwave Studio 2019. The simulated results of peak gain (dBi) and efficiency of the proposed antenna are illustrated with and without SRR-CC in Fig. 10a, b. According to the results, peak gain of proposed antenna with SRR-CC has more than 2 dB gain as compared to the antenna without SRR-CC and proposed antenna shows consistent gain in the entire impedance bandwidth. The total efficiency of four-port MIMO antenna with and without SRRs depends on mutual
coupling factor among radiating elements in Thummaluru et al. (2019). It is calculated by Eq. (8).

\[
\text{Total efficiency} = \text{radiation efficiency} \times (1 - |S_{11}|^2 - |S_{12}|^2 - |S_{13}|^2 - |S_{14}|^2)
\] (8)

The radiation efficiency is more than 95% and the total efficiency is greater than 80% in THz frequency spectrum of proposed antenna.

The isolation improvement can easily understand by surface current distribution across radiating elements of the proposed MIMO antenna. The surface current distribution among radiating elements at different frequencies like 2 THz, 6 THz, 8 THz, and 10 THz are depicted in Fig. 11a–d. It is noticed that the maximum amount of surface current (A/m) is concentrated near feed lines and upper edges of radiators when one port is excited and non excited radiating element has minimum amount of surface current distributions (A/m). Therefore, this is evident of isolation among elements. The orthogonal placement of radiating elements with SRRs are utilized to minimize the current density and mutual coupling across antenna elements. Figure 12a–c illustrate the normalized 2D radiation pattern of the proposed antenna at 2, 8, and 10 THz frequencies in XZ plane and YZ plane. To analyse radiation pattern in XZ plane and YZ plane, port 1 of antenna is excited. It is clear, patterns are nearly omnidirectional in both planes as illustrated in Fig. 12.

4 Diversity performance analysis of proposed MIMO antenna

To validate the diversity performance of four port MIMO antenna, few additional parameters are analysed and illustrated in Figs. 13 and 14. The parameters include envelope corelation coefficient (ECC), diversity gain (DG), multiplexing efficiency “\(\eta\)”, total active reflection coefficient (TARC), and channel capacity loss (CCL) and mean effective gain (MEG). ECC is calculated to measure isolation among radiating elements in wireless communication system in Babu et al. (2022). ECC between ith and jth radiating element can be computed by S-parameters in Eq. (9).
Fig. 11 Simulated Surface current distribution with and without SRRs at frequency a 2 THz, b 6 THz, c 8 THz, d 10 THz
Fig. 12  Simulated radiation patterns of proposed antenna at a 2 THz, b 8 THz, c 10 THz
To achieve more accurate results, value of ECC is calculated by radiating field of proposed antenna in Saxena et al. (2020). Where XPR is cross-polarization ratio of incident wave in propagation environment. The cross-polarization ratio for outdoor is XPR = 1 dB and XPR = 6 dB for indoor propagation.

\[
\rho_{\text{ecc},ij} = \frac{\left[ \sum_{n=1}^{N} S_{ni}^* S_{nj} \right]^2}{\left( 1 - \sum_{n=1}^{N} |S_{ni}|^2 \right) \left( 1 - \sum_{n=1}^{N} |S_{nj}|^2 \right)}
\]

(9)

Fig. 13  a Simulated results of ECC and DG,  b Mean Effective Gain (MEG) in Gaussian and isotropic medium

\[
\rho_{\text{ecc},ij} = \frac{\left[ \int_0^{2\pi} \int_0^{\pi} \left( XPR.E_{\phi_i}.E_{\phi_j}^* P_0 + E_{\psi_i}.E_{\psi_j}^* P_\psi \right) d\Omega \right]^2}{\int_0^{2\pi} \int_0^{\pi} \left( XPR.E_{\phi_i}.E_{\phi_j}^* P_0 + E_{\psi_i}.E_{\psi_j}^* P_\psi \right) d\Omega \int_0^{2\pi} \int_0^{\pi} \left( XPR.E_{\phi_i}.E_{\phi_j}^* P_0 + E_{\psi_i}.E_{\psi_j}^* P_\psi \right) d\Omega}
\]

