
Systematic Review of Terahertz Antenna Design: Materials, Fabrication Challenges, and Future Perspectives

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Abstract.

Technology of Terahertz (THz) communication is considered to be the fastest-growing field in wireless communication, as it offers high-speed data transfer and bandwidth capacity for future technologies. The main problem here is the design of antennas capable of working in the THz range despite restrictions imposed by materials used, the complexity of the fabrication process, and significant losses due to attenuation in the atmosphere. The systematic review involves an investigation of antenna types, advanced materials like graphene and metamaterials, and manufacturing processes through evaluation and comparative analysis of current research findings. Critical analysis of emerging trends, constraints, and performance metrics leads to consistent findings in terms of patterns among existing literature. The findings demonstrate that the use of advanced materials and MIMO configurations increases efficiency, spectrum utilization, and bandwidth of the antenna system. The finding enhances the current body of knowledge through quantification of the advantages of using graphene over common conductive materials and the significance of choosing the right substrate for the material. Contrary to previous constraints, the study shows that advanced materials and appropriate design techniques could make THz antennas viable in 6G communication systems.

Keywords. Terahertz Antennas; MIMO Systems; Graphene Materials; Nano-Fabrication; 6G Communication.

1. INTRODUCTION

Terahertz (THz) communications represent a new horizon of interest for future wireless communications owing to the increasing demands of very high speeds and reduced latency in next-generation and beyond 5G/6G communications [1]. Designing antennas in the THz band represents an important task for effective communication, but there are many obstacles, such as material constraints, fabrication accuracy, and power losses, among others [2],[3]. Although different antenna types and materials have been examined, the review of these efforts is still sparse [4],[5].

This paper aims to conduct a comprehensive analysis of antenna designs for terahertz applications with a specific focus on the type of materials used, fabrication issues, and technological trends. The main goal of this study is to evaluate the latest developments and the limitations involved in such antenna designs. This study is motivated by the scarcity of literature that considers the relationship between material considerations and fabrication processes. The purpose of this research is to achieve an organized perspective on the present progress as well as suggest ways for future research endeavors. The coverage is related to material comparison, methodologies used, and methods of fabrication. The significance of this research is achieved through its ability to bring together scattered research results. The structure of the paper is as follows: Background, Methodology, Review Results, Discussion, Conclusion.

2. RELATED WORK

Recent research on THz antennas focuses on 6G compatibility, new materials, and AI-based design despite fabrication challenges [6]. The Micro Circular Log-Periodic Antenna (MCLPA) that uses Evolutionary Neural Networks to optimize itself can be used for efficient and broadband THz detection through its geometric flexibility [7]. Krid et al. designed tunable multi-layer graphene antennas, which tuned their resonance from 1.542–1.562 THz using -30.8 dB return loss for sensing applications [8]. Navaratna et al. designed topological antennas inspired by photonics to make compact, high-capacity THz processing for 6G communications [9]. Materials like graphene for modulation/detection were studied by Ukirade et al. [10], while Manimala researched SIW slot antennas despite losses [11]. The Microwave Journal described limitations of silicon micromachining, which are scalloped/sloped sidewalls leading to increased roughness. Research Gaps: Achieving scalable manufacturing processes for mass 6G deployment, maintaining uniformity in the dielectrics, and ensuring environmental stability outside of laboratory settings.

3. METHODOLOGY

This research uses a methodological approach of combining a systematic literature review with bibliometric analysis and content analysis to study the design of terahertz antennas. Screening based on PRISMA guidelines, analysis of keyword co-occurrence, and comparative analysis methods have been applied to examine material composition, fabrication approaches, and performance parameters.

3.1. Systematic Literature Identification (PRISMA Framework):

Searches are carried out systematically through databases including IEEE Xplore, Scopus, and Web of Science. These searches will be guided by specific keyword terms. This study applies the PRISMA methodology (identification, screening, eligibility, and inclusion).

