A 6G THz MIMO antenna with high gain and wide bandwidth for high-speed wireless communication

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ABSTRACT

This study presents a comprehensive industrial and innovation design and thorough analysis of a terahertz (THz) multiple-input multiple-output (MIMO) antenna, addressing the increasing demand for high-performance multi-antenna systems in THz communication applications. The primary objective of this research is to develop a compact and efficient MIMO antenna that operates over a wide frequency range and provides high isolation, specifically within the 1–10 THz spectrum. The proposed antenna achieves an impressive total bandwidth of approximately 9 THz, featuring seven distinct resonance frequencies at 1.39 THz, 3.26 THz, 4.72 THz, 5.96 THz, 7.07 THz, 8.194 THz, and 9.426 THz. The design employs a polyimide substrate and a graphene patch. Key performance metrics include a maximum gain of 15 dB, efficiency of 99.8%, and isolation values that range from 28 dB to 63 dB. An resistor inductor capacitor (RLC) equivalent circuit using advanced design system (ADS) software. Additionally, the antenna displays remarkable diversity metrics, with an envelope correlation coefficient (ECC) of 0.000778 and a diversity gain of 9.99961 dB. With compact dimensions of (65×180) μm^2 and outstanding performance characteristics, this design is confirmed to be suitable for THz applications, fulfilling the research goal of facilitating efficient and reliable communication in sophisticated multi-antenna systems.

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1. INTRODUCTION

When designing advanced antennas, it's important to achieve optimal performance by paying attention to metrics such as resonance frequency, bandwidth, isolation, gain, efficiency, and material composition [1]. Short-range wireless communication refers to the transfer of data over short distances without the need for physical links [2]. This form of communication is typically utilized for devices that are in proximity to one another, generally within a range of a few meters up to around a hundred meters [3]. Wireless communication functions within the radio frequency spectrum, encompassing a broad range of frequencies. Various wireless systems utilize particular frequency bands within this spectrum for their communication needs. Electromagnetic waves can travel through air, space, or water, based on the specific environment in which communication occurs [4]. Elements like distance, barriers, disruptions, and signal loss can greatly affect the transmission of wireless signals [5]. Wireless communication systems generally consist of transmitters in devices that send information, paired with receivers that collect the transmitted data. Transmitters convert information into electromagnetic signals, which are then sent out through antennas. Conversely, receivers use antennas to capture these signals and transform them back into usable information [6]. One major advantage of wireless communication is its capability to create wireless networks, allowing devices to connect and utilize shared resources without requiring physical connections. Wireless networks include several categories, such as local area networks (LANs), wide area networks (WANs), cellular networks, and satellite networks [7].

Terahertz (THz) wireless communication represents a novel technology that involves the transmission of data through electromagnetic waves in the THz frequency range, which typically spans from 0.1 to 10 THz [8]. This advanced field of research shows significant potential to transform data transfer rates and exceed the current limitations of traditional wireless technologies [9]. One challenge faced by THz communication is the considerable atmospheric absorption of these waves, which limits their capacity to travel long distances [10]. Consequently, THz communication is best suited for use in applications that require short-range transmission [11]. Nevertheless, ongoing improvements in antenna design, signal processing, and beamforming techniques provide hope for extending the range of THz communication systems in the future.

The data in Table 1 provides a comprehensive comparison of various ongoing projects, focusing on their fundamental principles. It examines a variety of operational parameters, including operating frequency, board dimensions, bandwidth, gain, isolation, and efficiency. Among the initiatives listed in the table, the suggested antenna stands out as featuring the widest bandwidth and achieving notable levels of isolation and gain. Prior works have reported gains of 7.23 dB, 4.5-10 dB, 8.82 dB, 8.2 dB, and 5.49 dB [12]-[14], while simulations in CST indicate an observed gain of 15 dB. CST also specifies a bandwidth of 9 THz for the proposed architecture, significantly higher than the bandwidth values cited in other sources: 0.6 THz, 0.3 THz, 1 THz, 2 THz, and 0.4 THz. Isolation levels in the proposed layout exceed -60 dB, in contrast with measured levels of -55 dB, -54 dB, -23 dB, -20 dB, -20 dB, and -25 dB for the reference works [10]-[15]. The recommended multiple-input multiple-output (MIMO) antenna demonstrates outstanding performance metrics compared to other options, with an EEC of less than 0.0007778 dB and a DG exceeding 9.99961 dB. Its radiation efficiency of 99.8% outperforms the values of 98% and 85% cited in studies [12], [15].