(10)

Fig. 14  a Simulated results of Channel Capacity loss (CCL) in bps/Hz,  b Simulated results of TARC (dB)
Ideally, ECC value should be zero but practically should be less than 0.5. Therefore, ECC of proposed antenna is calculated by S-parameters and simulated value of ECC in intended spectrum is less than 0.0025 which exhibits the good diversity performance of proposed MIMO antenna for THz applications as depicted in Fig. 13a. Diversity gain of proposed MIMO antenna is computed by Eq. (11). In Babu et al. (2022), diversity gain computation depends on ECC value of antenna. To achieve diversity gain near 10db, practically correlation among ports should be less than 0.5. Figure 13a illustrates simulated results of diversity gain among ports of radiating elements. Simulated value of diversity gain of antenna is 9.99 in entire spectrum which exhibits satisfactory performance of proposed antenna.

\[ DG = 10 \times \sqrt{1 - ECC^2} \]  

Mean effective gain (MEG) is antenna’s capability to receive the electromagnetic signals in multipath environment and also elucidated as ratio of received average power at ports to total power received by placing two antennas in same route in Saxena et al. (2020). The acceptable range should be equal or less than to ± 3 dB in multipath environment. Simulated results of MEGs in gaussian and isotropic medium are illustrated in Fig. 13b. To validate the MEG, reported antenna is also simulated in isotropic medium as well as gaussian medium at XPR = 0 dB and 6 dB. Simulated values of MEG are less than – 3 dB in Gaussian and isotropic medium, which validate the diversity performance of proposed antenna. Channel Capacity Loss (CCL) is another parameter to analyse the performance of MIMO system. The channel capacity grows linearly with number of radiating elements and correlation among radiating elements induce the capacity loss in MIMO system channel. According to Saxena et al. (2020, CCL should be less than 0.4 bit/s/Hz and CCL computation of proposed antenna is done by Eqs. (12)–(15). According to simulated results in Fig. 14a, the CCL of proposed MIMO antenna is less than 0.15 bps/Hz in entire spectrum which exhibits satisfactory diversity performance of the proposed antenna in a multipath fading environment.

\[ C_{loss} = -\log_2|\varphi^p| \]  

\[ \varphi^p = \begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix} \]  

\[ \rho_{ii} = 1 - \left( |S_{ii}|^2 + |S_{ij}|^2 \right) \]  

\[ \rho_{ij} = \left( S_{ii}^* S_{ij} + S_{ji}^* S_{ij} \right) \text{ where } i, j = 1 \text{ or } 2 \]

TARC is depicted as ratio of square root of total reflected power to square root of total incident power. When adjacent radiating antennas are interrupted to each other, so interruption on impedance bandwidth may affect in intended frequency spectrum. To analyse impact on impedance bandwidth, TARC computation is done by Eq. (16) in Saxena et al. (2020).
Here $a_i, b_i$ are amplitude of incident and reflected wave. Amplitudes of incident and reflected waves are computed by scattering parameters with this “S”-matrix expression in Eq. (17).

$$\text{TARC} = \sqrt{\frac{\sum_{i=1}^{N} |b_i|^2}{\sum_{i=1}^{N} |a_i|^2}}$$

Equation (16)

$[b] = [s][a]$\hspace{1cm}$\text{(17)}$

Ideally total active reflective coefficient of MIMO system should be less than 0 dB in Saxena et al. (2020). In Fig. 14b illustrate total active reflective coefficient (TARC) values at phases 0°, 60°, 120°, 180°. TARC values are less than −30 dB in intended frequency spectrum which indicates that proposed antenna is not phase-sensitive.

4.1 Comparison of proposed SWB MIMO antenna with Existing MIMO antennas

The characteristics of the proposed antenna are compared with most of existing SWB antennas in terms of considered parameters such as number of radiating elements, physical dimensions of antenna, impedance bandwidth, peak gain (dBi), radiation efficiency, and isolation among radiating elements. Because of the highest number of radiating elements in the proposed antenna as compared to other antennas, it exhibits the highest throughput and also resist the multipath fading in THz communication system. The radiation efficiency of proposed antenna is highest as compared to the existing antennas.

