Graphene-based high-gain MIMO antenna for enhanced 6G wireless communication systems

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ABSTRACT

This paper presents a novel design and analysis of a high-performance multiple-input multiple-output (MIMO) terahertz (THz) antenna intended for next-generation sixth-generation (6G) wireless communication systems. The proposed antenna operates over a wide frequency range of 1 THz to 4.9 THz, achieving a broad bandwidth of 3.9 THz with three distinct resonant frequencies at 2.05 THz, 3.9 THz, and 4.52 THz, each exhibiting excellent return loss characteristics. The antenna features a graphene-based patch with a copper ground plane, etched on a polyimide substrate with a dielectric constant (εr) of 3.5 and a thickness of 10 micrometers (μm). Key performance metrics, including a high gain of 15.9 decibels (dB), an efficiency of 95.95%, an envelope correlation coefficient (ECC) of 0.0005, and a diversity gain (DG) of 9.997 dB, indicate outstanding performance. The measured isolation between the two antenna elements is -31.91 dB, signifying excellent isolation. An equivalent resistor-inductor-capacitor (RLC) circuit model is developed using advanced design system (ADS), validated by comparing S11 results from both computer simulation technology (CST) and ADS simulations. The proposed MIMO antenna's wide operating range and robust performance demonstrates great potential for high-speed THz wireless communication, imaging, spectroscopy, sensing, and offers valuable contributions to industry and innovation.

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1. INTRODUCTION

The rapid advancement of wireless communication technologies has driven the need for higher data rates and more reliable connections. Terahertz (THz) technology, operating within the range of 0.1 to 10 THz, stands out as a promising solution to these demands [1]. However, leveraging THz frequencies presents significant challenges, including high propagation losses, limited coverage, and the need for precise material and antenna designs to ensure efficiency and reliability. Offering data rates up to 10 Gbps and beyond, potentially reaching terabits per second (Tbps), THz communication is poised to revolutionize the landscape of wireless connectivity [2]. One of the critical applications of THz technology is in multiple-input multiple-output (MIMO) antenna systems. These systems enhance communication performance by utilizing multiple antennas at both the transmitter and receiver ends, thereby increasing data rates and improving reliability through spatial diversity and multiplexing [3]. MIMO antennas operating in the THz range can overcome the challenge of the narrow bandwidth of GHz frequencies, providing higher reliability and low fading, which are essential for the next generation of wireless communications [4].

The development of 6G communication networks, expected to succeed the current 5G infrastructure, heavily relies on THz technology. 6G aims to deliver ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and augmented reality (AR) capabilities, among other advanced applications [5], [6]. This future network will cater to both indoor and outdoor environments, facilitating seamless satellite and mobile communication as well as internet of things (IoT) applications [7]. Existing antenna designs, while effective at GHz frequencies, struggle to meet the performance metrics required for THz communication due to material losses, design complexity, and poor impedance matching. This work addresses these constraints by proposing a high-gain, ultrawide-band patch antenna optimized for MIMO systems operating at the THz band. The goal of this research is to enhance data rates and reliability while ensuring efficiency in 6G applications. Recent work in the field of THz antennas has focused on overcoming the technical challenges associated with higher frequencies. Innovations in material science, antenna design, and signal processing have contributed to significant advancements, paving the way for the practical implementation of THz MIMO systems. These efforts are crucial in achieving the high data rates and reliability required for 6G communication. In addition to enhancing communication networks, THz technology holds potential for various medical applications [8]. Its ability to penetrate biological tissues with minimal damage opens new possibilities for medical imaging and diagnostics [9].

