

Compact Wheelchair-shaped THz Multiple-Input Multiple Output (MIMO) Antenna with Enhanced Isolation for Ultra-high-speed 6G Networks

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Abstract—In this paper, a compact, high-gain 2×2 Multiple-Input Multiple-Output (MIMO) microstrip patch antenna design is introduced for ultra-high-speed wireless communication in the prospective Sixth-Generation (6G) and beyond system. The suggested antenna can be used in the THz range, with dual resonances at 3.6368 THz and 4.8179 THz, covering a wideband region of 2.2047 THz from 2.839 THz to 5.017 THz. The maximum gain of 11.875 dB, an Envelope Correlation Coefficient (ECC) of 0.0002845, and a Diversity Gain (DG) of 9.998, indicating that this MIMO system can perform well in a multipath environment. An isolation of -30.334 dB and an efficiency of 80.62 % in the radiation are obtained by the antenna. The small 160×360 μm size, together with high performance and a validated Resistor-Inductor-Capacitor (RLC) equivalent circuit model, makes the antenna performance in terms of bandwidth, gain, isolation, efficiency, and RLC integration also exceed that of available THz antenna designs, making it a potential candidate for 6G wireless communication, intelligent sensing, and high-resolution imaging applications.

Keywords—Sixth-Generation (6G), dual resonance, wideband, high gain, industrial and innovation

I. INTRODUCTION

The evolution in wireless communication from the 1G system to the current 5G system has brought about remarkable enhancements in data speed, spectral efficiency, and massive network access [1].

However, despite these advancements, 5G is fundamentally limited by its sub-100 GHz operating band, restricted channel bandwidth, elevated energy consumption, and diminished efficiency in extremely dense, high-mobility, or interference-laden environments [2]. Due to these limitations, it is unable to facilitate emerging applications such as holographic telepresence, immersive Extended Reality (XR), real-time intelligent robotics, autonomous vehicle communication, and massive machine-type communication. These applications all require data rates of Terabits Per Second (Tbps), data latency of less than one millisecond, and exceptional reliability [3]. As a result, it is projected that Sixth-Generation (6G) wireless communication would make use of the vast 0.1–10 THz spectrum [4]. This spectrum provides an amazing bandwidth, less interference from the atmosphere, and very small antennas as a result of very small wavelengths.

There is a wide range of antenna types, such as DRAs, horn antennas, and planar monopole antennas, each with its own advantages and disadvantages. DRAs have high efficiency but are larger and require a more complex fabrication process, making them unsuitable for compact, integrated systems. Horn antennas offer very high gain but are very large and not suitable for very small applications where space and size are constraints. Although planar monopoles are simple to design, they typically do not provide sufficient bandwidth and efficiency for

high-end 6G and beyond applications, particularly in the terahertz band. To overcome this issue, a microstrip antenna is selected for its suitability for high frequencies and its compact size, high-gain, and high-level of integration structures [5]. Such structures enable multi-functional sensing, high-resolution imaging, chip-level wireless communication, and futuristic communications systems. For enabling future 6G applications (smart environment, holographic communications, autonomous cyber-physical systems, and Integrated Sensing and Communication (ISAC)) and associated use cases, 6G microstrip antennas are indispensable [6].

Terahertz (THz) frequencies and Multiple-Input Multiple-Output (MIMO) technologies are expected to boost wireless communication system performance and capacity [7]. Short wavelengths at THz frequencies allow antenna elements to be placed close together, enabling Ultra Massive-MIMO (UM-MIMO) arrays with various spatial multiplexing paths, adaptive beamforming, and high channel capacity [8]. These arrays increase connection stability, eliminate multipath fading, and enable high-speed data transmission over short and long distances. Despite advances in THz antenna and MIMO system research, considerable literature gaps remain. THz MIMO antennas are mostly used in narrow frequency bands, restricting their applicability for wideband or multi-resonant 6G applications [9]. Many designs stress high gain or ultra-compact dimensions, but achieving ultra-wide bandwidth, robust inter-element isolation, lowest footprint, and stable radiation characteristics at terahertz frequencies is difficult. Additionally, current studies seldom verify MIMO performance. Mutual coupling reduction, isolation augmentation, diversity measurements, and comparable circuit-level modeling are typically overlooked [10]. This limits the physical understanding and scalability of present systems, notably for ultra-massive MIMO. Few studies focus on broadband THz MIMO capabilities within crucial 6G spectral bands (0.1–10 THz), assuring low mutual coupling and high radiation effectiveness [11]. These limits indicate the need for a compact, broadband, and thoroughly validated THz MIMO antenna design for high-capacity wireless communication and integrated sensing in beyond-5G and 6G systems. THz MIMO systems have great potential for 6G applications like Industry 4.0 automation, smart healthcare monitoring, intelligent transportation systems, holographic telepresence, high-definition security imaging, and ubiquitous Internet of Things ecosystems [8]. They also offer improved spectroscopy, ultra-fast inter-chip communication, high-precision remote sensing, and next-generation integrated communication-sensing systems.

The proposed MIMO antenna resonates at 3.6368 THz, 4.8179 THz, and 5.017 THz in the broad terahertz range from 2.38 to 11.18 THz. The antenna supports Beyond-5G (B5G) and 6G wireless communication, vehicular radar, THz imaging, advanced additive manufacturing, non-invasive medical diagnostics, and

astronomical radiometric sensing due to its wide spectral coverage [12]. The 0.55–10.6 THz and 1.5–10 THz operational resonances are widely used for biomedical sensing, Industry 4.0 connectivity, IoT communication, and next-generation wireless systems [13, 14]. Cancer diagnosis, explosive identification (e.g., (High Melting eXplosive) (HMX)), biotin sensing, high-frequency mixers, aircraft instrumentation, deep-space communication, and wireless body area networks have shown promise in these frequency ranges. The resonances at 3.6368 THz and 4.8179 THz match the expected 0.631–4.962 THz operational range for early 6G THz use cases [15] and the 3.6–15.8 THz spectrum for ultra-high-speed THz wireless networks [16]. These bands are relevant to MIMO communication, high-resolution THz imaging, intelligent sensing, and sophisticated spectroscopy systems in the 0.1–5.0 THz dynamic range [17]. Additionally, the 5.017 THz resonance is in the 5–9 THz region, making the suggested antenna suitable for high-frequency terahertz detector applications [18]. All resonant modes are within the 0.33–10 THz frequency range, making them ideal for terahertz applications like Beyond-5G (B5G) and future 6G communications, vehicular communication systems, terahertz imaging, advanced 3D printing, THz radar, healthcare diagnostics, and astronomical radiometric sensing [19].

We compare the proposed structure to literature-based THz antenna designs and shows its higher performance across all technical criteria. Most antennas operate at lower frequencies and have narrower bandwidths and poor isolation in Refs. [20–24]. However, the proposed antenna has a remarkable bandwidth of 2.2074 THz, much higher than the 0.4 THz, 0.723 THz, and 0.04 THz reported in past research [20–24]. The antenna has a high gain of 11.875 dB, surpassing other designs, including those in Refs. [20–24], while preserving constant radiation characteristics over both resonant bands. Isolation boosts performance significantly. While most earlier tests have revealed isolation values close to –25 dB, the recommended design achieves much higher isolation. –30.334 dB. Less mutual interaction between antenna elements improves MIMO efficiency. The radiation efficiency of 80.62% is close to that of high-efficiency THz antennas as Ref. [24], which have 92% efficiency. This is true even if higher THz frequencies have higher propagation losses.