Table 1. Result comparison between the proposed MIMO antenna and other publications

Ref	Resonance frequency (THz)	Bandwidth (THz)	Port	Antenna size (um^2)	Isolation (dB)	Gain (dB)	Efficiency (%)	ECC DG (dB)	Material
[12]	3.5	0.6	2	130×85	-55	7.23	N/A	0.000168/ 9.999	N/A
[13]	1.9	0.3	2	120×90	−54	4.5–10	N/A	0.000023/ 9.99	N/A
[14]	2.8	1	2	70×35	–23	N/A	98%	0.004859/ 9.99	Teflon
[15]	1.1	N/A	2	380×380	−20	8.28	N/A	N/A	Pyrex
[16]	0.72–2	2	2	125×125	-20	8.2	N/A	0.0015/ N/A	Polyimide
[17]	0.35–0.75	0.4	2	600×300	-25	5.49	85.24%	0.015/ 9.99	Polyimide
This work	1-10	9	2	65×180	-63	15	99.8	0.000778/ 9.99961	Polyimide

The work presents a new antenna design operating across a wide frequency range (1-10 THz) with a bandwidth of 9 THz. Using polyimide as the material, it achieves -63 dB isolation, 15 dB gain, and 99.8% efficiency. These characteristics demonstrate the potential for significant advancements in antenna performance and application diversity.

2. DESIGNING OF THE SINGLE-ELEMENT ANTENNA AND ITS RESULT

In Figures 1(a) and (b), we observe the design specifications for a single-element antenna as follows: patch width (Wp)=55 um, patch length (Lp)=30 um, feed length (Lf)=30.50 um, feed width (Wf)=4 um, inset width (Wi)=2 um, and inset length (Li)=13 um. The substrate and ground dimensions are both 65 um by 65 um. The substrate material is polyimide with a dielectric constant of 3.5 and tangent loss of 0.0027, and the patch is graphene. The graphene is characterized at a temperature of T=300 K with a chemical potential of (μc)=10 eV, and s relaxation time (τ)=0.1 ps [18]. The substrate thickness is 10 um, the patch thickness is 0.8 um, and Copper was used as ground.

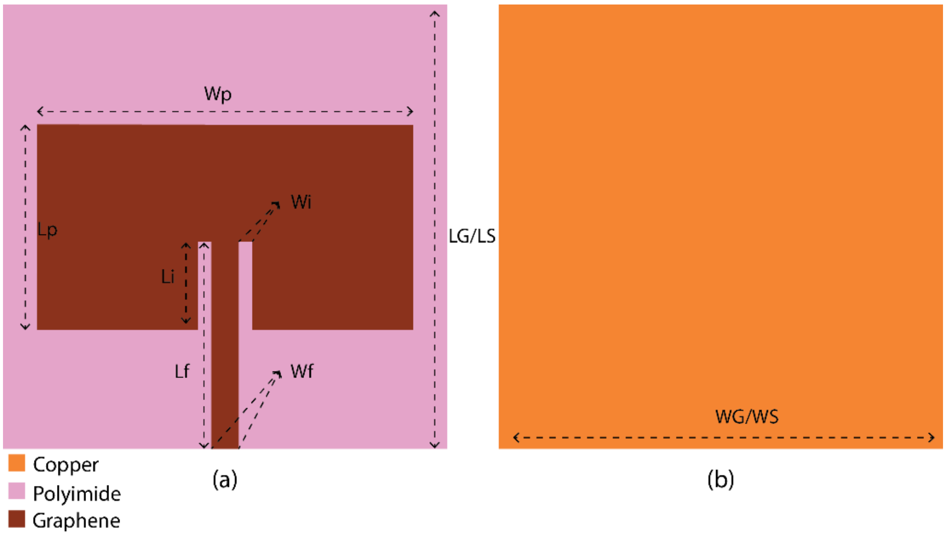

Figure 1. Side of single-element antenna: (a) front and (b) back

In Figure 2(a), the S11 curve illustrates the reflection coefficient, revealing seven resonance frequencies within a single bandwidth. The frequency range spans 1-10 THz, achieving a total bandwidth of approximately 9 THz. The specific resonance frequencies and their corresponding return losses are: 1.39 THz with -24 dB, 3.26 THz with -55.5 dB, 4.72 THz with -26.81 dB, 5.96 THz with -33.54 dB, 7.07 THz with -39.621 dB, 8.194 THz with -47.795 dB, and 9.426 THz with -44.869 dB. In Figure 2(b), the gain and efficiency of our single-element antenna. The gain was around 14.5 dB, and the efficiency was around 99%.

