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Design and Simulation of a High-Gain Terahertz Antenna for 6G IoT Application

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Abstract

This paper presents a new terahertz antenna for 6G IoT applications, highlighting significant advancements in high-frequency communication. Utilizing a Rogers RO3210 substrate with excellent electrical and thermal properties (relative permittivity of 10.8, low electric loss tangent of 0.0027, and thermal conductivity of 0.81 W/K/m), the antenna dimensions ($800\times650\times100$ µm³) are optimized for the desired resonant frequencies, radiation patterns, and impedance essential for 6G IoT. Simulation results show a return loss (S11) of -25.79 dB at 0.325 THz, indicating excellent impedance matching and minimal signal reflection, which is essential for efficient signal transmission and reception. The 3D and far-field radiation patterns at 0.325 THz demonstrate the antenna's ability to radiate energy effectively in all directions and over long distances. Additionally, the antenna has a simulated directivity gain of 6.34 dBi at 0.325 THz, allowing it to focus energy in specific directions and support long-range communication with minimal signal loss. These features fulfill the advanced requirements of 6G IoT, such as enhanced mobile broadband, large-scale machine communication, and ultra-reliable low-latency communication. The proposed antenna is anticipated to play a vital role in the evolution of 6G IoT technology, providing robust, high-speed, and reliable communication solutions.

1. Introduction

The rapid advancement of Internet of Things (IoT) technologies is changing how we interact with the world. IoT devices, from smart home gadgets to industrial sensors, are increasingly part of our daily lives, driving the need for more efficient, reliable, and high-speed communication systems [1], [2]. Terahertz (THz) antennas are an emerging technology that promises to meet these needs. Terahertz technology operates between 0.1 to 10 THz, bridging microwave and infrared frequencies. This spectrum offers high bandwidth, supporting ultra-high-speed data transfer rates and large data capacities [3]. Terahertz waves can penetrate various materials with minimal energy loss and provide high-resolution imaging, making them ideal for many applications [4].

Traditional communication frequencies in the microwave range are becoming congested, causing interference and limited bandwidth, which affects IoT performance. Terahertz antennas offer solutions with several key advantages. Their expansive bandwidth supports data rates up to several terabits per second (Tbps), essential for handling large data volumes from IoT devices in applications like high-definition video streaming, real-time data analytics, and large-scale sensor networks [5]. Higher terahertz frequencies reduce latency, crucial for time-sensitive IoT applications such as autonomous vehicles, industrial automation, and telemedicine. Shorter wavelengths allow for miniaturizing antennas, making them suitable for compact IoT devices without compromising performance [6]. Additionally, the narrow beamwidth and high directionality of terahertz signals enhance communication security, making it harder for unauthorized entities to intercept the signals.

Terahertz antennas for IoT applications typically operate within specific sub-bands, each suited for different communication needs. The 0.1 to 1 THz range is optimal for short-range, high-throughput applications, ideal for indoor environments with high-speed data transfer between devices, wireless personal area networks (WPANs), and short-range IoT communications [7]. The 1 to 3 THz range suits medium-range communications, such as wireless local area networks (WLANs), point-to-point communications, and high-resolution imaging systems. The 3 to 10 THz range is reserved for specialized applications demanding ultra-high data rates and precision, like advanced medical imaging, spectroscopy, and security screening. These sub-band operations enable terahertz antennas to meet diverse IoT communication needs, providing tailored solutions for different scenarios [8], [9]. Integrating terahertz antennas in IoT devices enables innovative applications across various sectors. In smart cities, terahertz communication enhances connectivity and efficiency in infrastructure like intelligent traffic management, environmental monitoring, and public safety systems [10]. In healthcare, these antennas support high-speed transmission of large medical imaging files, enable remote diagnostics, and advance wearable health monitors [11]. For industrial IoT (IIoT), terahertz antennas provide reliable, low-latency communication for sensors and control systems in manufacturing plants. In consumer electronics, their integration in devices like smartphones, smartwatches, and AR glasses boosts data transfer rates, improves connectivity, and unlocks new features and functionalities. Despite its many benefits, terahertz technology faces hurdles in widespread IoT adoption, such as creating efficient and affordable terahertz sources and detectors, reducing atmospheric absorption, and ensuring compatibility with current communication standards [12]. Researchers are addressing these issues by improving materials, fabrication methods, and signal processing. Once resolved, terahertz antennas will be crucial for faster, more reliable, and secure communication in many IoT applications. Terahertz antennas represent a transformative advancement for next-generation 6G IoT devices, offering unparalleled data transfer rates, low latency, and compact size. The terahertz frequency band, with its expansive bandwidth, can support data rates up to several terabits per second (Tbps), essential for the vast amounts of data expected from 6G IoT applications [13].