The proposed antenna is small and integrable. The port size of $160 \times 360 \mu\text{m}$ is significantly smaller than most THz antenna designs currently in use. Examples of larger structures include the $600 \times 300 \mu\text{m}$ arrangement in Ref. [20] and the even larger structure in Ref. [22]. The antenna fits into System-on-Chip (SoC) devices, wearable sensors, and compact THz imaging or communication modules because of its small size. The proposed antenna design offers a 2×2 MIMO configuration and a proven RLC equivalent circuit model, unlike previous designs that lack MIMO capabilities or equivalent circuit representation. Increased diversity gains, channel reliability, and insights into antenna resonance

behavior result from this. This is essential for manufacturing, optimization, and future expansion to ultra-massive MIMO systems. The suggested MIMO antenna outperforms [25–28] antennas in the THz range. It operates with twin resonances at 3.6368 THz and 4.8179 THz, covering 2.839–5.017 THz, exceeding the operational ranges of the referenced research. The proposed design has a maximum bandwidth of 2.2047 THz, surpassing 0.15/0.15/0.63 [25], 0.021/0.036 [26], 1.25 [27], and 1.59 [28]. With a maximum gain of 11.875 dB and radiation efficiency of 80.62%, it compares well to other designs. The suggested antenna's -30.334 dB isolation exceeds the -25 dB isolation in Refs. [26–28], resulting in less mutual coupling and improved MIMO performance. The recommended antenna features a 2×2 MIMO configuration with RLC circuit validation, making it a reliable and tested design for broadband THz wireless applications.

In terms of bandwidth, isolation, and gain, compact size, radiation behavior, and practical adaptability, the proposed MIMO antenna introduces significant enhancements over the existing THz MS designs. Its large operational range, remarkable MIMO capabilities, and ultra-compact architecture position it as a formidable platform for next-generation terahertz communication, biological sensing, high-resolution imaging, spectroscopy, and integrated sensing-communication systems. Moreover, it is small in design. The architecture that has been offered, which is in line with crucial THz windows that are being employed in current and upcoming 6G research, is a daunting promise for future terahertz-based wireless technologies and communication frameworks that go beyond. Table I presents a comprehensive performance comparison between the proposed antenna and previously reported THz MIMO designs.

TABLE I. PERFORMANCE COMPARISON OF THE PROPOSED ANTENNA WITH OTHER PUBLICATIONS

Ref.	Resonance Frequency (THz)	Frequency Range	BW (THz)	Gain (dB)	Efficiency (%)	Isolation (dB)	Board Size	Substrate Material	MIMO Configuration	RLC
[20]	0.512	0.35–75	0.4	5.49	85.24	-25	600×300	Polyimide	1×2	NO
[21]	1.195, 1.598	0.93–1.653	0.723	7.5	97	-20	110×130	Polyimide	–	NO
[22]	0.128, 0.178	126–129, 175–180	0.00598, 0.00613	6.24	90	-25	2700×3650	Polyimide	1×2	NO
[23]	0.65	0.62–0.66	0.04	11.3	66.45	>25	1200×2200	–	–	NO
[24]	2.2	1.74–2.52	0.78	4.4	92	-20	100×105	Polyimide	–	YES
[25]	–	1.62–1.77, 2.55–2.70, 4.16–4.79	0.15, 0.15, 0.63	9.6	70	–	100×80	–	–	No
[26]	0.445, 0.540	0.43–0.451, 0.515–0.552	0.021 0.036	7.9	85.64	-25	2490×1600	Polyimide	4×4	YES
[27]	3.82	3.2–4.45	1.25	10.8	>80	>20	120×180	SiO ₂	1×2	NO
[28]	1.89	1.41–3.0	1.59	4.6	74.5	-25	38×25	SiO ₂	2×2	No
Proposed	3.6368, 4.8179	2.839–5.017	2.2047	11.875	80.62	-30.334	160×360	Polyimide	2×2	YES

II. RESEARCH GAP AND CONTRIBUTION

THz microstrip and MIMO antenna research still has low gain, impedance bandwidths, radiation efficiency, and strong mutual coupling effects that reduce MIMO channel capacity. Many THz antennas only work in sub-THz or lower-THz ranges and fail to display sustained multi-resonant behavior across the 0.1–10 THz spectrum needed for 6G communication, high-precision biomedical imaging, real-time spectroscopy, and ultra-fast chip-to-chip interconnects, thereby limiting their suitability for truly broadband, high-capacity, and low-latency next-generation systems. Due to their large physical footprints and insufficient decoupling, THz MIMO topologies frequently lack isolation, spatial variety, and integration for small systems. Many THz antenna studies lack equivalent circuit modeling, making impedance dynamics and resonance behavior difficult to understand. The THz MIMO antenna minimizes mutual coupling with its small 2×2 structure, ultra-wide 2.2074 THz bandwidth, and increased isolation of -30.334 dB, outperforming standard antennas (-20 to -25 dB). In the

THz regime, propagation and material losses are substantial, but the device achieves 11.875 dB gain and 80.62% radiation efficiency, boosting performance. The 160×360 μm footprint is suitable for 6G devices, chip-scale sensors, wearable biomedical platforms, and portable THz imaging systems. THz antenna literature rarely addresses resonance creation, reactive energy storage, and frequency-selective behavior, but this study presents a thoroughly proven RLC equivalent circuit model. For 6G THz communication, Industry 4.0 automation, aeronautical linkages, explosive and chemical detection, cancer diagnostics, and wireless body area networks, the suggested antenna's resonances fall within numerous THz application windows (1.5–10 THz, 0.631–4.962 THz, 3.6–15.8 THz). Research contributed:

- Our ultra-compact 2×2 THz MIMO antenna has a wider bandwidth than conventional designs.
- Increased isolation (-30.334 dB) results in better MIMO performance than typical THz systems.
- High gain (11.875 dB) and efficiency (80.62%), exceeding THz propagation restrictions.

- A verified RLC equivalent circuit improves analytical precision and physical insight.
- Compact size ($160 \times 360 \mu\text{m}$) enables system-on-chip integration and medical/industrial sensor applications.
- Multi-band terahertz is useful for communication, imaging, sensing, and spectroscopy.
- In bandwidth, gain, isolation, analytical modeling, and miniaturization, the proposed antenna outperforms current THz designs, filling critical research gaps and making it a strong candidate for 6G and beyond 6G communication, sensing, and intelligent ISAC platforms.

III. DESIGN METHODOLOGY

This article discusses the evolution of antennas from single to Multi-Input Multi-Output (MIMO), depicted in Fig. 1, to improve the quality, efficiency, and flexibility of wireless communication. This development enables the exploitation of spatial diversity and multiplexing to meet the growing 6G demands of higher data rates, lower latency, and higher capacity. Material choice is essential for this advancement. Due to high conductivity, graphene is used as the patch and ground [29, 30], but the substrate is polyimide due to its favorable dielectric properties, like dielectric constant of 3.5 and very low loss tangent of 0.0027 [31]. Reduced signal attenuation and efficient wave propagation, provided by a 10- μm -thick polyimide substrate, endorse the performance of 6G antennas.

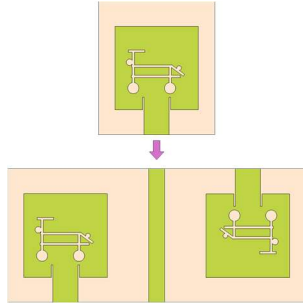


Fig. 1. The development of the suggested antenna.