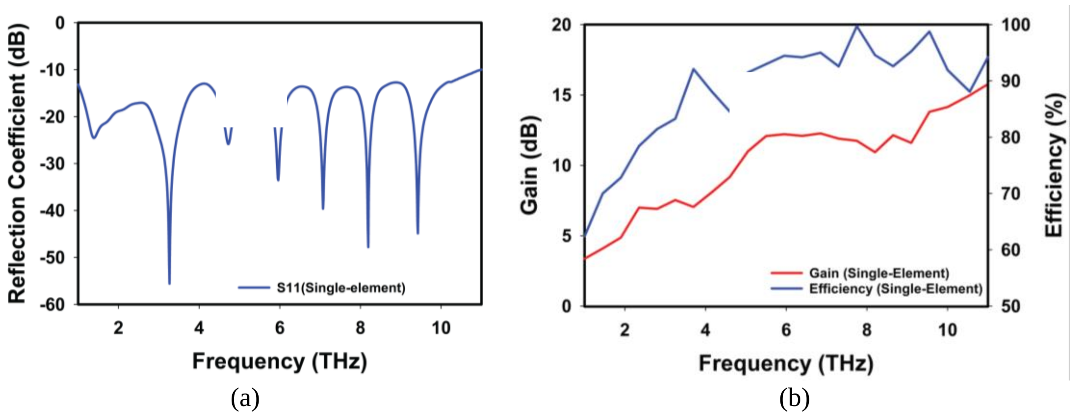

Figure 2. Results of the single-element antenna: (a) reflection coefficient and (b) gain and efficiency

3. DESIGN OF THE PROPOSED ANTENNA AND ITS RESULT ANALYSIS

The purpose of designing the MIMO antenna was to improve the antenna's result [19]. In Figure 3 the proposed MIMO antenna is depicted. The antenna utilizes decoupling with copper. The patch material is graphene, and the substrate is made of polyamide. The decoupling width (DW) is 50 micrometers, the length (DL) is equivalent to the substrate length (LS), and the ground length (LG) is 65 micrometers. The substrate width (WS) and ground width (WG) are both 180 micrometers.

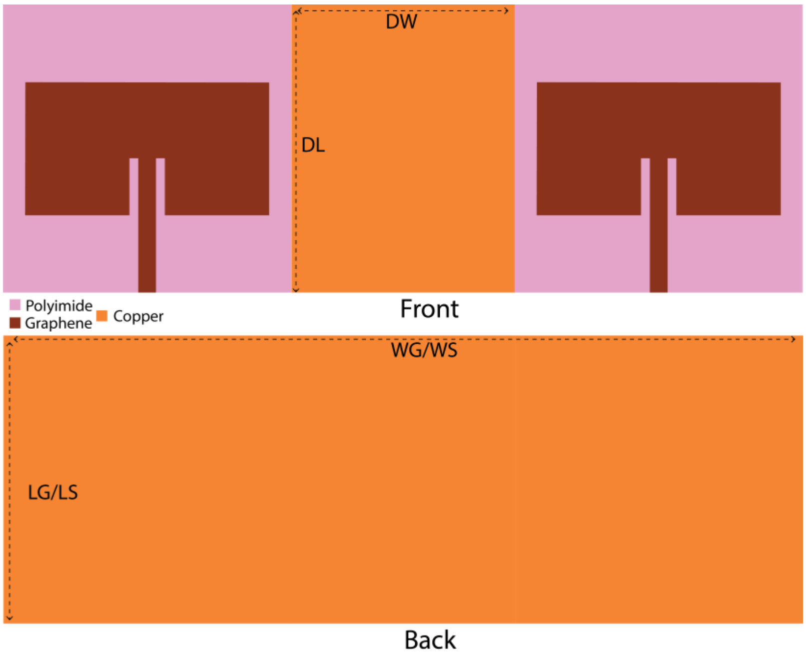

Figure 3. The front and back sides of the proposed MIMO antenna

3.1. Reflection coefficient and transmission coefficient

In Figure 4, the S-parameter of our MIMO antenna is depicted. It directly influences the antenna's efficiency and performance [20]. The blue curve in the graph represents the S11 parameter, also known as the reflection coefficient, while the red curve corresponds to isolation. Our MIMO antenna is meticulously designed to exhibit seven resonance frequencies, all falling within a single bandwidth. An important feature of the MIMO antenna is its isolation capability, and our antenna accomplishes this with a minimum isolation of approximately 28 dB and a maximum isolation of approximately 63 dB.