Reduced latency facilitated by terahertz communication is crucial for real-time applications such as autonomous vehicles, remote healthcare, and industrial automation, where instantaneous data transmission can significantly enhance performance and safety [14]. The compact size of terahertz antennas, due to shorter wavelengths, makes them ideal for integration into the smaller and more diverse IoT devices anticipated in the 6G era [15].

As the IoT ecosystem continues to expand and evolve, integrating terahertz antennas will be essential in meeting the growing demand for high-speed, reliable, and efficient wireless communication [16]. This will allow for new applications like ultra-high-definition video streaming, immersive augmented reality, advanced sensor networks, and smart city infrastructures [17]. Deploying terahertz technology in 6G IoT applications promises to revolutionize device communication, providing the speed, reliability, and efficiency necessary to support the next generation of connected technologies [18].

2. Proposed Antenna Design Methodology

Figure 1 shows the front and back views of the proposed terahertz antenna for 6G IoT applications. This antenna uses a Rogers RO3210 substrate, known for its excellent electrical and thermal properties, making it ideal for high-frequency use. The substrate has a relative permittivity (εr) of 10.8, which ensures it performs well at terahertz frequencies. It also has a low electric loss tangent of 0.0027, meaning it loses very little energy, which is important for maintaining strong and efficient signals in high-speed communications. Additionally, its thermal conductivity of 0.81 W/K/m helps manage heat, keeping the antenna reliable and effective during use. The size of the substrate is L×W × h that is used in this work 800 µm ×650 µm ×100µm. These dimensions are carefully chosen to optimize its performance in the terahertz frequency range, ensuring it meets the desired resonant frequencies, radiation patterns, and impedance characteristics needed for 6G IoT applications. These design choices ensure the antenna can support the ultra-high data rates, low latency, and compact size required for the next generation of IoT devices, playing a key role in the development of 6G technology.

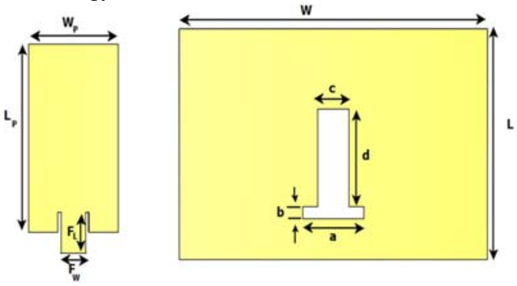

Figure 1. Proposed antenna design, showcasing both the antenna patch of front view and back view of the antenna

Table 1. Parameters Used in the Antenna Design

Variable	Value (in µm)	Variable	Value (in µm)
W_P	264	L	650
L_P	466.67	a	200
F_L	141.67	b	30
F_W	72	c	80
W	800	d	200

3. Results and Discussion

Figure 2 displays the simulated return loss (S11) of the proposed terahertz antenna, which is -25.79 dB at an operating frequency of 0.325 THz. This low return loss means the antenna has excellent impedance matching and minimal signal reflection, crucial for efficient performance at this high frequency. With a low return loss at 0.325 THz, the antenna can transmit and receive signals effectively with minimal power loss, supporting the high data rates, low latency, and reliable communication needed for 6G IoT applications.