IV. SINGLE-ELEMENT ANTENNA

The first stage in antenna synthesis is designing a single-element configuration based on an organized, measurable performance viewpoint. Here are the mathematical equations for selection of the design for required resonant frequencies.

$$\lambda = \frac{c}{f} \quad (1)$$

$$\varepsilon_{eff} = \left(\frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \right) \times \left(1 + 12 \times \frac{h}{W} \right)^{-0.5} \quad (2)$$

$$W = \frac{c}{2f} \times \sqrt{\frac{2}{\varepsilon_r + 1}} \quad (3)$$

$$L = \frac{c}{(2f\sqrt{\varepsilon_{eff}})} - 2 \times \Delta L \quad (4)$$

$$\Delta L = 0.412h \times \frac{\varepsilon_{eff} + 0.3}{\frac{W}{h} + 0.264} \sqrt{\frac{\varepsilon_{eff} - 0.258}{\frac{W}{h} + 0.8}} \quad (5)$$

In Eq. (1), λ represents the wavelength, which is the distance over which the wave's shape repeats. c is the speed of light, and f is the resonant frequency. The effective dielectric constant (ε_{eff}) is calculated using Eq. (2), considering the relative dielectric constant of the substrate $\varepsilon_r = 3.75$, quartz, for quartz, along with the ratio of the substrate Height (h) to patch Width (W). The patch width for optimal resonant frequency is determined by Eq. (3), and the patch Length (L) is calculated by Eq. (4). The extension in the patch length (ΔL) due to fringing is given by Eq. (5). Together, these calculations provide an accurate and effective design, ensuring the antenna meets the stringent performance requirements for the 6G system. At this stage, the materials and thicknesses are optimized to achieve the best conductivity, flexibility, and effective signal transduction. As shown in Fig. 2, the antenna has an overall size of $160 \times 140 \mu\text{m}^2$ and is suitable for high-frequency communications. The main radiating element is a graphene patch of $100 \times 100 \mu\text{m}^2$, which was chosen owing to its high conductivity and mechanical flexibility. The substrate is polyimide, and a graphene ground plane is implemented on the other side; both layers are of equal thickness of $2 \mu\text{m}$. The suggested patch is made of five rectangular frames and two circular slots, which are shaped in a wheelchair form to improve the radiation performance, bandwidth, and gain. The combination of graphene and polyimide allows for low loss and high signal transmission. The entire design is simulated in CST software for electromagnetic performance. Therefore, the complex geometry of this single-element antenna and its optimized design form a good potential candidate for futuristic high-frequency wireless systems.

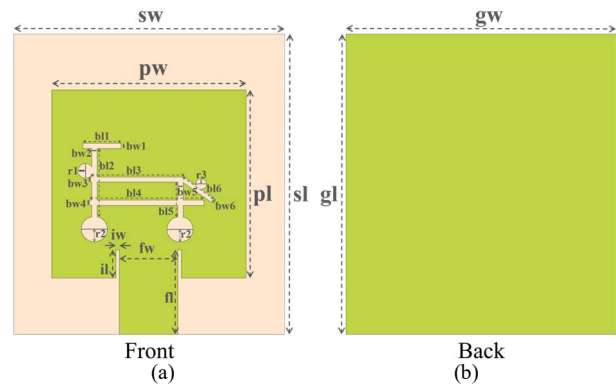


Fig. 2. Single element antenna: (a) Front view and (b) back view.

V. DEVELOPMENT OF THE SINGLE-ELEMENT ANTENNA

The single-element antenna design is iteratively refined to achieve optimal resonant behavior. This is the process of evolution shown in Fig. 3, whereas Fig. 4 and Fig. 5 show the reflection coefficient and the gain response, in this order. Performance limitations are identified and

pushed in each iteration by rigorously analyzing simulated results of the structure.

This antenna has a rectangular patch element with two symmetrical slots on either side of the feed line. The design has a single bandwidth of 0.6213 THz, but performs poorly. In Fig. 4, the return loss is low, and the bandwidth is limited. Low gain (Fig. 5) renders the antenna unsuitable for high-performance 6G applications. These results indicate that mechanical enhancements must be pursued for higher efficiency and larger bandwidth.

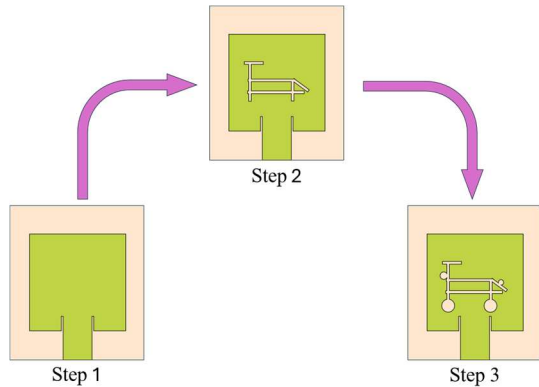


Fig. 3. Evolution of single element.

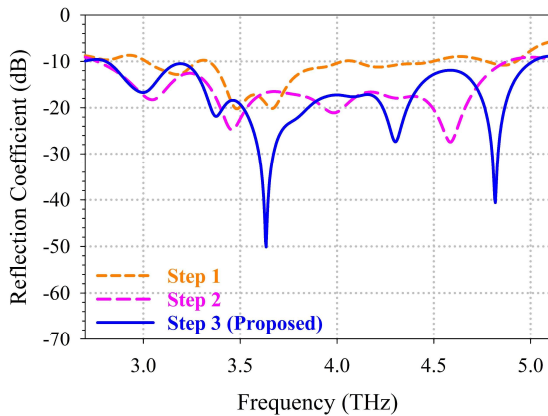


Fig. 4. Reflection coefficient during each design phase of the single-element antenna.

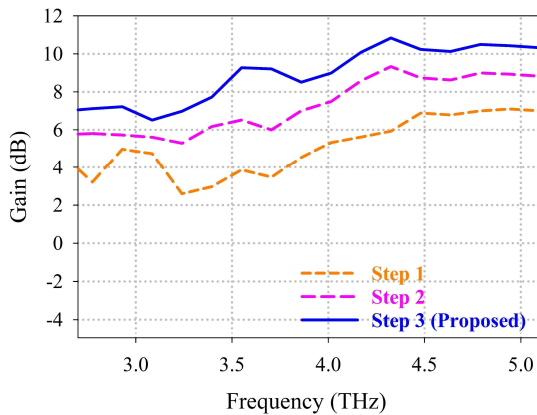


Fig. 5. Gain during each design phase of the single-element antenna.

Step two addresses these concerns by employing five rectangular frames to form a wheelchair frame.

This modification improves resonance and gain, demonstrating a single bandwidth of 2.178 THz and two resonances at 3.486 THz and 4.426 THz, but the return losses remain insufficient for terahertz applications. As a result, the bandwidth and gain exhibit slight enhancement from the first stage estimator according to simulation results, but the improvements are not sufficient to fulfill the 6G performance demands. Additional tuning is needed.

Step three includes big design changes to increase performance. Four circular elements with different diameters are located at specific positions to improve load distribution and radiation efficiency, inspired by the design of wheels and handles of a wheelchair. The finished design features 2.104 THz bandwidth, 2 resonant frequencies at 3.63 THz and 4.81 THz, and optimal return losses of -50.12 dB and -40.61 dB, with a maximum gain of 10.83 dB, making it ideal for next-generation high-frequency transmission.

The single-element rectangular patch-based antenna design has evolved through incremental design progression and performance-driven refining. The technological refining process is iterative, with each level building on prior iterations. Ideal antenna dimensions: $sw = 140$ μm , $sl = 160$ μm , $pw = 100$ μm , $pl = 48$ μm , $fw = 100$ μm , $fl = 30$ μm .