3.2. Gain and efficiency

Two key parameters to focus on when analyzing antenna performance are gain and efficiency [21]. Our meticulously designed MIMO antenna has achieved an outstanding maximum gain of approximately 15 decibels (dB), highlighting its exceptional signal amplification capabilities. Additionally, the antenna exhibits an impressive efficiency level of around 99.8%, demonstrating its effectiveness in converting input power into radiated energy [22]. A visual representation of these findings can be observed in Figure 5, where the gain is depicted by the red curve and the efficiency is denoted by the blue curve.

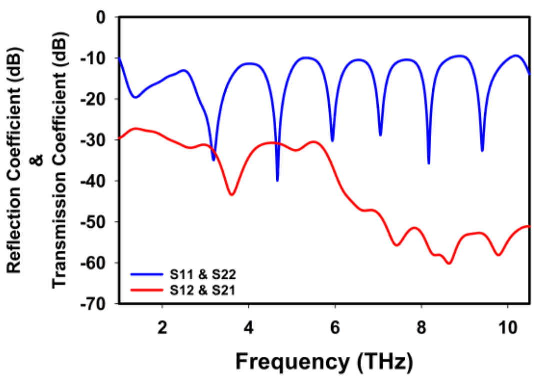

Figure 4. S11 curve and return loss of the proposed MIMO antenna

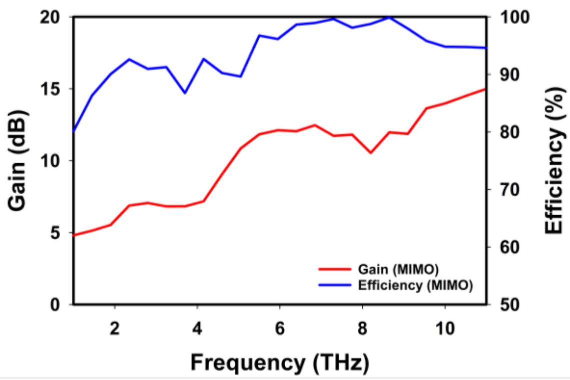

Figure 5. Gain and efficiency curve of the proposed MIMO antenna

3.3. Envelope correlation coefficient and diversity gain

In Figure 6, we can observe the envelope correlation coefficient (ECC) and diversity gain (DG) displayed as a frequency function simulated in THz. The ECC is represented in red, while the DG is shown in blue. Throughout the frequency range, the ECC curve exhibits consistently low values, with a peak of 0.000778, signifying minimal correlation between the antenna elements, which is a desirable trait for MIMO antenna systems. On the other hand, the DG curve remains consistently close to 10.000 (with a maximum value of 9.99961), indicating exceptional diversity performance [23].

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

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

DG quantifies the enhancement in signal reliability and strength resulting from diversity, with higher values being more desirable [24]. In Figure 6, the ECC and DG demonstrate the effectiveness of the antenna system in reducing signal correlation and maximizing diversity gain across the frequency range from 1 to 11 THz.

3.4. Radiated power and accepted power

Figure 7 depicts the power characteristics of our proposed antenna, displaying the radiated and accepted power across a frequency range of 1 THz to 11 THz. The red curve represents the radiated power, beginning at approximately 0.34 W at 1 THz, reaching a peak of around 0.4908 W between 7 THz and 9 THz, and exhibiting minor peaks and troughs towards 11 THz. The blue curve illustrates the accepted power, starting at a higher value of about 0.49847 W at 8 THz and showing significant oscillations across the frequency range. The accepted power demonstrates a pattern of distinct peaks and dips, consistently oscillating between 0.35 W and 0.50 W. This behaviour suggests that the antenna’s efficiency varies with frequency, displaying better performance in specific frequency bands. The accepted power generally remains higher than the radiated power, indicating that not all accepted power is radiated, possibly due to losses or impedance mismatches within the antenna system [25].