The proposed antenna design, detailed in Table 1, showcases substantial advancements and superior performance metrics compared to existing designs. It achieves significantly broader bandwidths of 3.9 THz, far exceeding the bandwidth values of 0.114 THz, 0.3 THz, 0.78 THz, 0.05 THz, and 0.4 THz reported in references [10]-[13]. The proposed antenna's isolation levels surpass -35.32 dB, effectively minimizing interference and outperforming the measured levels of ≥-35 dB, >-20 dB, >-25 dB, >-20 dB, >-25 dB, and >-20 dB cited in [9]-[12], [14], [15]. With an efficiency of 95.95%, the proposed design outshines the efficiencies of 94%, 92%, 76.45%, and 85.24%, mentioned in studies [10], [12], [14], [15]. The gain of the antenna achieves 15.9 dB which outperforming the measured value 4.4 dB, 10 dB, 4 dB, 8.28 dB, 11.67 dB and 5.49 dB in the referenced work [10]-[15]. Furthermore, with an envelope correlation coefficient (ECC) of 0.0005 and a diversity gain (DG) of 9.997 dB, the proposed antenna shows exceptional metrics compared to ECC values of 0.0002, 0.000023, 0.006, 0.003, and 0.015, and DGs of 9.99 dB reported in the literature [10]–[12], [14], [15]. Notably, the suggested design differs from the preceding designs and performs much better since the inclusion of resistor-inductor-capacitor (RLC) components. All things considered, the thorough analysis highlights the noteworthy improvements and excellent performance metrics of the suggested antenna design, underscoring its potential to be a leader in the field of antenna technology.

Table 1. Performance comparisons with the published state of the art

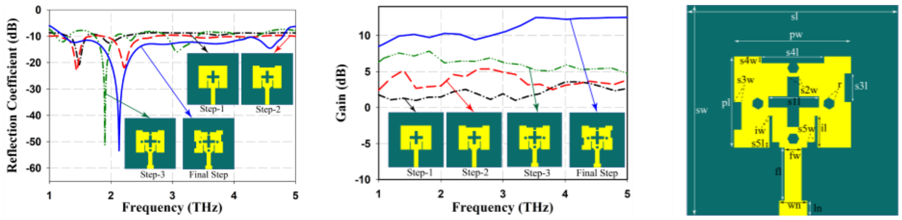
Ref.	Resonance frequency (THz)	Bandwidth (THz)	Port	Isolation (dB)	Gain (dB)	Efficiency (%)	ECC DG (dB)	Material	RLC
[10]	-	0.114	4	-17	4.4	94	0.0002/ 9.99	Rogers RO4835-T	No
[11]	1.9	0.3	2	−35	10	N/A	0.000023/ 9.99	N/A	No
[12]	2.2	0.78	-	–20	4	92%	0.006/ 9.99	Polyimide	No
[13]	1.1	N/A	2	−20	8.28	N/A	N/A	Pyrex	No
[14]	0.654	0.05	-	-25	11.67	76.45	0.003/ 9.99	Polyimide	No
[15]	-	0.4	2	-25	5.49	85.24%	0.015/ 9.99	Polyimide	No
This work	2.05, 3.9, 4.52	3.9	2	-31.91	15.9	95.95	0.0005/ 9.997	Polyimide	Yes

2. DESIGNING OF THE SINGLE-ELEMENT ANTENNA

In our pursuit of developing a state-of-the-art antenna for THz applications, we meticulously crafted a single-element antenna, refining its structure through four iterative stages to achieve peak performance. Figure 1(a) shows the reflection coefficient of each stage, while Figure 1(b) illustrates the gain, and Figure 1(c) presents the proposed single-element antenna. We selected polyimide as the substrate due to its excellent dielectric properties, including a dielectric constant of 3.5 and a low-loss tangent of 0.0027.

Graphene was chosen for the patch element, and copper was employed for the ground element, ensuring the optimal combination of materials [16]. The design consistently incorporated a full ground plane.

In the initial stage, we designed a rectangular patch with a feedline, added insets on both sides, and introduced a plus-shaped slot at the center of the patch. However, the initial results were suboptimal, featuring a return loss of -20.12 dB, a gain of 3.59 dB, and a bandwidth of only 0.15 THz, highlighting significant limitations in impedance matching, signal strength, and operational frequency range. Progressing to the second stage, we added a slot at the center top of the patch and two slots at the bottom of the insets. This modification resulted in a dual-band antenna, yet the performance parameters remained unsatisfactory. In the third stage, we incorporated four hexagonal slots at the top of each side of the plus-shaped slot. This modification led to a remarkable enhancement in performance, achieving a return loss of -51.29 dB, a gain of 7.8 dB, and a bandwidth of 0.4 THz. While these improvements in return loss and gain were notable, the bandwidth still remained constrained. Ultimately, in the fourth stage, we enhanced the design by adding two insets on the left and right sides of the patch. This final configuration achieved a resonance frequency at 2.13 THz with an impressive return loss of -53.4 dB, a substantial bandwidth of 3.57 THz, and a gain of 12.62 dB, underscoring its potential for deployment in advanced 6G communication systems.