VI. PARAMETRIC ANALYSIS

A. Patch Thickness (pt)

The study of variation in the thickness of the patch shows that thickness has a significant effect on the performance of the antenna [32]. Reduction of thickness with the predetermined value will lead to a small amount of return loss and limited bandwidth, which has two narrow bands of 1.12 THz and 0.284 THz, shown in Fig. 6. Conversely, increasing the thickness gives rise to a single wide band of 2.187 THz but does not provide sufficient gain, as can be seen in Fig. 7. The results indicate a subtle compromise between patch thickness and return loss, and bandwidth. Therefore, precise tuning of the thickness is necessary to obtain good performance and maintain strong resonance in the working frequency band.

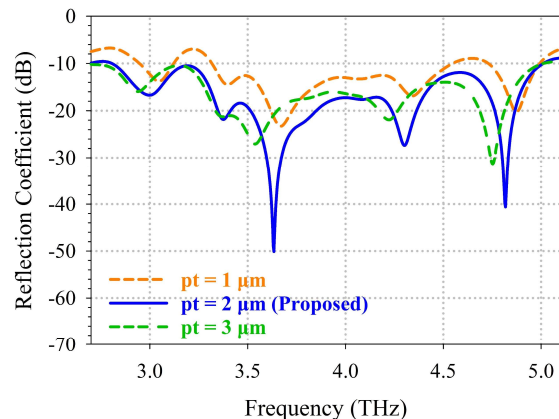


Fig. 6. Reflection coefficient of various patch thicknesses.

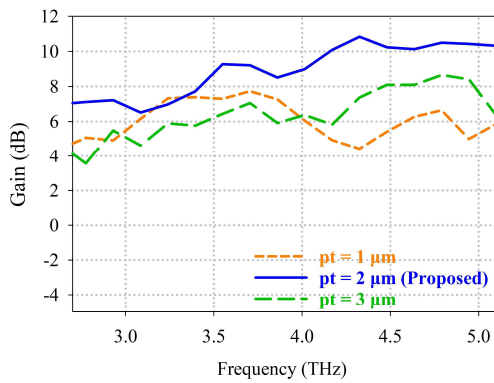


Fig. 7. Gain of various patch thicknesses.

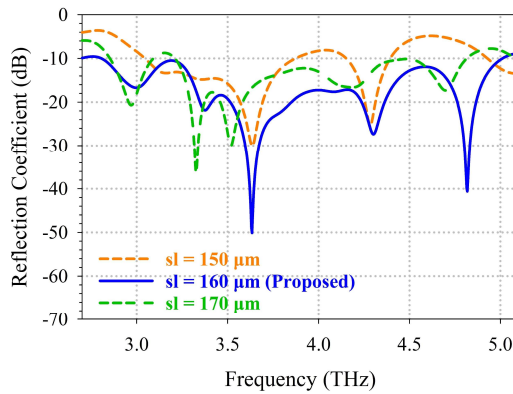


Fig. 8. Reflection coefficient of various substrate lengths.

B. Substrate Length (sl)

Changes in substrate length affect the antenna's performance [33]. As seen from Fig. 8, the return losses of two resonances for the substrate length that is smaller

than the optimum value are limited to two narrow bands of 0.841 THz and 0.314 THz, corresponding to 0.675 and 0.217 THz. In contrast, extending the substrate generates three bands at 1.634, 1.476, and 0.243 THz, but the gain is very small (Fig. 9). This shows the correlation between return loss and bandwidth with the antenna substrate length. This demonstrates how critical precise tuning is for balanced performance and antenna efficiency.

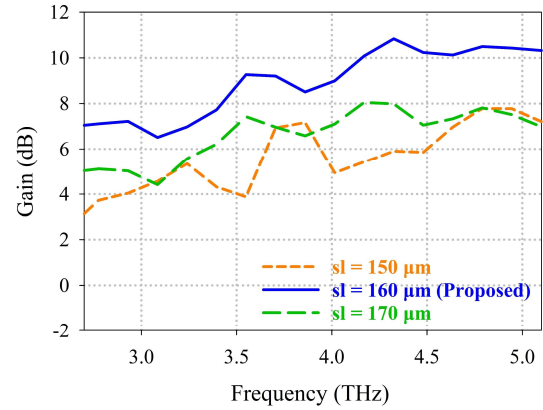


Fig. 9. Gain of various substrate lengths.

VII. PATCH MATERIAL ANALYSIS

Electrical properties of the patch material influence the antenna operating frequency, gain, and return loss [34]. This study aims to find and evaluate the best THz radiating materials by analyzing their high-frequency properties and electromagnetic parameters. Fig. 10 shows antennas with different patch materials and simulation results for reflection coefficient (S_{11}) and gain (Fig. 11 and Fig. 12).

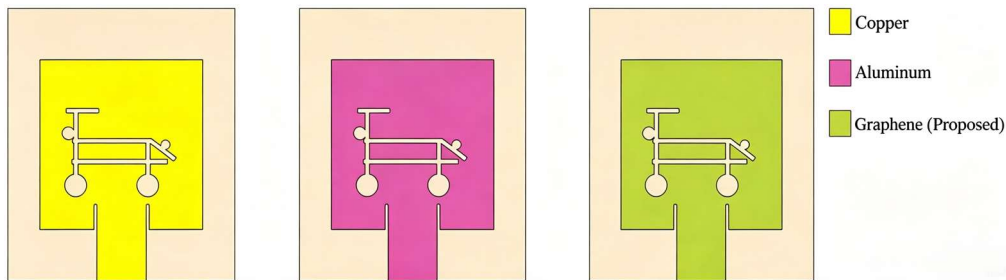


Fig. 10. Single element with different patch material.

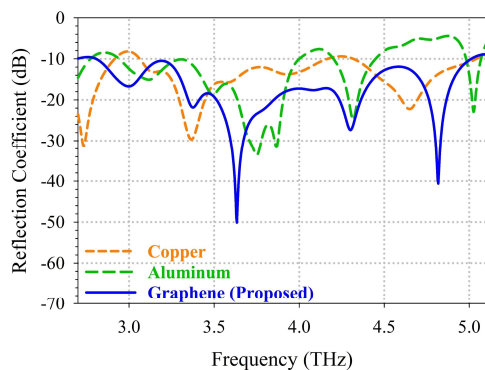


Fig. 11. Reflection coefficient for different patch materials.

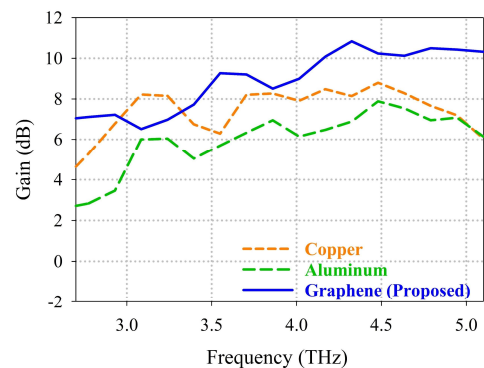


Fig. 12. Gain for different patch materials.

First, copper is taken as the patch material since it is a better conductor of electricity and is widely used for making antennas [35]. Simulations show two bandwidths of 1.125 THz and 0.67 THz, with a gain of 8.63 dB. One of these two resonant frequencies is more symmetrical with increased return loss. THz applications need more than these little gains because copper-based architecture is restricted by bandwidth/high-frequency losses.

Subsequently, aluminum is taken as an alternative. The antenna structure has some resonance frequencies due to its narrow bandwidth of 0.401 THz, 0.654 THz, 0.347 THz, and 0.175 THz. Changing the material substantially impacts the efficiency of performance. Even though the four resonances of aluminum possess good S_{11} values, it is not good for broadband terahertz applications due to the very limited bandwidth and very weak gain.