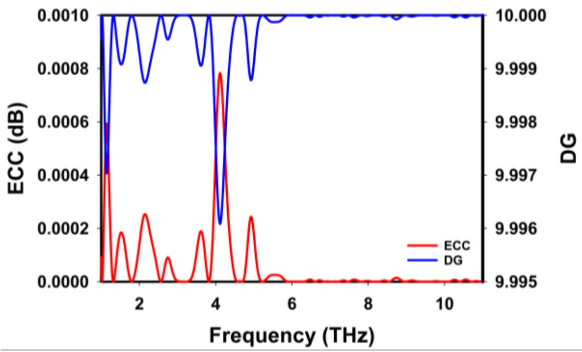

Figure 6. The ECC and DG of the proposed antenna

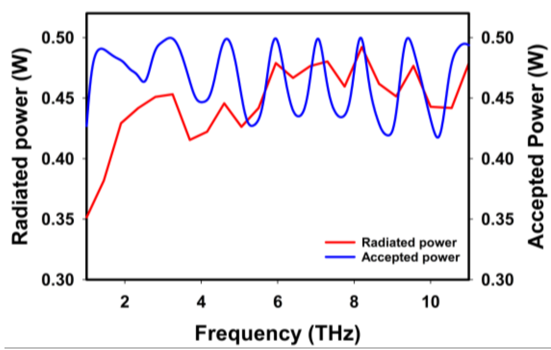

Figure 7. Power analysis of the proposed antenna

4. RADIATION PATTERN

In the polar plot labeled as Figure 8, we can observe the far-field electric field (E-field) at a radius of 1 meter, specifically at an azimuth angle (Phi) of 90 degrees for the THz patch antenna we have designed. The circular plot includes degrees marked around the circumference from 0 to 360 degrees and radial lines at various angles to aid data interpretation. The red line represents the far-field (broadband) E-field pattern, depicting the radiation pattern’s behavior in the far field. Figure 8 shows key metrics, such as a main lobe magnitude of 1.84 dBV/m, a main lobe direction at 83.0 degrees, an angular width (3 dB) spanning 42.3 degrees, and a side lobe level at -1.4 dB. The plot is annotated with Phi values at the circumference (Phi=0, Phi=90, Phi=180, Phi=270) to indicate angles in degrees, while the radial axis denotes the E-field strength in dBV/m. At the bottom of the plot, the axis is labeled Theta (in degrees) versus E-field strength (dBV/m). The legend in the top right corner identifies the red line representing the far-field (broadband) E-field data. In addition to the E-field, the plot also provides information on the H-field, which is crucial for a comprehensive understanding of the antenna’s radiation characteristics [26], [27].

