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Graphene-based THz antenna with a wide bandwidth for future 6G short-range communication

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ABSTRACT

In this study, we present the design and investigation of a terahertz (THz) frequency antenna optimized for the 2-10 THz range, featuring both single-element and multiple-input multiple-output (MIMO) configurations, with a focus on industrial and innovative applications to enhance future 6G communication systems. The antenna, constructed on a polyimide substrate with dimensions of 90×30 µm, achieves a bandwidth from 4.0328 to 10 THz. The MIMO configuration, which includes two ports, demonstrates excellent isolation with a value of -27 dB. The proposed antenna system achieves a gain of 12.38 dB and an efficiency of 89%, making it highly appropriate for THz communication applications. Furthermore, the envelope correlation coefficient (ECC) of 0.002 and diversity gain (DG) of 9.99 affirm the antenna's effectiveness in MIMO systems. A resistance inductance capacitance (RLC) circuit model was employed to accurately represent the S11 curve, ensuring precise characterization of the antenna's performance. These results underscore the probability of the proposed antenna for high-speed, short-range communication systems.

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1. INTRODUCTION

The rapid growth of wireless communication technologies has spurred the exploration of novel frequency bands to meet the growing demand for high data rates and huge bandwidths [1]. Among these, the terahertz (THz) frequency range, ranging from 0.1 to 10 THz, has garnered significant interest due to its potential to support ultra-fast data transmission and high-capacity communication systems [2]. Unlike conventional microwave and millimeter-wave frequencies, the THz band offers an extensive bandwidth that can facilitate data rates exceeding hundreds of gigabits per second (Gbps) [3]. This makes it particularly suitable for emerging applications such as ultra-high-definition video streaming, high-speed wireless networks, and next-generation mobile communications [4].

However, designing antennas that operate efficiently at THz frequencies poses several challenges, including high propagation losses, fabrication precision, and material selection [5]. The choice of substrate material is vital, as it affects the antenna's impedance matching, bandwidth, and radiation efficiency [6]. In this study, we employ a polyimide substrate due to its favorable dielectric properties, low-loss tangent, and mechanical flexibility, making it an ideal candidate for THz applications [7].

Multiple-input multiple-output (MIMO) technology has become a cornerstone in modern wireless communications, offering significant enhancements in channel capacity, spectral efficiency, and signal reliability [8]. By deploying multiple antennas at together the transmitter and receiver, MIMO systems activity spatial diversity and multiplexing gains. This technology is especially promising in the THz domain, where it can mitigate the effects of high path loss and limited power output of THz sources [9]. Our research attention is on the design and investigation of a THz antenna system that incorporates MIMO technology, aiming to achieve high gain, broad bandwidth, and low mutual coupling between elements.

A key aspect of antenna design is the accurate modeling of its impedance characteristics, typically represented by the S11 parameter. In this work, we employ a resistance inductance capacitance (RLC) circuit model to simulate the S11 curve of the proposed MIMO antenna, providing a detailed understanding of its resonant behavior and input impedance. The RLC model helps to capture the complex interaction between the antenna elements and the substrate, offering insights into optimizing the design for improved performance.

This paper presents a comprehensive investigation of a THz antenna system, covering both single-element and MIMO configurations. The proposed antenna demonstrates a bandwidth range of 4.0328-10 THz, which is better compared to [10]-[14], which is shown in Table 1, a gain of 12.38 dB better then [10], [11], [13], and an efficiency of 89% [10], [11], [13]. The MIMO configuration, with two ports, achieves excellent isolation of -27 dB, an envelope correlation coefficient (ECC) of 0.002, and a diversity gain (DG) of 9.99, indicating robust MIMO performance. These characteristics highlight the antenna's potential for high-speed, short-range communication systems.