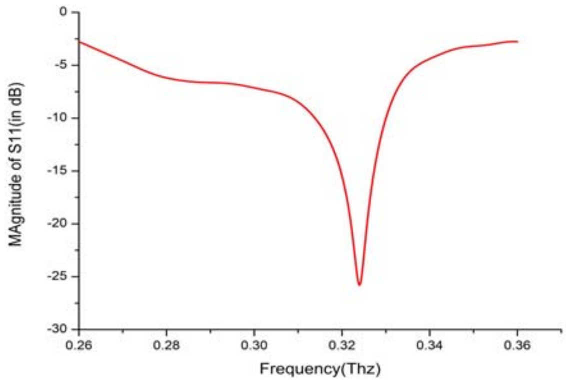

Figure 2. Simulated return loss (S11) of the proposed terahertz antenna for IoT application

Figure 3 shows the 3D radiation patterns of the proposed terahertz antenna at 0.325 THz, highlighting its efficient energy radiation in all directions. Figure 4 presents the far-field radiation patterns at the same frequency, demonstrating how the antenna sends out energy over long distances. These patterns are important for understanding how the antenna performs in real-world scenarios.

The antenna has a simulated directivity gain of 6.34 dBi at 0.325 THz. This high gain means the antenna can focus energy in a specific direction, which is crucial for long-range communication with minimal signal loss. This is especially beneficial for 6G IoT applications, which require high data rates, reliable connectivity, and efficient energy use. The focused radiation patterns and high gain make sure the antenna can handle the advanced requirements of 6G IoT, like improved mobile broadband, large-scale machine communication, and very reliable, low-latency communication.

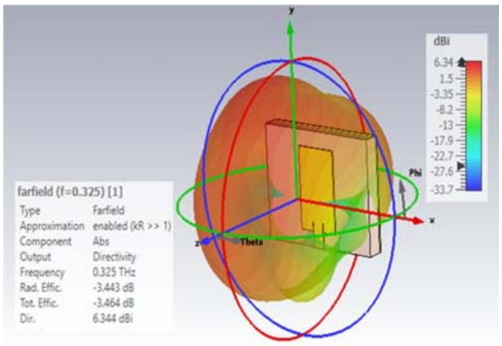

Figure 3. 3D Radiation Patterns Performance Analysis at 0.325 THz for 6G IoT Applications

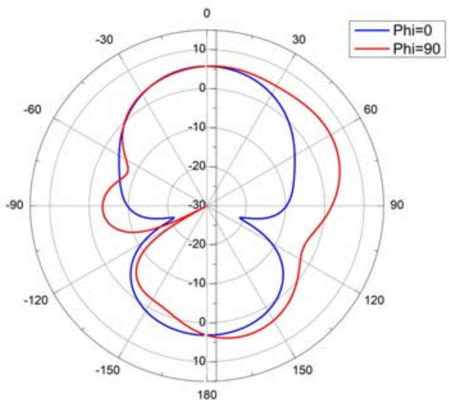

Figure 3. Performance Analysis of far-field radiation patterns at 0.325 THz

Table 2. Comparative Study of Proposed work with previous work

Reference No.	**Frequency (THz)**	**Return Loss (S11) (in dB)**	**Directivity Gain (in dBi)**
[19]	0.725	-35	5.09
[20]	0.472	-52	4.27
[21]	0.45	-20	5
[22]	0.3	__	2.3
[23]	0.312	-50	5.6
[24]	0.18	-11.8	4.5
[25]	0.119/0.172	-25/-26.2	2.44/4.2
This Work	0.325	-25.79	6.34

4. Conclusion

The proposed terahertz antenna for 6G IoT applications shows great progress in high-frequency communication technology. It uses a Rogers RO3210 substrate, known for its excellent electrical and thermal properties, with a relative permittivity of 10.8, a low electric loss tangent of 0.0027, and thermal conductivity of 0.81 W/K/m. The antenna's dimensions (800×650×100 mm³) are carefully chosen to support the needed resonant frequencies, radiation patterns, and impedance for 6G IoT. Simulation results show a return loss (S11) of -25.79 dB at 0.325 THz, which means excellent impedance matching and minimal signal reflection. This is crucial for efficient signal transmission and reception, needed for high data rates and low latency in 6G IoT applications. The 3D and far-field radiation patterns at 0.325 THz confirm the antenna’s ability to radiate energy efficiently in all directions and over long distances. The antenna has a simulated directivity gain of 6.34 dBi at 0.325 THz, meaning it can focus energy in specific directions, supporting long-range communication with minimal signal loss. These features are crucial for 6G IoT's advanced needs, such as improved mobile broadband, large-scale machine communication, and reliable low-latency communication. The proposed antenna is set to be a key player in the future of 6G IoT technology, offering strong, high-speed, and reliable communication solutions.