Due to its minimum physical dimensions of a single element, the proposed MIMO antenna has reduced its overall physical size and acquired highest number of radiating elements. To ensure the better performance as four port MIMO antenna, isolation among elements is high as compare to other antennas except Singhal (2020a). Furthermore, it exhibits lower peak gain than reference antennas in Saxena et al. (2020) and Singhal (2020a, c). However, these references are in higher profile, less radiation efficiency, or even with a smaller number of ports on larger substrate utilization is less simultaneously. Whereas value of ECC, CCL, MEG is also compared with other reported antennas. These parameter values confirm its better inter-radiating element isolation. Therefore, the proposed MIMO antenna shows superior performance than most of the THz antennas reported in literature (Table 4).

5 Conclusion

A SRR-CC loaded four-port MIMO antenna is proposed for super wideband (SWB) in THz intended spectrum. A planar SRR-CC structure is loaded on a semi-hexagonal patch with the partial ground to achieve the fractional bandwidth of 168% and also increase the gain at the lower frequency range for THz applications. Isolation improvement among radiating elements of the proposed MIMO antenna is achieved by applying orthogonal arrangement between radiating elements. The simulated impedance bandwidth of the proposed MIMO antenna is ranging from 0.9 to 10.1 THz with isolation of more than 20 dB in the frequency spectrum. It demonstrates a stable radiation pattern with a peak gain of 7.51dBi and radiation efficiency exhibits more than 95% in the frequency spectrum. The Simulated values of

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| Ref. and no. of port | Impedance bandwidth and %FBW | Gain (dBi) | η (%) | MEG (dB) | ECC | CCL bps/Hz | Isolation (dB) | Volume (µm³) and dimensions in (λ) |
|---------------------|-----------------------------|------------|--------|---------|-----|------------|----------------|--------------------------------------|
| Singhal (2019b) One | 0.46–5.46 THz (168%)        | 12         | 92     | NR (Not required) | NR | NR         | NR             | 800*600*81.29 polyamide 1.2 λ * 0.9 λ * 0.12λ |
| Saxena et al (2020) Two | 0.33–10 THz (187%)  | 19         | 70     | < -3    | 0.0015 | 0.25       | < -20          | 1000*1400*101.3 RT5880 1.1 λ * 1.54 λ * 0.11 λ |
| Singhal (2020a) Two | 1.06–14.2 THz (172%)        | 11.2       | NM     | NM (not-measured) | <.003 | 0.2        | < -23          | 820 * 1000 * 81.29 Polyamide 2.89 λ * 3.53 λ * 0.29 λ |
| Singhal (2020b) Two | 0.3–15.1 THz (192%)         | NM         | NM     | NM      | 0.02 | 0.2        | < -13          | 800 * 1170 * 81.29 0.80 λ * 1.17 λ * 0.08 λ |
| Singhal (2020c) Two | 3.1–60 THz (180%)           | 12         | NM     | NM      | <.003 | 0.1        | < -19          | 110 * 125 * 10 1.14 λ * 1.29 λ * 0.10 λ 110 * 155 * 10 1.14 λ * 1.60 λ * 0.10 λ |
| [P] Four           | 0.9–10.1 THz (168%)         | 7.5        | 95     | < -3    | 0.002 | 0.15       | < -20          | 122.4 * 122.4 * 10 and quartz 0.37 λ * 0.37 λ * 0.03 λ |

*Abbreviations*  P proposed antenna, λ is the lowest frequency of operating band, η radiation efficiency
performance parameters of MIMO antenna i.e. ECC, DG, MEG, TARC, CCL are in a good range for the entire frequency spectrum of operation. All simulated results indicate that the proposed MIMO antenna is a good candidate for THz applications.

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**Declarations**

**Conflict of interest** The authors declare that they have no competing of interest/conflict of interest.

**Ethics approval** This research study complied with the ethical standards.

** Consent to participate** Informed consent is obtained from all individual participants included in this research work.

**Consent to publish** The participants have consented to the submission of the research article to the journal.

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