Table 1. Performance evalution of the proposed MIMO antenna in comparison to related work

Ref	Resonance (THz)	BW (THz)	Isolation (dB)	Gain (dB)	Efficiency (%)	ECC (dB)	DG (dB)	Substrate material	Board size (μm^2)	MIMO configuration
[10]	1.89	1.59	-25	4.60	74.5	15.6×10^{-10}	≈10	SiO_2	38×25	-
[11]	-	0.114	-17	4.4	94	0.006	9.97	Rogers RO4835-T	2000×1000	2×2
[12]	10.51	1	-	-	-	-	-	Silicon dioxide	-	-
[13]	2.3, 3.2, 4.5	0.038, 0.043, 0.06	-17, -30, -23	5	60	0.2	9.99	Polyimide	50×40	
[14]	2.8	1.5	-	-	-	-	-	RT/duriod6010	-	-
Proposed	8.096	(4.0328-10)	-27.62	12.38	-89.0		9.99	Polyimide	90×30	2×2

2. DESIGN METHOD

2.1. Single element design

In our single-element antenna design process, we start with a circular patch shape, changing its shape in several steps to improve performance. We use graphene for the patch material, a circular patch shape with radius 'r', placed on a substrate, and copper as the ground material. Both patch and ground have a thickness of 0.75 micrometers and substrate dimensions are 30 micrometers in length and 25 micrometers in width [15]. A circular slot is in the center of the substrate and two square slots are on either side of the feed line, flanked by two insets. Further modifications include a rectangular ground plane (30 by 25 micrometers) with a central circular structure of radius 'r' [16]. There is also an inset ground along the feed line. These modifications and our target improve impedance matching, bandwidth, gain, and radiation pattern. We then simulate the antenna using CST software to evaluate the return loss, radiation pattern, and gain, gaining insight into its behavior across different conditions and frequencies. We can see the design in Figure 1.

2.2. Analysis of the result of the single element by using graphene and copper

First, we attempted to design a single-element antenna, using copper for both the patch and ground. In the second stage design patch and ground graphene. In the third stage we use copper we use patch materials graphene and ground materials, copper. At this stage, we tried to find the best results in graphene and copper combinations [17]. We can see the design changes in Figure 2. In the first step for Figure 2(a) and for the second step Figure 2(b) we get the result return loss -38 dB and -44 dB. In the third stage, we get the result frequencies 5.66 and 7.94 return loss -66.48 and -75.25 dB for proposed Figure 2(c), this is our propped single-element antenna result and shown graphically in Figure 2(d). Substrate width (sw)=25 micrometer, substrate thickness (st)=3 micrometer radios (r)=10 micrometer slot1 (s11)=2 micrometer, ground width (bw)=25 micrometer, ground length (bl)=30 micrometer, patch thickness (t)=0.75 micrometer, feedline width (fw)=3 micrometer feedline length (fl)=6 micrometer, edge-to-edge gap1 (d)=3.5 micrometer, edge-to-edge gap2 (d2)=4 micrometer, inset length (x)=0.5 micrometer, and inset width (y)=4 micrometer.