5. References

1. H. Hong, J. Zhao, T. Hong and T. Tang, "Radar–Communication Integration for 6G Massive IoT Services," *IEEE Internet of Things Journal,* **9**, 16, 2022, pp. 14511-14520, doi: 10.1109/JIOT.2021.3064072.

2. Z. Liu, J. Liu, Y. Zeng and J. Ma, "Covert Wireless Communication in IoT Network: From AWGN Channel to THz Band," *IEEE Internet of Things Journal*, **7**, 4, 2020, pp. 3378-3388, doi: 10.1109/JIOT.2020.2968153.

3. D. Srinivasan, M. Premkumar, S. Deepa Nivethika, P. Dhilipkumar, S. Parameswari and M. K. Chowdary, "A Review on Wideband High-Gain Low-THz Antennas for Wireless Applications," *11th International Conference on Computing for Sustainable Global Development (INDIACom)*, 2024, pp. 1644-1648, doi: 10.23919/INDIACom61295.2024.10499069.

4. Rashmi Pant, Leeladhar Malviya, "THz antennas design, developments, challenges, and applications: A review", *International Journal of Communication Systems*, **36**, 8, 2023., doi: 10.1002/dac.5474.

5. S. V. Reddy, N. K. Kumar, J. S. Naik, R. Meram, N. Ramesh and R. S G, "Achieving Covertness in the Wireless Mode-based Communication in the IoT Connection with use of THZ Band and AWGN Channel," *Second International Conference on Trends in Electrical, Electronics, and Computer Engineering*, 2023, pp. 298-305, doi: 10.1109/TEECCON59234.2023.10335770.

6. R. Salama, C. Altrjman, F. Al-Turjman, S. P. Yadav, S. Vats and R. Gupta, "Terahertz Communications and Sensing Overview," *3rd International Conference on Advancement in Electronics & Communication Engineering (AECE)*, 2023, pp. 393-400, doi: 10.1109/AECE59614.2023.10428466.

7. S. Moghe, R. Yadav and L. Malviya, "Sub-Terahertz MIMO Array Antenna for Future Wireless Applications," *IEEE 11th International Conference on Communication Systems and Network Technologies (CSNT)*, 2022, pp. 49-53, doi: 10.1109/CSNT54456.2022.9787576.

8. Y. He, Y. Chen, L. Zhang, S. -W. Wong and Z. N. Chen, "An overview of terahertz antennas," *China Communications*, **17**, 7, 2020, pp. 124-165, doi: 10.23919/J.CC.2020.07.011.

9. W. Jiang et al., "Terahertz Communications and Sensing for 6G and Beyond: A Comprehensive Review," *IEEE Communications Surveys & Tutorials*, 2024, doi: 10.1109/COMST.2024.3385908.

10. Omar A. Saraereh, Luae Al-Tarawneh, Ashraf Ali and Amani M. Al Hadidi, "Design and Analysis of a Novel Antenna for THz Wireless Communication", *Intelligent Automation & Soft Computing,* **31**, 1, 2022, pp. 607-619. doi: 10.32604/iasc.2022.020216

11. G. K Soni, D. Yadav and A. Kumar, "Design consideration and recent developments in flexible transparent and wearable antenna technology: A review", *Transactions on Emerging Telecommunication Technologies*, **35**, 1, 2024, pp. 1-28, doi: 10.1002/ett.4894.