Eventually, graphene yields the best patches. Its active resonant frequencies are 3.63 THz and 4.81 THz with a bandwidth of 2.178 THz and the highest gain of 10.83 dB. Broad bandwidth of graphene, stronger conductivity, and suitable response to electromagnetic waves suggest that graphene is a better candidate compared to other materials for THz frequencies. It is a superior material for the next generation of terahertz antennas, given that it is flexible, low-loss, and an efficient radiator [36].

VIII. DIFFERENT MIMO CONFIGURATION

Antennas have evolved from single-element designs to Multiple-Input Multiple-Output (MIMO) configurations over the past years to boost system capacity and data rates [37]. The introduction of spatial diversity, channel capacity, multipath propagation, and communication security with reduced interference is being achieved. Single-element structures are typically more adaptable for dynamic, highly-accelerated wireless communication applications exploiting MIMO architectures. This step is crucial to antenna configuration because performance and signal reception are influenced at least by antenna part orientation and layout. Antennas 1, 2, and 3 were tested for impact on reflection and transmission coefficients, among other things, in Fig. 13 over certain bandwidths.

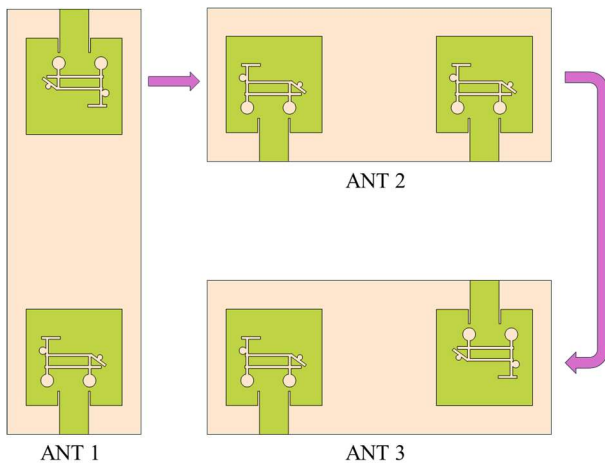


Fig. 13. Different MIMO configurations.

In Antenna-1, one element was inverted to investigate radiation and loss characteristics. In Antenna-2, the sections were lined up, while in Antenna-3, the whole parts were placed adjacent but rotated 180 degrees. The changes from single-element to MIMO are shown in Fig. 14 and Fig. 15. Though Antenna-1 showed poor isolation (-15.753 dB) and worse resonant features than the single-element structure, it had reflection coefficients of -19.895 and -25.853 . Although Antenna-2 was far better with return loss of -36.895 and -26.105 dB, and isolation of -20.794 dB, the antenna was still not suitable for MIMO operation.

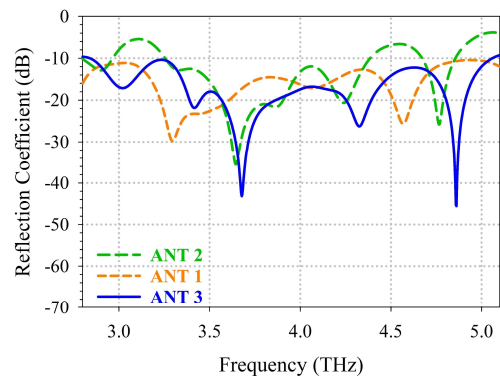


Fig. 14. Reflection coefficient for each MIMO configuration.

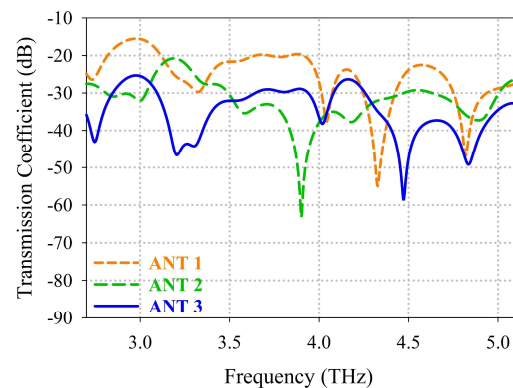


Fig. 15. Transmission coefficient for each MIMO configuration.

The maximum performance of Antenna-3 was with two resonant frequencies, for which return losses are -44.593 dB, and -46.641 dB reflection coefficients, and an isolation value of -25.705 dB. The single-element antenna has good performance on the first resonance, but Antenna-3 has better performance on the second. This comprehensive study presents that element alignment has a significant impact on the resonance, return loss, and isolation, which confirms Antenna-3 as the optimum candidate for next-generation wireless communications high-performance MIMO antenna systems. However, certain enhancements can be implemented.

IX. MIMO ANTENNA WITH DECOUPLER

With the introduction of isolation walls into MIMO antenna element topologies, the performance has significantly improved as the inter-element coupling

decreases and isolation increases [38]. Fig. 16 illustrates the suggested MIMO antenna configurations both with and without isolation walls, whilst Fig. 17 and Fig. 18 depict their reflection and transmission coefficients.

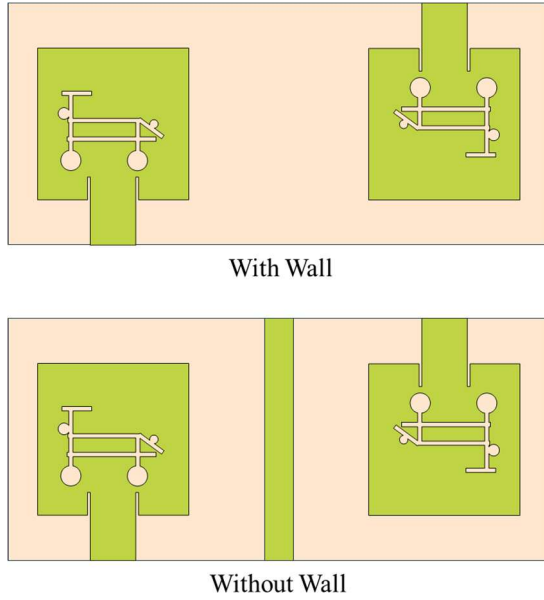


Fig. 16. MIMO antenna in the presence and absence of wall.

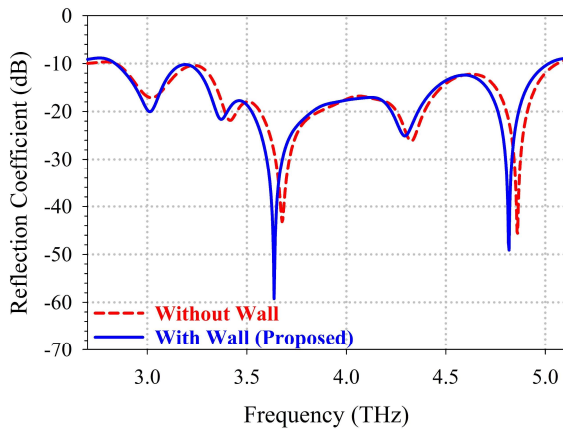


Fig. 17. Reflection coefficient for both the presence and absence of wall.

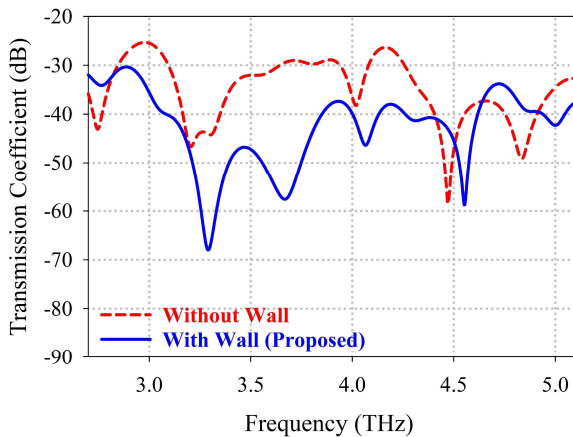


Fig. 18. Transmission coefficient for both the presence and absence of wall.