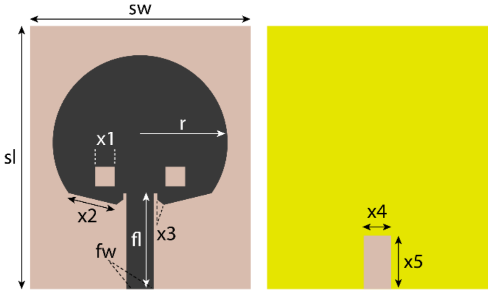
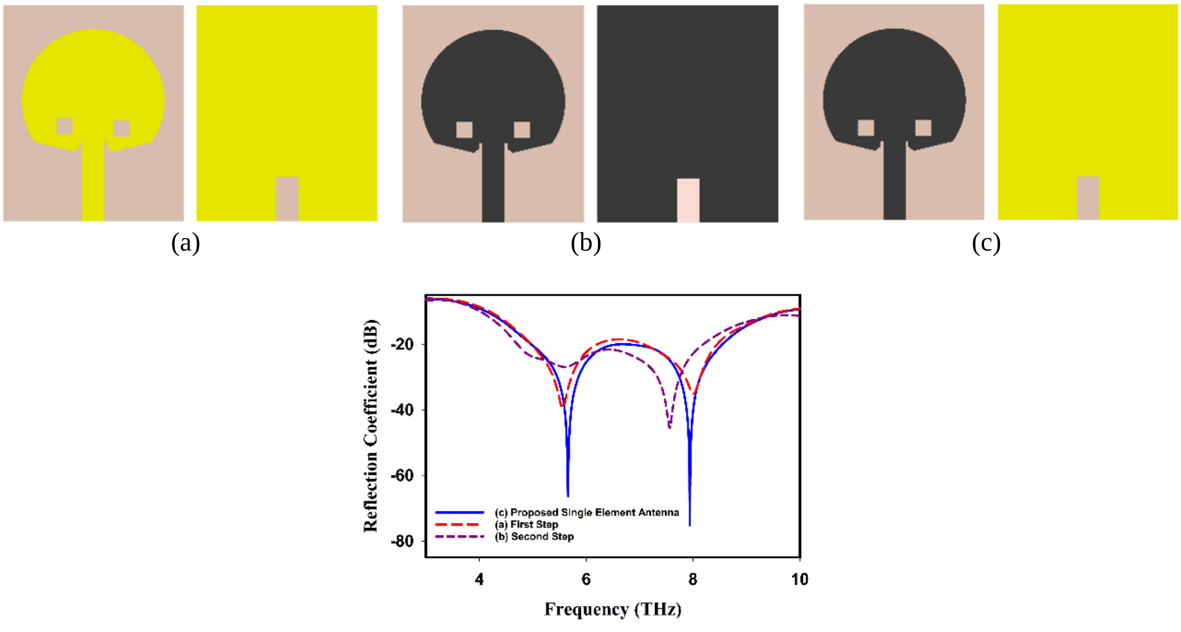


Figure 1. Front and ground views of single-element configuration



(a) (b) (c)

(d)

Figure 2. Evolutionary progression and result of single element; (a) first step, (b) second step, (c) proposed singlement element antenna, and (d) graphics

2.3. Single element vs multiple-input multiple-output

In our current endeavors focused on global 5G applications, our developmental trajectory is centered on advancing antenna technology for forthcoming 6G applications [18]. In this section, we will try to find the difference between single-element antenna and MIMO. Initially, a shift from single-element antennas to MIMO configurations, marked a transformative progression. This advancement is primarily motivated by the pursuit of enhanced performance, efficiency, and adaptability within wireless communication systems. Additionally, cognitive technologies such as AI are leveraged to enable high-speed, low-latency communications operating at existing radio frequencies and achieving speeds significantly surpassing those of fifth-generation networks [19]. The transition from single-element antennas to MIMO configurations allows us to harness spatial diversity, multiplexing gain, and improved spectral efficiency. These attributes are crucial for meeting the escalating demands for higher data rates, reduced latency, and expanded network capacity in 6G networks. From our single-element antenna to MIMO, our range of mobility and work is wide.

2.4. Multiple-input multiple-output antenna

In this section, we will explain the conversion technique in a MIMO formation. At this stage, it is decided to convert to a MIMO configuration for increasing antenna performance and spatial diversity, increasing capacity, facilitating multipath exploitation, and more extensive, more unknown information or search results. The section details the details of the microstrip MIMO patch antenna. In our MIMO antenna design methodology, we explain how to build a 2-port MIMO configuration using a single-element antenna as a basic element, with the goal of spatial diversity, interference mitigation, power enhancement, multipath absorption, and signal reception through height to do [20]. Improve protection This important advance is motivated by the need to ensure the optimal orientation of the antenna elements, thus achieving the necessary level of isolation important for superior performance. To realize the optimal MIMO antenna configuration, we initially used two single-element antennas. The basic patch and ground structure of a single-element antenna is laid out like a single-element antenna. Next, we use decoupling in MIMO to improve the results. At this stage, the decoupling length and width were changed to 30 micrometers and 40 micrometers, and the decoupling area ground was all copper [21]. Conversion to a MIMO formation achieves the best results. We can see the proposed MIMO antenna in Figure 3.