(a) (b) (c)

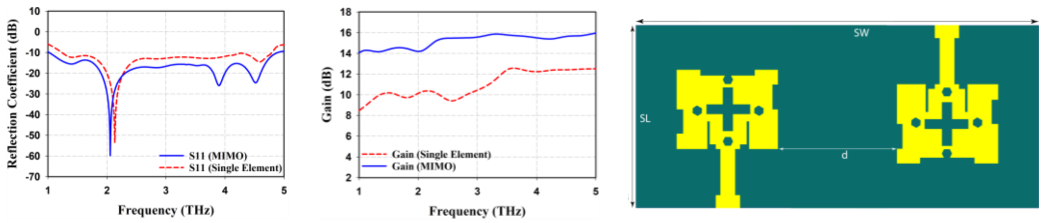
Figure 1. Analysis of the single element antenna: (a) S11 comparison, (b) gain comparison of three steps, and (c) single element antenna

3. DESIGN OF THE PROPOSED MIMO ANTENNA

MIMO technology is essential for enhancing wireless communication systems, as it significantly increases data throughput and link reliability by exploiting multiple transmission and reception paths. This technology is crucial for meeting the ever-growing demand for higher data rates and improved performance in modern communication networks [17].

In this section, we discuss how a single-element antenna was enhanced to create a 2-port MIMO antenna. Figures 2(a) and (b) illustrates the return loss and gain comparison between the single-element and MIMO antennas. Figure 2(c) illustrates the proposed MIMO antenna configuration, where two elements are positioned side by side with a 180-degree orientation relative to each other. The edge-to-edge distance between the two antennas is maintained at 85 micrometers, and the overall dimensions of the antenna are 100 by 240 micrometers. This strategic placement ensures optimal performance by maximizing spatial diversity and minimizing mutual coupling, leading to improved signal quality and reliability.

After implementing the MIMO configuration, we observed three resonance frequencies at 2.05 THz, 3.9 THz, and 4.52 THz. A broad bandwidth of 3.9 THz encompasses these three resonance frequencies, as shown in Figure 2(a). Additionally, Figure 2(b) demonstrates a maximum gain of 15.9 dB. Comparisons of return loss and gain between the single-element and MIMO antennas are depicted in Figures 2(a) and (b), respectively, clearly showing that the MIMO antenna exhibits significantly better performance than the single-element antenna.



(a) (b) (c)

Figure 2. Overview of the MIMO antenna: (a) comparison of S11 parameters, (b) gain analysis, and (c) MIMO

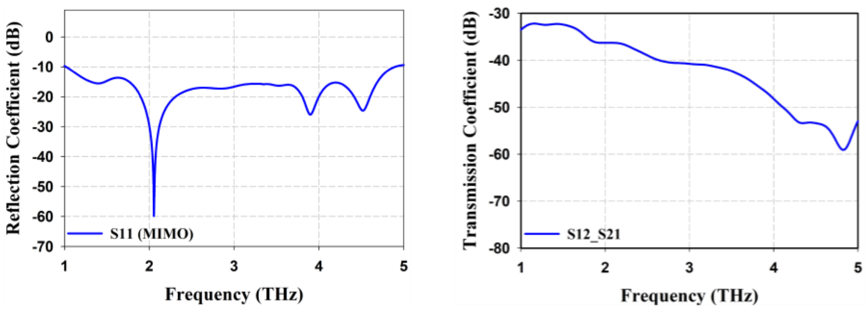
3.1. Reflection coefficient and transmission coefficient

The reflection coefficient, represented by return loss, is a crucial parameter in MIMO system. A lower return loss indicates better impedance matching, resulting in minimal power reflection and enhanced efficiency [18]. Figure 3(a) demonstrates that the proposed THz MIMO antenna resonates primarily at 2.05 THz with an impressive return loss of -60.1 dB. Additionally, the antenna exhibits two secondary peaks at 3.9 THz and 4.52 THz, with return losses of -25.58 dB and -24.4 dB, respectively. These secondary resonances are significant as they enhance the antenna's overall performance across a broader spectrum. The antenna's operating range extends from 1.01 THz to 4.9 THz, resulting in a high bandwidth of 3.89 THz.