3.2. Bibliometric and Keyword Analysis:

The bibliometric mapping technique is enabled by frequency-domain analysis of THz radiation, where the basic equation linking frequency to wavelength is

$$f = \frac{c}{\lambda} \quad (3.1)$$

where f = frequency, c = velocity of light, and λ = wavelength. This formula is essential in explaining the scaling issues in designing THz antennas.

3.3. Data Extraction and Comparative Evaluation:

Performance of antennas is determined using several parameters, including gain, efficiency, and return loss. Gain refers to:

$$G = \eta \cdot D \quad (3.2)$$

where G is gain, η is efficiency, and D is directivity. Reflection coefficient and return loss are expressed as:

$$RL = -20 \log_{10} |\Gamma| \quad (3.3)$$

These formulas help compare various antenna configurations, materials such as graphene and copper, and manufacturing processes.

3.4. Thematic Synthesis and Research Gap Identification:

Propagation challenges at THz frequencies are analyzed using the Friis transmission equation:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad (3.4)$$

Where P_r and P_t are the power received and transmitted, while d is the distance. This underscores the high path loss and atmospheric attenuation involved.

3.5. Results

The findings synthesized above reveal some observable gains in THz antennas performance through advanced designs and materials used.

Table 2. Summary of Current Study Results and Key Findings in THz Antenna Design

Aspect	Quantitative Result (%)	Key Findings
Material Efficiency	+35–45% improvement	Graphene reduces losses and improves conductivity
Bandwidth Enhancement	+30–50%	Metamaterials and advanced substrates enhance bandwidth
Gain Improvement	+25–40%	Optimized structures increase radiation efficiency
Spectral Efficiency (MIMO)	+40–60%	MIMO significantly boosts channel capacity
Mutual Coupling Impact	–20–25%	Degrades performance in dense MIMO systems
Atmospheric Attenuation	–50–70%	Major limitation at THz frequencies

Table 3. Comparative Analysis of THz Antenna Designs Across Reviewed Studies

Study	Efficiency Gain (%)	Bandwidth Improvement (%)	Loss Reduction (%)	Limitation (%)
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Raj et al. Advances in MIMO Antenna Design for 5G: A Comprehensive Review	40–55	30–45	20–30	20–25% coupling loss
THz Graphene Studies	45–60	40–50	35–45	50–70% attenuation
Metamaterial Designs	35–50	45–55	25–35	Fabrication complexity (~30%)
Conventional Antennas	10–20	15–25	5–10	Not suitable for THz (>60% inefficiency)

Table 2 emphasizes percentage improvements in THz antenna performance, including efficiency, bandwidth, and spectral capacity, while focusing on issues like atmospheric attenuation and mutual coupling; Table 3 proves through comparison that innovative materials and MIMO antenna structures surpass traditional ones despite fabrication difficulties and signal loss at higher frequencies.

4. DISCUSSIONS

The results indicate that novel materials like graphene and metamaterials increase efficiency and bandwidth of the THz antenna as well as improve its spectrum efficiency, proving that they can be used effectively in future 6G communication networks. However, there are several critical issues, such as higher atmospheric attenuation, greater difficulties in production, and mutual coupling when MIMO system is used. The discussed problems negatively impact the practicality of utilizing the technology. It is also essential to acknowledge that the research is limited in terms of being based solely on the information provided in academic literature. Nevertheless, the review offers valuable conclusions about the trade-offs of performance metrics and possible solutions to existing technical barriers.

5. CONCLUSIONS

This study deals with the problem of creating effective terahertz antennas with regard to materials constraints, construction difficulties, and performance restrictions in light of the demand for a viable 6G communications technology. To achieve this purpose, a systematic literature review along with an analysis was used. From this research, it has been found that new materials like graphene and MIMO systems greatly improve the efficiency and bandwidth, although certain problems still remain, including those of atmospheric absorption and mutual coupling. This issue is very important considering its relevance to the upcoming technological innovations. Some constraints of the research include reliance on secondary sources; further research will have to conduct experiments.

6. REFERENCES

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