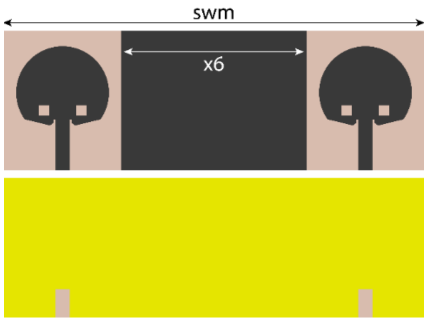


Figure 3. Comparative analysis MIMO antenna and performance antenna configurations

3. RESULT ANALYSIS OF PROPOSED MIMO ANTENNA

3.1. Reflection and transmission coefficient

The reflection coefficient, also acknowledged as the S_{11} parameter, serves as a pivotal metric in evaluating antenna performance, offering valuable insights into the efficacy of power transfer between the transmission line and the antenna. It governs the magnitude of radio frequency (RF) power redirected from a microstrip patch antenna back toward the feed line. Defined as a ratio expressed in decibels (dB), it juxtaposes reflected power against incident power from the feed line. A diminished reflection coefficient, denoted by a negative dB value, signifies minimal power reflection and optimal impedance matching, which is pivotal for efficient power transfer and antenna performance [22]. Conventionally, an exemplary value for a well-matched antenna is deemed to be -10 dB or lower. The meticulously engineered microstrip patch antenna showcases auspicious attributes, characterized by dual resonant frequencies situated at 8.096 THz, as depicted in Figure 4. At both resonance frequencies, commendable return loss values are attained, peaking at -35.23 dB at 8.096 THz. Such performance translates into efficient signal transmission and negligible reflections at the resonant frequencies, significantly enhancing the antenna's overall efficacy. Furthermore, the antenna boasts a commendable bandwidth spanning 5.968 THz (ranging from 4.0315 THz to 10 THz), denoting the spectrum of frequencies over which it maintains satisfactory performance [23].

3.2. Gain and efficiency

Gain is a crucial factor in the performance of MIMO systems, impacting coverage, signal strength, and data rate. It measures the system's ability to effectively focus and direct transmitted and received signals, reducing unwanted noise from other directions. Higher gain results in stronger signals reaching a wider area, thus extending the system's coverage range. The simulated gain for the proposed MIMO antenna is illustrated in Figure 5. The antenna demonstrates a peak gain of 12.38 dB, with gains of 11.92 dB at resonant frequencies of 8.096 THz respectively. This suggests a potentially more focused radiation pattern, making the antenna suitable for applications requiring extended coverage. Efficiency is also crucial in MIMO systems, directly impacting power consumption, data rate, and overall performance [24]. It measures how effectively the system converts input power into useful transmitted or received signal power. In the case of microstrip patch antennas, efficiency is particularly significant as it directly influences overall antenna performance.

A higher efficiency indicates a greater proportion of input power being converted into useful radiated power, enhancing signal strength and communication quality [25]. The simulated efficiency gains for the proposed MIMO antenna, depicted in Figure 5, show a high efficiency of 89%, consistently exceeding 86% across its range. This indicates superior performance in changing input power into useful radiated power, contributing to enhanced signal strength and communication quality.