The proposed design delivers an outstanding bandwidth of 3.89 THz, exceeding the performance of the designs reported in [10]-[12], [14], [15]. This substantial bandwidth is highly beneficial for high-speed data transmission and communication applications, providing enhanced flexibility and operational reliability. Additionally, the pronounced return losses across both resonance bands highlight superior impedance matching, reducing signal reflection and improving overall antenna efficiency [19].

Isolation is another important parameter, ensuring that the antenna elements operate independently without significant interference from one another. The proposed THz MIMO antenna achieves a minimum isolation of -31.91 dB between any two antenna elements as shown in Figure 3(b).

With an isolation level of -31.91 dB, the proposed antenna outperforms the designs reported in [10], [12]-[15]. This exceptional isolation demonstrates effective separation between antenna elements, significantly reducing cross-talk and interference, which are vital for maintaining superior system performance [20].



(a) (b)

Figure 3. Performance of the proposed MIMO antenna: (a) reflection coefficient and (b) transmission coefficient

3.2. Gain and efficiency

Gain and efficiency are key indicators of an antenna's performance. Figure 4 illustrates that the proposed antenna achieves a maximum gain of 15.9 dB across the operating range, which is particularly high and beneficial for directing energy efficiently [21]. The gain at specific frequencies is also notable: 14.3 dB at 2.05 THz, 14.5 dB at 3.9 THz, and 14.6 dB at 4.52 THz.

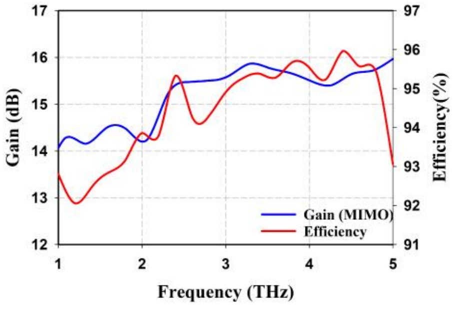


Figure 4. Gain and efficiency of the proposed THz MIMO antenna

Achieving an exceptional peak gain of 14.6 dB, the proposed antenna outshines earlier designs, including [10] with 4.4 dB, [11] with 10 dB, [12] with 4 dB, [13] with 8.28 dB, [14] with 11.67 dB, and [15] with 5.49 dB. This remarkable improvement highlights the antenna's advanced performance and superior engineering [22]. Additionally, the antenna maintains a maximum efficiency of 95.95% across the operating range, with efficiencies of 93.2% at 2.05 THz, 94.9% at 3.9 THz, and 95.1% at 4.52 THz as shown in the same figure of Gain.

Demonstrating an impressive efficiency of 95.95%, the proposed design exceeds the performance levels reported in studies [10], [12], [14], [15], which achieved efficiencies of 94%, 92%, 76.45%, and 85.24%, respectively. These high efficiencies indicate that the antenna converts a significant portion of the input power into radiated energy, minimizing losses and optimizing performance [23].

3.3. Envelope correlation coefficient and diversity gain

The ECC measures the similarity between the radiation patterns of the antenna elements, with a lower value indicating better diversity performance [24]. The value of ECC can be figured out by (1).

$$\frac{\left|\int_{4\pi}\left[E_1(\theta,\varphi)*E_2(\theta,\varphi)\right]d\Omega\right|^2}{\int_{4\pi}|E_1(\theta,\varphi|^2 d\Omega \int_{4\pi}|E_2(\theta,\varphi|^2 d\Omega} \tag{1}$$

Figure 5(a) shows that the antenna achieves an ECC value of 0.0005, which is exceptionally low and desirable. With an ECC of 0.0005, the proposed antenna surpasses the ECC values found in the literature, including 0.0002 in [10], 0.000023 in [11], 0.006 in [12], 0.003 in [14], and 0.015 in [15]. This indicates minimal correlation between the signals from different antenna elements, ensuring superior isolation. Consequently, the antenna is highly suitable for applications where high isolation and low interference are critical.