The presence of walls greatly reduces the propagation of surface currents between antenna elements and thus less unwanted electromagnetic coupling, better impedance matching, and the stability of resonant modes in the whole working band can be obtained. In the case of no walls, the reflection coefficients are -44.593 dB and -46.641 dB, and the isolation is -25.705 dB, which is not good enough for high-frequency applications in terahertz. Meanwhile, for the integrated wall structure, the reflection coefficients are -59.259 dB and -49.108 dB with improved isolation of -30.334 dB, as shown in Fig. 18. These modifications provide a boost in resonance and signal integrity, while reducing coupling. The proposed wall-mounted MIMO antenna presented in this article demonstrates improved stability and efficiency, and is more suitable for the future terahertz communication systems in high assurance and spectrum efficiency.

X. RESULTS AND DISCUSSION

A. Reflection Coefficient

The reflection coefficient S_{11} evaluates how well the antenna reflects the incident signal with its own reflected signal, indicating whether the antenna is working at its frequency of operation [39]. The transmitted power could be increased by a smaller reflection coefficient, which meant more efficiency. The reflection coefficient of the proposed MIMO antenna shows, which provides dual-band operation with good resonance. The antenna resonates at 3.6368 THz and 4.8179 THz with return losses of -59.259 dB and -49.108 dB. The antenna applies to a wide frequency range with a bandwidth of 2.2047 THz and a working frequency of 2.839 THz– 5.017 THz. Fig. 19 shows the reflection coefficient at some resonance frequencies.

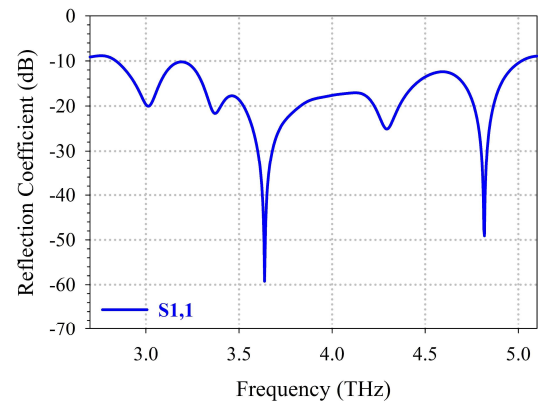


Fig. 19. Reflection coefficient of the proposed MIMO.

B. Transmission Coefficient

The transmission coefficient (or S_{21} for a two-port system) quantifies signal flow between antenna elements and determines MIMO systems' mutual coupling [40]. Ideal MIMO performance requires low transmission coefficients (high isolation) to reduce element interference. The proposed antenna offers a minimum isolation of -30.334 dB, and the maximum isolation is -68 dB, indicating multi-antenna diversity performance. Fig. 20

shows the proposed MIMO antenna's transmission coefficient, which verifies the isolation.

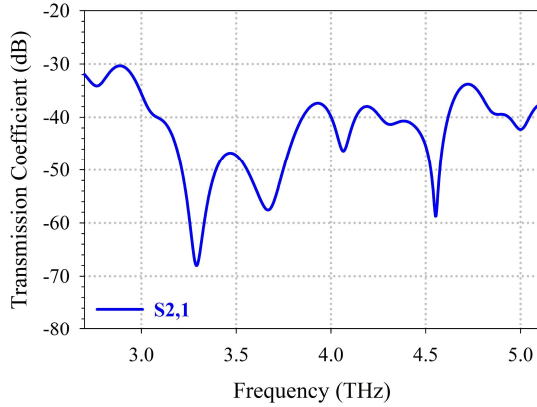


Fig. 20. Transmission coefficient of the proposed MIMO.

C. Gain and Efficiency

Gain characterizes the quality of the antenna [41]. Gain is a measure of how well the antenna focuses energy, while efficiency is a measure of how efficiently it converts power to radiated energy. Higher gain and efficiency mean a more tightly spaced, more effective, and intense signal. Fig. 21 demonstrates that the proposed antenna provides a maximum gain of 11.875 dB for all bands, which exhibits strong signal power. With the 80.62% efficiency assumed constant over the band, this is an efficient antenna with very little energy loss.

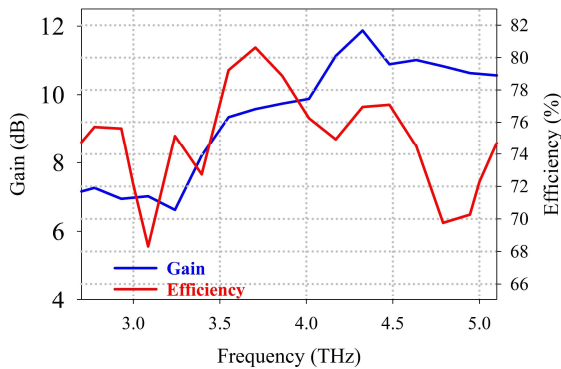


Fig. 21. Gain and Efficiency of the proposed MIMO antenna.

D. Diversity Performance Analysis

MIMO antenna systems' performance of diversity in multipath reduces the fading, and the reliability of the received signals is enhanced [42]. ECC and DG are the dominant criteria.

1) Diversity Gain (DG)

By diversity, a good DG will enhance the robustness and quality of the signal. The proposed MIMO antenna has a DG 9.998, which is very near the theoretical upper-bound. The antenna shows reliability in a multipath environment. In Fig. 22, the quasi-optimal gain, low envelope correlation coefficient, and the anti-interference, anti-fading characteristics of the advanced terahertz band are realized by the antenna.

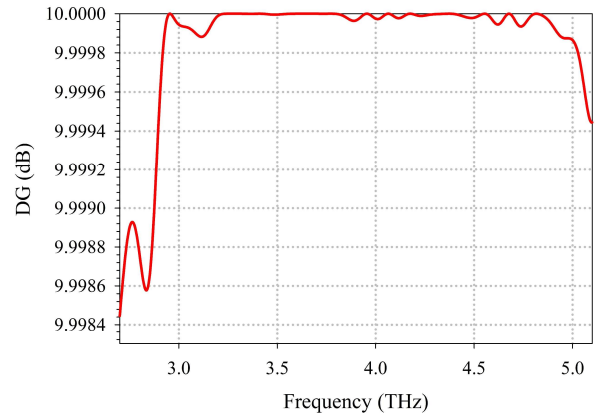


Fig. 22. Diversity Gain (DG) of the proposed MIMO antenna.

2) Envelope Correlation Coefficient (ECC)

The ECC measures the degree of similarity of signals across the antenna elements. An ECC less than 0.5 indicates low correlation and thus provides geographical diversity which results in better system performances. The proposed MIMO antenna has ECC 0.0002845 as shown in Fig. 23. The antenna provides good spatial diversity so that it improves channel capacity, link reliability, and resilience, which is ideal for high-frequency wireless communication applications.

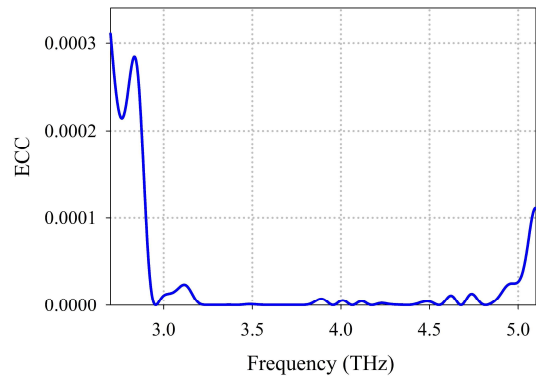


Fig. 23. Envelope Correlation Coefficient (ECC) of the proposed MIMO antenna.