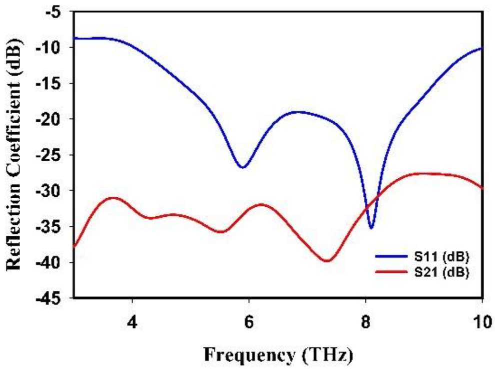


Figure 4. Reflection coefficient of the proposed MIMO antenna

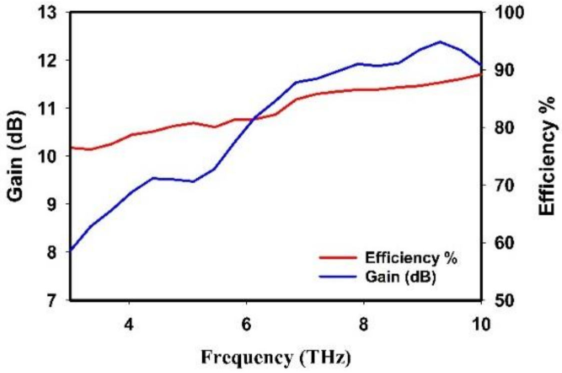


Figure 5. Efficiency and gain of the proposed MIMO antenna

3.3. The envelope correlation coefficient

The ECC holds significant importance in MIMO systems, as it directly impacts the system's capability to leverage spatial diversity and achieve optimal channel capacity [26]. It quantifies the association between the envelopes of signals received by different antennas within the MIMO system. Essentially, it measures the similarity or correlation in the amplitudes of received signals across multiple antennas. In the context of MIMO systems, a low ECC, preferably close to zero, is desirable for optimal performance. We can see the ECC in Figure 6. This is because a low ECC indicates a high level of diversity among the multiple antennas, which is advantageous for maximizing system performance.

3.4. Diversity gain

DG is essentially what we use to measure the development in system performance due to the practice of multiple antennas and to experience independent fading. Additionally, MIMO systems contribute significantly to improved system reliability, coverage, and capacity. One of the primary goals of MIMO systems is to achieve DG. The value of DG can be calculated below.

The simulated DG for the suggested MIMO antenna is shown in Figure 7. It can be seen that the antenna achieves the lowest DG of 9.99. This value of DG suggests a considerable improvement in signal reliability and robustness due to the use of multiple antennas in a MIMO system [5].

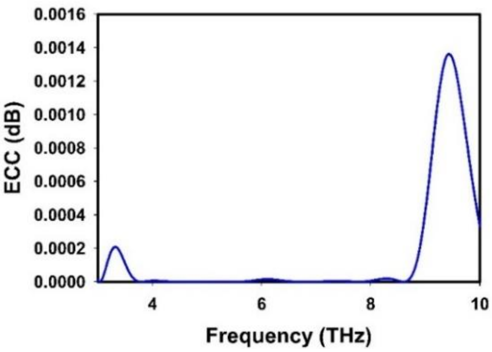


Figure 6. ECC of the proposed MIMO antenna

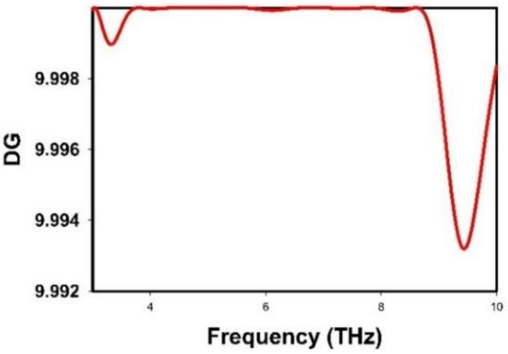


Figure 7. DG of the proposed MIMO antenna

4. RADIATION PATTERN

The radiation pattern of an antenna is a graphical representation of the radiation dispersion from the antenna with respect to spatial direction. It is important to consider the orientation and properties of the E field and the H field when designing and placing antennas [27]. A magnitude of 22.4 dB V/m is associated with the E field lobe at theta =90°, a half-power beam width of 52°, and an H field magnitude of 900. As for the main lobe magnitude, it is -38.5 dBA/m, and the HPBW is 54.30 degrees. The half-power beam width is 124.6°, the E field of the primary lobe at =90° in the H-field is 8 dBV/m, and the magnitude for the H field of the lobe at =90° is -29.2 dB A/m. Figure 8 shows that the E-field, with theta =0 degrees, has an HPBW of 89.9 degrees and a primary lobe magnitude of 17.1 dB V/m [28].