The DG, which quantifies the improvement in signal quality achieved through diversity, is nearly ideal at 9.997 as shown in Figure 5(b). The value of DG can be determined by (2) [25].

$$DG = 10\sqrt{1 - ECC^2} \tag{2}$$

With a DG of 9.997 dB, the proposed antenna significantly outperforms the designs reported in [10], [11]-[15], which achieved DG values of 9.99 dB. This demonstrates the antenna's superior ability to reduce signal degradation and enhance overall system performance, making it highly suitable for reliable and robust MIMO applications.

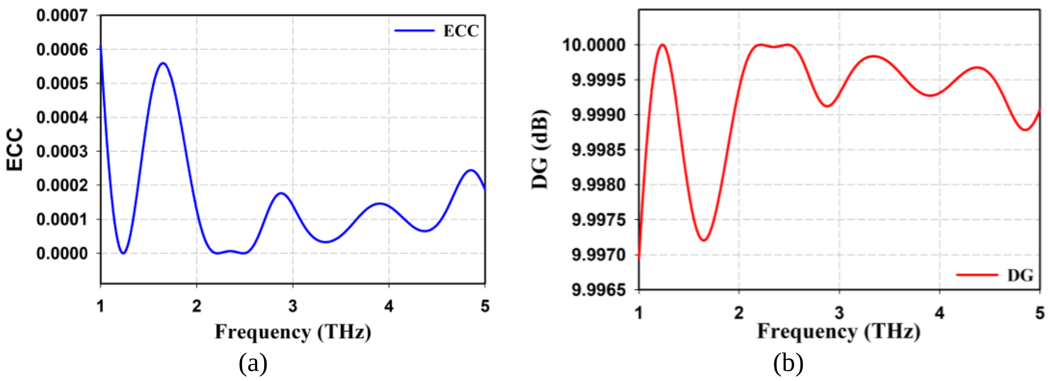


Figure 5. Diversity performance of the proposed THz MIMO antenna: (a) ECC and (b) DG

4. RADIATION PATTERN

The proposed antenna exhibits distinct radiation patterns at the resonance frequency of 2.05 THz, as shown in Figure 6. At $\phi = 0°$, the E-field's main lobe magnitude is 14.5 dBV/m with a half-power beamwidth (HPBW) of 72.3 degrees, while the H-field's main lobe magnitude at the same angle is -41.3 dBA/m and has a HPBW of 31.5 degrees [26]. For $\phi = 90°$, the E-field's main lobe magnitude is 6.24 dBV/m, with a HPBW of 95.6 degrees, and the H-field's main lobe magnitude is -33.7 dBA/m, with a corresponding HPBW of 57.3 degrees. Additionally, at $\theta = 90°$, the E-field reaches a main lobe magnitude of 18 dBV/m, and a HPBW of 55.4 degrees, while the H-field's main lobe magnitude is -34.2 dBA/m, with a HPBW of 36.9 degrees. These characteristics highlight the antenna's directional capabilities and its performance efficiency at the specified operating frequency.