E. Channel Capacity Loss (CCL)

The performance of a MIMO antenna system is assessed by Channel Capacity Loss (CCL), a critical metric that indicates the decline in data transmission efficiency due to correlation across antenna elements. The channel capacity of a MIMO system theoretically grows with the number of antennas. Nevertheless, in practical systems, this capacity is diminished due to reciprocal coupling and correlation among the antenna parts. The CCL parameter measures the decrease in channel capacity and indicates the effective usage of the MIMO channel [43]. The CCL can be determined using Eq. (6).

$$CCL = -\log_2 \det(p_R) \quad (6)$$

The receiver two-port correlation matrix can be determined using Eq. (7).

$$p_R = \begin{pmatrix} \rho_{xx} & \rho_{xy} \\ \rho_{yx} & \rho_{yy} \end{pmatrix} \quad (7)$$

where:

$$\begin{aligned} \rho_{xx} &= 1 - (|S_{xx}|^2 + |S_{xy}|^2) \\ \rho_{yy} &= 1 - (|S_{yy}|^2 + |S_{yx}|^2) \\ \rho_{xy} &= |S_{xx}^* S_{xy} + S_{yx}^* S_{xy}|^2 \\ \rho_{yx} &= |S_{yy}^* S_{yx} + S_{xy}^* S_{yx}|^2 \end{aligned}$$

which measures the interactions between ports x and y for ports 1 and 2. Generally, optimal MIMO performance is attained when the CCL is below 0.5 bps/Hz. As illustrated in Fig. 24, the proposed antenna exhibits a relatively uniform channel capacity loss of around 0.4 bps/Hz throughout the operational bandwidth. The low CCL value signifies little inter-port correlation and validates the antenna's appropriateness for effective MIMO operation.

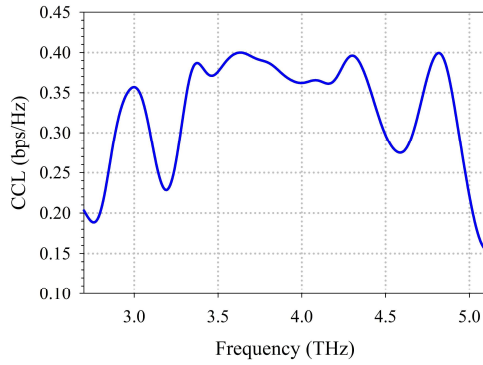


Fig. 24. Channel capacity loss of the proposed MIMO antenna.

F. Total Active Reflection Coefficient (TARC)

A crucial parameter for assessing MIMO antenna performance is the Total Active Reflection Coefficient (TARC), which incorporates transmitted and received powers while factoring in active components like matching networks and amplifiers. To ensure efficient antenna performance and minimal reflected power, the TARC value must be below 0 dB [44]. Reflected power directly influences impedance matching and must be controlled to decrease TARC, as excessive reflection results in standing waves, diminished radiation efficiency, and heightened interference in wireless communication systems.

$$TARC = \frac{\sqrt{(|S_{xx}| + |S_{xy}|)^2 + (|S_{yx}| + |S_{yy}|)^2}}{\sqrt{4}} \quad (8)$$

The proposed MIMO antenna exhibits superior performance during active operation, with TARC values consistently below -10 dB throughout the operational frequency range, as illustrated in Fig. 25. These findings validate effective impedance matching and demonstrate minimal power reflection, hence enhancing radiation efficiency and ensuring consistent MIMO performance.

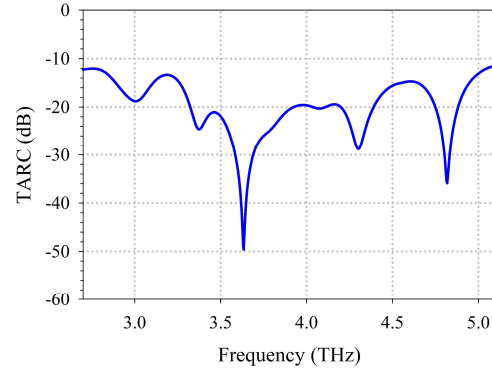


Fig. 25. Total active reflection coefficient of proposed MIMO antenna.

G. Radiation Pattern

The E-field and H-field radiation patterns are used to evaluate the performance of an antenna [45]. The polarization of the antenna is the same as that of the E-field vector, but the H-field vector is perpendicular [46]. This orthogonality is what uniquely defines the complete transmitting characteristics of an antenna. Fig. 26 shows the 2D projected radiation pattern of the proposed structure at 3.63 THz. The 3.63 THz electric field has a main lobe magnitude of 18 dBV/m at $\varphi = 0^\circ$, and the half-power beamwidth is 95.2° at $\varphi = 90^\circ$. The antenna produces an intense terahertz beam of radiation. The H-field response for the same operating point shows a principal lobe peak of -39 dBA/m at $\varphi = 0^\circ$ with a half-power beam width of 31.6° at $\varphi = 90^\circ$. The H-field distribution has a narrower angular spread than the E-field distribution, and a more tightly localized but less pronounced angular dispersion. The antenna design efficiently reduces side-lobe radiation, concentrating most of the power in the main lobe, which is essential for high-precision imaging and sensing applications. Nonetheless, minor side-lobe levels persist, a typical attribute of MIMO systems resulting from mutual coupling among elements. The E- and H-field radiation patterns-based investigation further confirms that the antenna can achieve a fine beam in the THz frequency and hence can be widely used in ultra-high frequency wireless communication and sensing applications.

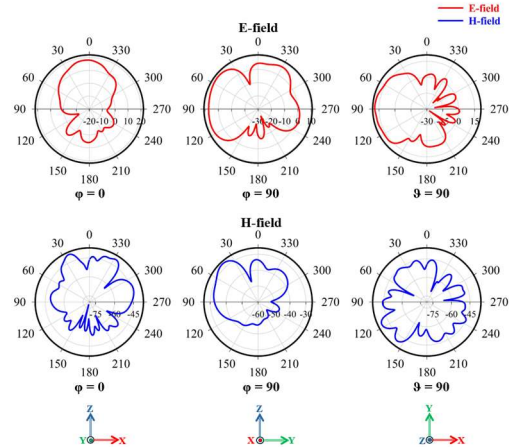


Fig. 26. Simulated radiation pattern of the recommended MIMO antenna.

XI. RLC EQUIVALENT CIRCUIT

An RLC equivalent circuit model was constructed to characterize the electromagnetic behavior of the proposed MIMO antenna [47, 48]. This model delineates antenna radiation, energy storage, and loss through Resistive (R), inductive (L), and Capacitive (C) elements. Resistance (R) mitigates radiation and conduction losses, Inductance (L) accumulates magnetic energy in current-conducting materials, and Capacitance (C) retains electric field energy across intervals or openings.

A full impedance simulation was performed using CST Studio Suite and Keysight ADS to characterize the circuit. The RLC circuit reproduces the scattered current distributions on the antenna and closely resembles full-wave electromagnetic models, capturing its key physical mechanism.

Antennas were approximated by lumped circuit segments. Lumped capacitors are wheelchair-shaped slots, which block the surface current flow channels and induce a localized capacitance. These capacitive elements store electrostatic energy and alter the slots' resonances. The radiating patch and the conductive interconnects act like "inductors", storing magnetic energy along conducting paths. Ohmic and radiation losses caused by the finite conductivity and by the energy flowing out into free space were simulated by using resistors.