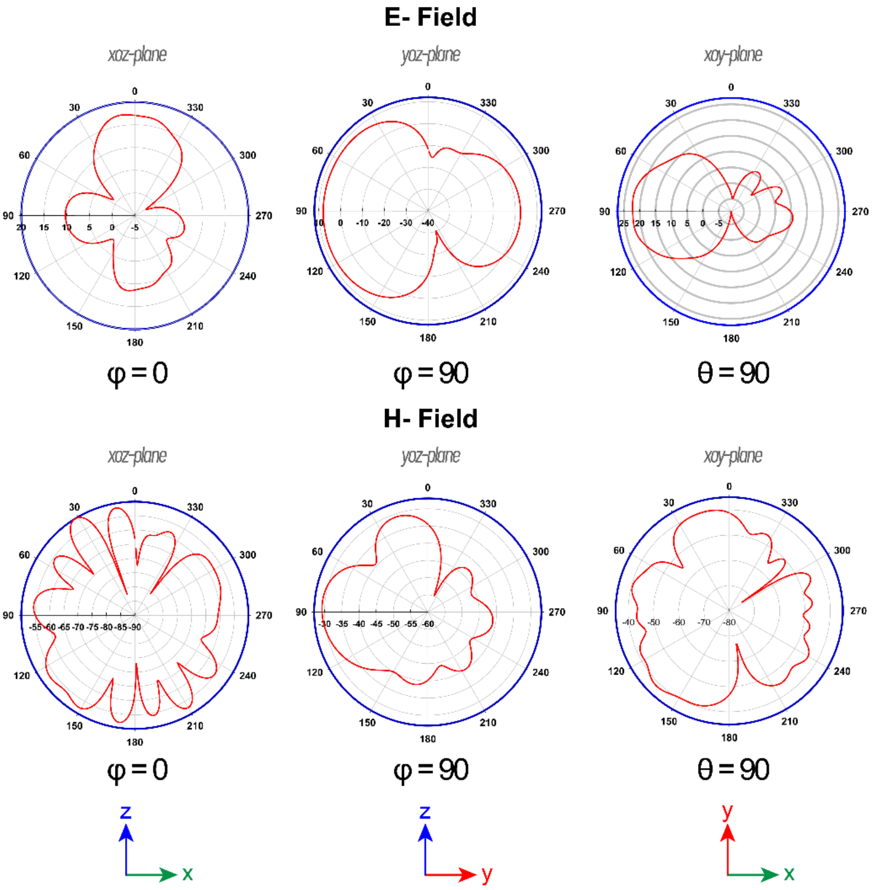


Figure 8. Simulated radiation pattern of recommended MIMO antenna

5. RESISTANCE INDUCTANCE CAPACITANCE EQUIVALENT CIRCUIT

In this section, we design an advanced antenna system to meet future wireless communication requirements. Our initial step involved developing an RLC circuit model to analyze the electromagnetic behavior of the system [29]. Figure 9 illustrates the equivalent circuit of the proposed MIMO antenna. The project aimed to precisely characterize the performance characteristics of the antenna structure and understand the complex relationships between its electrical components. To ensure accuracy, we meticulously extracted the R-L-C parameters directly from our antenna simulations using sophisticated tools such as CST Studio. In our antenna design, the patch element plays a crucial role in achieving two separate resonance frequencies. We utilized two parallel circuit configurations with resistance (R1), capacitance (C1), and inductance (L1) to construct these resonance frequencies carefully. Additionally, another two parallel circuits consisting of (L2+C3), (R2+C4), and R3 are responsible for the slot placed beside the feedline of the antenna. By combining these circuit elements, we created a model that accurately replicates the behavior of our single-element antenna [30]. When transitioning to a MIMO configuration, we accounted for mutual impedance between antenna elements using a parallel circuit of L3, R4, R5, and C5. To verify the accuracy of the Agilent advanced design system (ADS) simulation, we conducted a comparative test between the results of the CST simulation and a parallel circuit simulation, focusing on the S11 parameter. Figure 9 provides a detailed assessment of the accuracy and reliability of our R-L-C circuit model by comparation the simulation results of both the circuit and CST simulations. This model can estimate the performance of the future MIMO antenna. The simulation results obtained using CST, along with the equivalent RLC circuit results from ADS, are displayed in Figure 10.