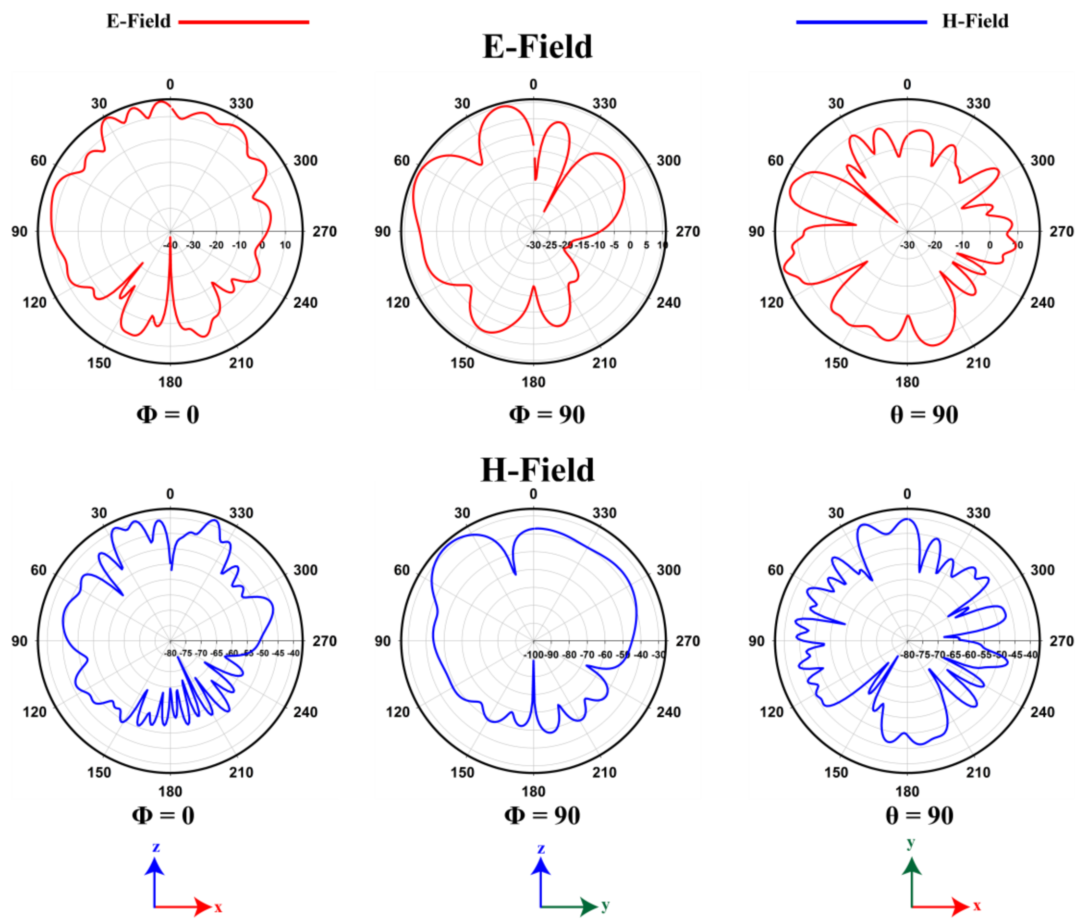


Figure 6. Simulated radiation pattern

5. RLC EQUIVALENT CIRCUIT

In our quest to revolutionize antenna technology, we investigated the electromagnetic behavior of our antenna using an RLC circuit model. Using computer simulation technology (CST) Studio, we meticulously extracted the RLC parameters from our antenna simulations. This analysis was further refined through circuit simulation in Agilent advanced design system (ADS), allowing for a thorough evaluation of the antenna's performance [27].

Initially, we designed a plus-shaped RLC circuit corresponding to the plus-shaped slot. This involved combining four parallel circuits of C and L in series with C to represent the plus-shaped slot. Additionally, four series circuits of C and L were used to represent the other slots of the antenna. These circuits were pivotal in determining the resonance frequency. For the feedline, we incorporated resistance (R3), capacitance (C12), and inductance (L9) parameters to accurately capture its electrical characteristics. By integrating these circuit elements, we constructed a model that accurately replicated the behavior of our single-element antenna.

We then extended this model to a MIMO antenna configuration, as illustrated in Figure 7. In transitioning to the MIMO setup, we accounted for mutual impedance between antenna elements using a parallel circuit of (L7+C10). This approach optimized performance evaluation. We validated the RLC circuit model through simulation in Agilent ADS, confirming its alignment with our antenna design. To ensure precision, we compared the CST simulation results with those of the parallel circuit simulation, focusing on the S11 parameter. Figure 8 elucidates this comparison, providing a comprehensive assessment of our RLC circuit model's accuracy in emulating the antenna's behavior.