Fig. 27 shows the RLC model of the MIMO antenna and has two resonant frequencies in its working bands. The first and second resonances are ruled by the parallel topology R2-L2-C2. This dual-resonance feature provides improved impedance matching and bandwidth utilization by tuning each resonance point for multi-band performances.

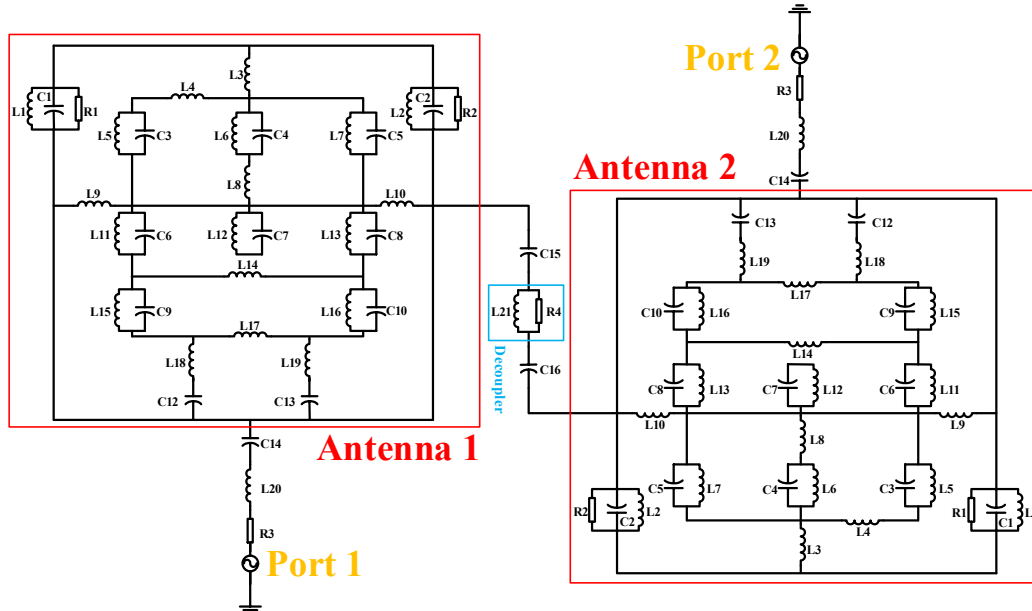


Fig. 27. RLC equivalent circuit of proposed MIMO antenna.

TABLE II. VALUES OF RLC COMPONENTS

Parameter	Value	Parameter	Value	Parameter	Value
L1	6.74 pH	C5	3.71 pF	L9, L10	9.47 pH
C1	3.16 pF	L11	7.74 pH	L14	5.75 pH
R1	50.14 Ω	C6	3.64 pF	L17	5.17 pH
L2	5.24 pH	L12	7.53 pH	L19, L19	1.95 pH
C2	3.47 pF	C7	4.63 pF	C12, C13	2.64 pF
R2	50.19 Ω	L13	6.73 pH	C14	3.73 pF
L5	3.42 pH	C8	3.23 pF	L20	7.76 pH
C3	2.35 pF	L15, L26	7.45 pH	R3	52.65 Ω
L6	4.73 pH	C9, C10	10.34 pF	C15, C16	12.78 pF
C4	6.12 pF	L3	4.82 pH	L21	3.87 pH
L7	3.31 pH	L8	6.65 pH	R4	50.03 Ω

Eight parallel LC networks (C3-L5, C5-L6, C5-L7, C6-L11, C7-L12, C8-L13, C9-L15, and C10-L16) are designed to reproduce the rectangular and circular slots of the wheelchair. L3, L8, L9, L14, and L17 signify current pathways between radiating patch slots, denoting magnetic energy storage. C12-L18 and C13-L19 illustrate the input and output feed configurations of the feedline, whereas R3, L20, and C14 model the impedance and

frequency-dependent characteristics of the transmission line.

In MIMO systems, analogous RLC modeling maintains antenna element attributes while examining mutual coupling effects. Graphene isolation structures restrict short-range electromagnetic interactions among antenna elements. Graphene membranes employ parallel inductive and resistive elements (L21 and R4) to emulate the

shielding and absorption characteristics of the graphene layer, hence enhancing port-to-port isolation.

This enhanced RLC model realistically characterizes MIMO antenna elements and their mutual coupling. Fig. 28 illustrates strong consistency between the S_{11} resonances obtained from the ADS equivalent circuit and CST full-wave simulations, verifying the calculation accuracy. Table II lists the RLC values of all components and further demonstrates that the equivalent circuit reliably predicts antenna impedance and resonant behavior.

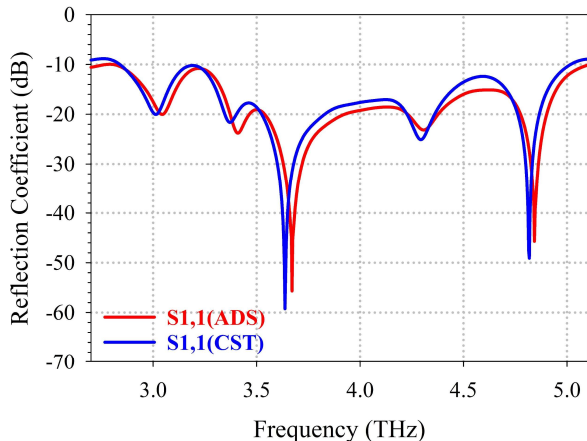


Fig. 28. ADS vs CST S_{11} of the proposed antenna.

XII. CONCLUSION

In this paper, a compact, high-gain 2×2 THz MIMO microstrip patch antenna for future 6G and beyond wireless communication is proposed. The antenna features dual resonances at 3.6368 THz and 4.8179 THz within a wide operating band from 2.839 THz to 5.017 THz, and hence enables important terahertz applications such as advanced sensing, high-resolution imaging, chip-to-chip communication, and ultra-fast wireless communications. A comparative study demonstrates significant enhancement over existing THz designs in bandwidth, gain, isolation, and integration. The achieved bandwidth of 2.2074 THz, gain of 11.875 dB, isolation of -30.334 dB, and radiation efficiency of 80.62% verify the suitability of the antenna for URLLC-level and high-throughput 6G applications. However, the study is limited by the lack of experimental validation, which was not possible due to constraints such as the unavailability of specialized lab facilities, the unavailability of graphene, and the scale of measurements required at terahertz frequencies. Future work should focus on addressing these limitations by conducting experimental measurements to validate the simulation results. The proposed antenna, based on the essential THz windows and the 6G performance requirements, with a compact 160×360 μm layout and a validated RLC equivalent circuit, is suitable for next-generation wireless communication, intelligent sensing, and integrated THz system architectures.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Md. Ashraful Haque wrote the original draft, administered the project, developed the methodology, performed formal analysis, and conceptualized the study; Fardin Ahmed Rifat contributed to writing the original draft, reviewed and edited the manuscript, developed the software and methodology, performed formal analysis, and conceptualized the study; Mehidy Hasan wrote the original draft, reviewed and edited the manuscript, developed the software and methodology, and conceptualized the study; Jun-Jiat Tiang reviewed and edited the manuscript, validated the results, developed the methodology, and acquired funding for the research; Narinderjit Singh Sawaran Singh wrote the original draft, supervised the project, and conceptualized the study; Mahafujul Haq Riad wrote the original draft, developed the methodology, conducted the investigation, and curated the data. All authors have read and approved the final version of the manuscript.

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