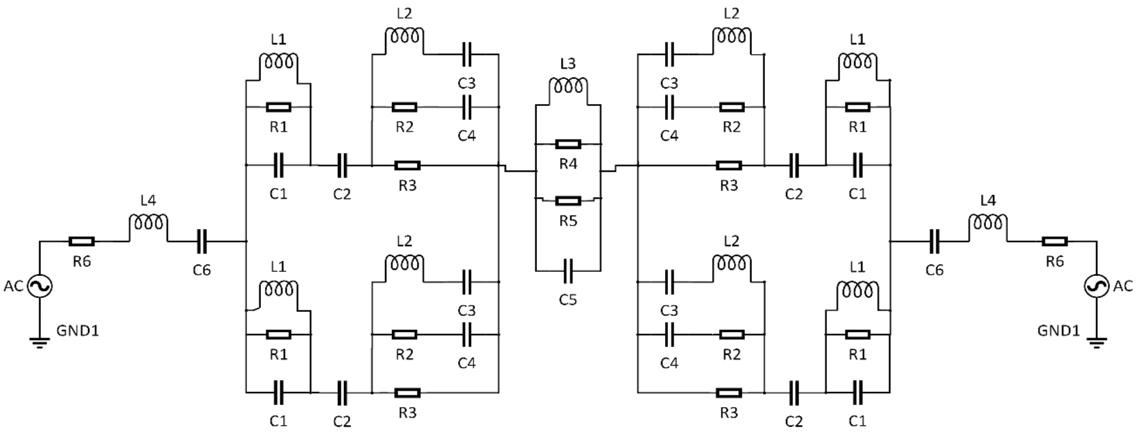


Figure 9. Final equivalent circuit is the result of the proposed MIMO antenna

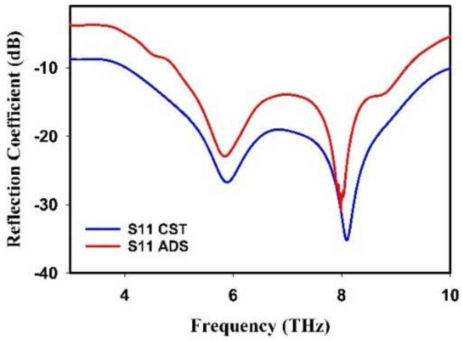


Figure 10. Simulated equivalent circuit reflection coefficient in ADS and CST

6. CONCLUSION

The proposed THz antenna, designed for the 3-10 THz frequency range, exhibits outstanding performance in both single-element and MIMO configurations. It provides a wide bandwidth from 4.0328 to 10 THz, a high gain of 12.38 dB, and an efficiency of 89%, meeting the stringent demands of contemporary THz communication systems. The MIMO configuration achieves superior isolation at -27 dB and demonstrates low ECC and high DG, indicative of excellent MIMO capabilities. The incorporation of an RLC circuit model enables the precise representation of the S11 curve, ensuring an accurate characterization of the antenna's input impedance and resonant behavior. The use of a polyimide substrate further enhances the antenna's performance and applicability. The findings of this study highlight the proposed antenna's potential for high-speed, short-range communication, making it a promising candidate for integration into advanced THz systems.

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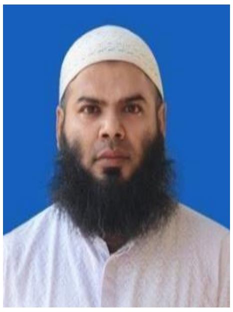

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