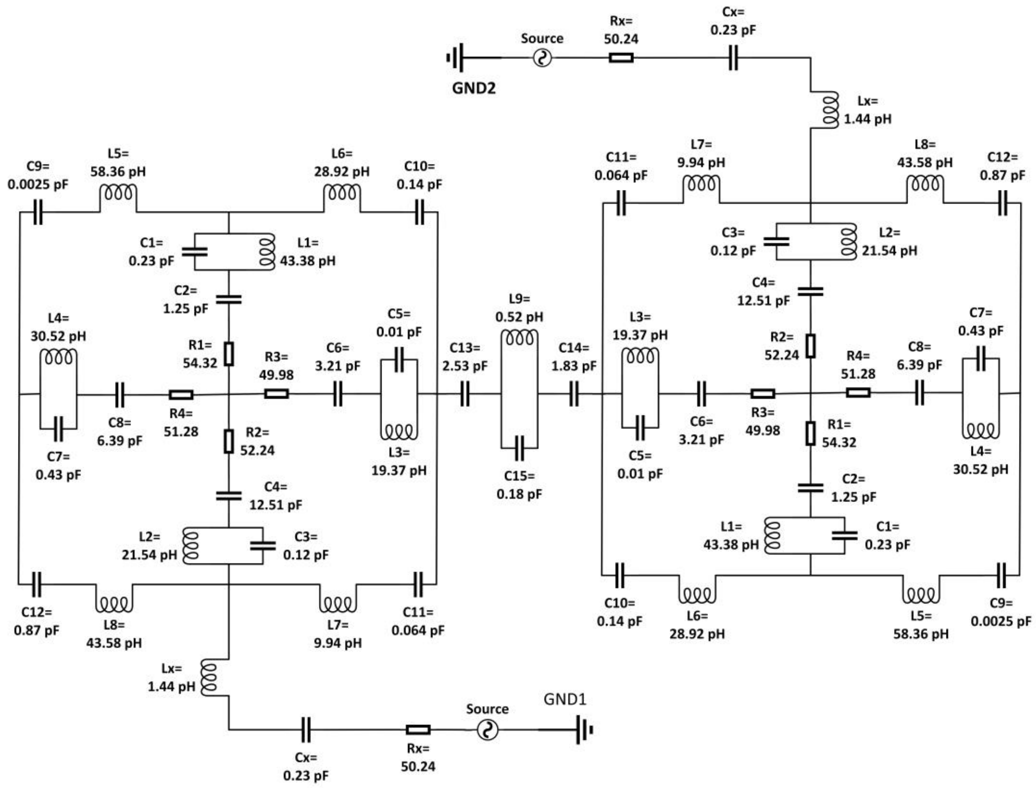


Figure 7. RLC equivalent circuit diagram for the suggested MIMO antenna

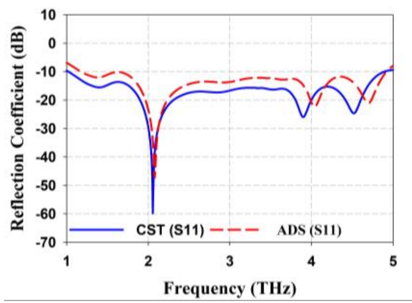


Figure 8. Comparative plot of S11 parameter from CST and ADS simulations

6. CONCLUSION

The development of the MIMO terahertz (THz) antenna presented in this paper marks a significant milestone in antenna technology for advanced 6G wireless communication systems. By advancing from a single-element design to a complex MIMO configuration, we have achieved a highly efficient antenna capable of operating across a broad frequency range of 1 THz to 4.9 THz. The antenna's exceptional performance metrics, including a gain of 15.9 dB, an efficiency of 95.95%, and outstanding isolation characteristics, underscore its suitability for high-frequency applications. This work not only demonstrates the antenna's potential for high-speed communication, imaging, spectroscopy, and sensing but also sets a foundation for future innovations in terahertz technology. The successful validation through both CST and ADS simulations confirms the design's reliability, paving the way for further research and development. Future research could focus on integrating massive MIMO technology to improve system capacity and coverage while leveraging metamaterials for enhanced performance and new functionalities. Applying machine learning, using models like artificial neural networks (ANN) and convolutional neural networks (CNN) with extensive datasets, offers a promising approach to optimize antenna parameters. These findings contribute significantly to the field and pave the way for advancements in THz sensing and communication technologies.

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AUTHOR CONTRIBUTIONS STATEMENT

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Sawaran Singh														
Md. Ashraful Haque				✓		✓		✓		✓	✓	✓		
Jamal Hossain Nirob	✓	✓	✓			✓		✓	✓	✓	✓		✓	
Kamal Hossain Nahin	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
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Liton Chandra Paul		✓		✓			✓			✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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