12. Xinran Ji, Yu Chen, Jing Li, Dian Wang, Yue Zhao, Qiannan Wu, Mengwei Li, "Design of High-Gain Antenna Arrays for Terahertz Applications", *Micromachines*, **15**, 3, 2024, doi: 10.3390/mi15030407.

13. Reem Hikmat Abd, Hussein Ali Abdulnabi, "Design of graphene-based multi-input multi-output antenna for 6G/IoT applications", *Indonesian Journal of Electrical Engineering and Computer Science*, **31**, 1, 2023, pp. 212-221, doi: 10.11591/ijeecs.v31.i1.

14. N. Chukhno et al., "Models, Methods, and Solutions for Multicasting in 5G/6G mmWave and Sub-THz Systems," *IEEE Communications Surveys & Tutorials*, **26**, 1, 2024, pp. 119-159, doi: 10.1109/COMST.2023.3319354.

15. D. Jung et al., "Terahertz Antenna-in-Package Design and Measurement for 6G Communications Systems," *IEEE Transactions on Antennas and Propagation*, **72**, 2, 2024, pp. 1085-1096, doi: 10.1109/TAP.2023.3320276..

16. G. K. Soni, D. Yadav, A. Kumar and L. Sharma, "Flexible Antenna Design for Wearable IoT Devices," *3rd International Conference on Technological Advancements in Computational Sciences (ICTACS)*, 2023, pp. 863-867, doi: 10.1109/ICTACS59847.2023.10389888.

17. M. Z. Chowdhury, M. Shahjalal, S. Ahmed and Y. M. Jang, "6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions," *IEEE Open Journal of the Communications Society*, **1**, 2020, pp. 957-975, doi: 10.1109/OJCOMS.2020.3010270.

18. R. Vadlamudi and D. S. Kumar, "Design of a THz Antenna with Broadband Radiation Characteristics for 6G Applications," *IEEE Wireless Antenna and Microwave Symposium (WAMS)*, 2023, pp. 1-4, doi: 10.1109/WAMS57261.2023.10242972.

19. S. Ananda, D. Sriram Kumar, Ren Jang Wu, Murthy Chavali, "Graphene nanoribbon based terahertz antenna on polyimide substrate", *Optik*, 125, 2014, pp. 5546-5549, doi: 10.1016/j.ijleo.2014.06.085.

20. E Fritz-Andrade, A. Perez-Miguel, R. Gomez-Villanueva, H. Jardon-Aguilar, “Characteristic mode analysis applied to reduce the mutual coupling of a four-element patch MIMO antenna using a defected ground structure”, *IET Microwave Antennas Propagation*, **14**, 2019, pp. 215–226, doi: 10.1049/iet-map.2019.0570.

21. A. Abohmra, H. T. Abbas, M. Ur Rehman, M. A. Imran and Q. H. Abbasi, "Flexible and Wearable Terahertz Antenna for Future Wireless Communication," *International Workshop on Antenna Technology*, 2022, pp. 277-279, doi: 10.1109/iWAT54881.2022.9810911.

22. M. Che, Y. Matsuo, H. Kanaya, H. Ito, T. Ishibashi and K. Kato, "Optoelectronic THz-Wave Beam Steering by Arrayed Photomixers With Integrated Antennas," *IEEE Photonics Technology Letters*, **32**, 16, 2020, pp. 979-982, doi: 10.1109/LPT.2020.3007415.

23. M. V. Hidayat and C. Apriono, "Design of 0.312 THz microstrip linear array antenna for breast cancer imaging application," I*nternational Conference on Signals and Systems,* 2018, pp. 224-228, doi: 10.1109/ICSIGSYS.2018.8372671.

24. Jeremiah Oluniyi Abolade, "Miniaturized multiband antenna for terahertz applications in wireless body area network", *Results in Optics*, **10**, 2023, pp. 1-7, doi: 10.1016/j.rio.2022.100340.

25. Tayfun Okan, "High efficiency unslotted ultra-wideband microstrip antenna for sub-terahertz short range wireless communication systems", *Optik-International Journal for Light and Electron optics*, **242**, 2021, pp. 1-13, doi: 10.1016/j.ijleo.2021.166859.