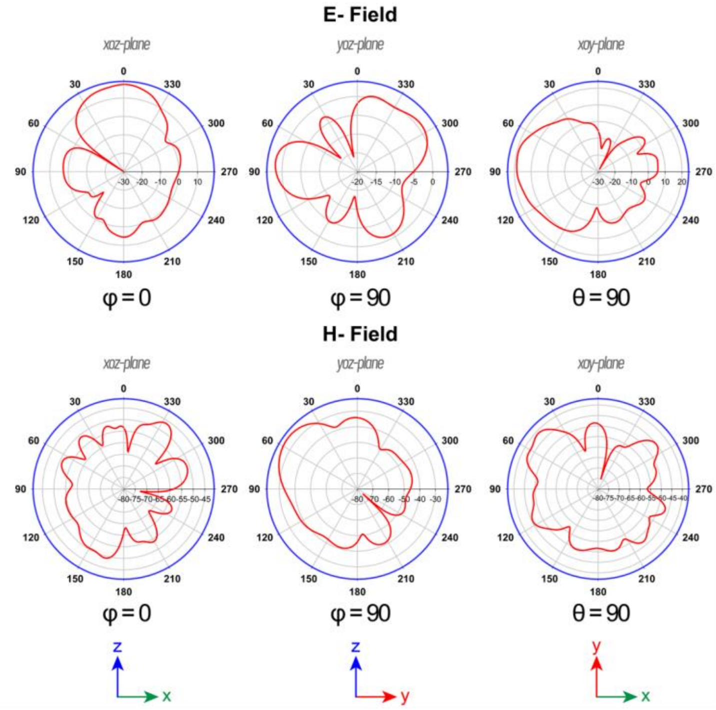

Figure 8. Radiation pattern of the proposed MIMO antenna

5. RESISTOR INDUCTOR CAPACITOR EQUIVALENT CIRCUIT AND RESULT ANALYSIS

The advanced design system (ADS) software is used to design the resistor inductor capacitor (RLC) equivalent circuit of the THz MIMO antenna and offers a comprehensive portrayal of its impedance characteristics at seven distinct resonance frequencies: 1.39 THz, 3.26 THz, 4.72 THz, 5.96 THz, 7.07 THz, 8.194 THz, and 9.426 THz [28]. This model encompasses resistive (R), inductive (L), and capacitive (C) components, which are crucial for understanding the antenna's behavior across these frequencies. The resistive values range from 125.04 Ohm to 161.18 Ohm, indicating inherent losses within the antenna structure. These losses significantly impact the antenna's quality factor and efficiency. The inductive components, with values ranging from 0.00002306 nH to 0.00452 nH, are notably small, reflecting the antenna's ability to operate at high frequencies typical of the THz range. The capacitive elements, ranging from 0.003366 pF to 0.03056 pF, also play a crucial role in tuning and impedance matching. These capacitance values are essential for ensuring the antenna's effective resonance at the desired frequencies and maintaining optimal performance across a wide bandwidth. The combination of these RLC components in the equivalent circuit model provides a comprehensive understanding of the antenna's electrical characteristics, facilitating accurate simulations and optimizations for high-frequency THz applications. Figure 9 shows the RLC model, and Figure 10 shows the result.

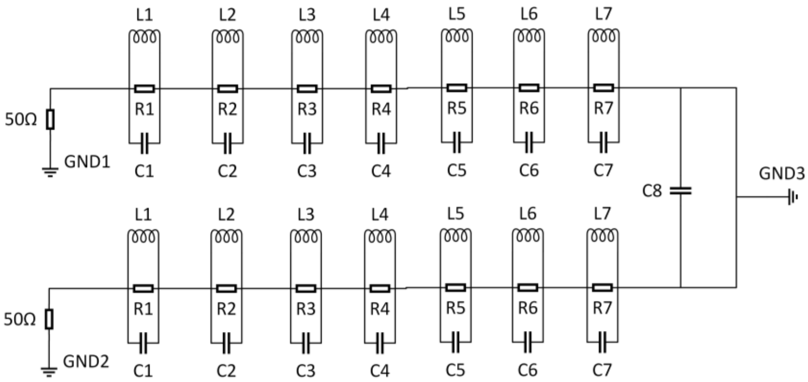

Figure 9. RLC equivalent circuit of the proposed antenna

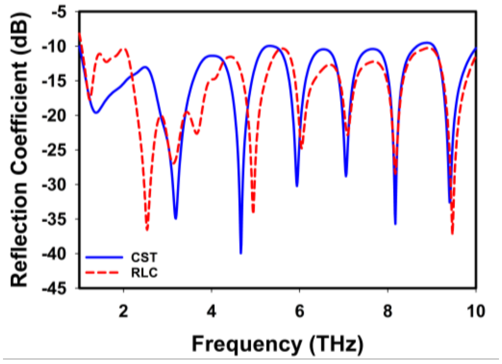

Figure 10. The S11 curve of the MIMO antenna and RLC circuit

6. CONCLUSION

The THz MIMO antenna is meticulously designed to operate across the 1-10 THz frequency range with exceptional performance. Its construction utilizes polyimide as the substrate, graphene for the patch, and copper for the ground and decoupling structures. The antenna boasts seven resonance frequencies, ensuring wideband operation and a high gain of 15 dB, along with an impressive efficiency of 99.8%, indicating superior signal strength and minimal energy loss. Furthermore, isolation values between 28 dB and 63 dB contribute to minimal interference between antenna elements, ensuring reliable communication. The low error correction coding (ECC) value of 0.000778 and high diversity gain of 9.99961 dB underscore the antenna’s capability to support robust MIMO systems. Despite its powerful performance, the antenna maintains a compact size of 65 µm by 180 µm, making it highly suitable for integration into advanced THz communication applications and offering a promising solution for future high-speed wireless networks.

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Md. Ashraful Haque					✓					✓	✓	✓		
Md. Kawsar Ahmed						✓	✓			✓				
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Liton Chandra Paul				✓	✓					✓			✓	

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author (N.S.S.S) upon reasonable request.

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