

Exploring the Applications of Future 6G Antenna Designs: A Literature Review

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Abstract: This review covers advanced antennas for 6G and THz. It looks at various antenna designs: SRR slotted microwave array, RCA, Cassegrain, circular lens, WHEMS, matrix arrangement, CP horn, Quasi Yagi-Uda, patch, transmission array, Vivaldi patch. It covers material, frequency range, and specifications. Additionally, it talks about modern fabrication methods like wire-cut EDM, PCB and LCP, Topas, 3D printing, laser drilling, and CNC machining. PCB has demonstrated promise for Vivaldi, WHEMS, and patches, particularly in terms of gain and bandwidth. But there are still many research challenges to develop new fabrication methods and antenna architectures to meet 6G requirements. This paper highlights the need for smart and adaptive antennas for high bandwidth, efficiency and seamless connectivity for next gen wireless.

Keywords: Adaptive Antenna Systems, 6G Antenna Design, High-Bandwidth Antenna Solutions, Innovative Antenna Materials, Miniaturized Antennas for THz Applications

1. Introduction

As we advance beyond 5G, the anticipated arrival of 6G technology is poised to reshape the global technological landscape in unprecedented ways. Envisioned to offer hyper-connected, intelligent, and immersive experiences, 6G aims to revolutionize digital communications by supporting real-time, holographic, and ubiquitous connectivity on a massive scale. This shift is expected to redefine industries, urban infrastructure, and personal digital interactions by providing far deeper integration of digital and physical realms[1,2]. At the core of this transformation lies the 6G Network Operation Support System (OSS), a fundamental infrastructure component that will enable sophisticated functionalities such as full network automation, pervasive artificial intelligence, and the use of digital twins. These digital twins generate real-time virtual representations of physical entities, enabling intelligent agents and systems to interact with the physical world seamlessly and with higher levels of autonomy[3-8]. Beyond connectivity, 6G is anticipated to incorporate advanced sensing, positioning, and

environmental awareness capabilities that will redefine what is possible in wireless communications. This enhancement will not only improve the reliability and quality of network services but will also support larger goals aligned with social and ethical standards, such as sustainable resource usage, equitable technology access, and resilient, secure digital infrastructures[9-14]. A critical aspect of achieving these goals is the development of design of antenna for supporting the difficult performance demands of 6G networks. Antenna systems for 6G must be designed with both high performance and aesthetic integration in mind, allowing them to function effectively in diverse environments, from smart cities to rural areas, while blending into modern architectural designs. Advances in The use of aerial technologies will be crucial in enabling essential 6G capabilities like high-precision beam forming, which improves signal accuracy and energy efficiency. Enhanced beam forming[10] is vital for reducing signal interference, maintaining network stability, and strengthening security against sophisticated

cyber threats that emerge with increasingly complex communication systems [9,11]. As 6G networks push communication into the terahertz frequency range, the demand for novel antenna systems that can operate reliably at ultra-high frequencies is paramount. This evolution in antenna design and functionality is fundamental to unleashing the full potential of 6G, which promises not only faster data transmission rates but also entirely new application ecosystems. These applications include ultra-responsive remote surgery in healthcare, automated and connected transportation systems, immersive augmented and virtual reality experiences, and other advancements that could radically transform daily life and industry operations [12-20]. Consequently, developing, refining, and implementing these advanced antenna systems is a cornerstone in building the foundational infrastructure for the era of 6G communications. In summary, the advent of 6G will demand a holistic rethinking of antenna technology, requiring robust, adaptable, and high-performance designs that can support the extreme data rates, reliability, and security standards of this new communication paradigm. The rapid progression toward 6G emphasizes the urgency of ground breaking antenna research and development to meet the connectivity needs of future digital ecosystems.

1.1 The Literature Review's Goals and Objectives

This literature review on 6G antenna design explores in detail the analysis of current study and advancements in the domain. Its key objectives are to:

- Offer a comprehensive overview of existing studies on antenna designs tailored for 6G applications.
- Examine the challenges and opportunities associated with the advancement in the frequencies, focusing on the designs, fabrication, and performance evaluation of terahertz (THz) band antennas.
- Highlight recent innovations and research progress in addressing the complex needs of advanced wireless communication as it advances from 5G to 6G.

This study provides meaningful insights for professionals in research, engineering, and industry by summarizing the latest trends and breakthroughs in 6G antenna technology. Additionally, it underscores the significant efforts made to overcome technical challenges, facilitating the seamless evolution toward advanced wireless networks.

The literature selection for this review follows a rigorous process based on well-defined inclusion and exclusion criteria, ensuring both relevance and quality. The primary inclusion criterion is subject relevance, focusing on studies that specifically explore design of an antenna methodologies, technology and algorithms for 6G applications. This ensures that all selected literature directly contributes to the revision's objectives and provides valuable insights into advanced antenna design for next-generation wireless networks. To maintain reliability and high-quality data, the review prioritizes publications from esteemed sources, including IEEE Xplore, Google Scholar, ScienceDirect, Springer Link, Wiley Online Library, IET Digital Library, Foundations and Trends in Machine Learning, and MDPI. Additionally, preference is given to articles published within the last eight years to capture recent advancements and innovations in 6G antenna technology.

This temporal criterion helps maintain the review's relevance to the current research landscape in this rapidly evolving field studies and publications that do not focus directly on 6G antenna design, such as those exploring 4G, 5G, or unrelated 6G components, are excluded. Publications from sources without rigorous peer-review standards or a history of questionable accuracy are also omitted to ensure data integrity. Older studies are only included if they offer essential foundational or historical perspectives relevant to the state of 6G antenna technology.

1.2 Systematic Literature Search and Database Overview

In 2024, a comprehensive search was conducted to explore next-generation antenna designs, with a particular emphasis on those suited for 6G applications. The initial search term, "**antenna design for 6G applications**," was used to identify

relevant studies across multiple academic databases. Figure 1 illustrates the search process, detailing each step and the corresponding results.

The initial query returned a diverse set of results, highlighting the extensive research interest in this domain. The number of publications retrieved from various databases included: **IEEE Xplore:** 140, **Scientific American:** 845, **Springer Link:** 5605, **The publisher Wiley Digital Library:** 55585, **IET Digital Library:** 65, **the search engine Scholar:** 16,800 **The Basics and Developments of Artificial intelligence:** 187,977 , **MDPI:** 196, To refine the selection and

focus on accessible research, a second search phase was conducted, prioritizing open-access publications. This step significantly narrowed the results to a more relevant and manageable dataset: **IEEE Xplore:** 2, **Google Scholar:** 6 , **Science Direct:** 2, **Wiley Online Library:** 1, **Foundations and Trends in Machine Learning:** 2 , **Springer Link, IET Digital Library, and MDPI:** No open-access results

This filtering process ensured that the review focused on high-quality, openly available research aligned with the study's objectives, facilitating broader accessibility and knowledge dissemination.

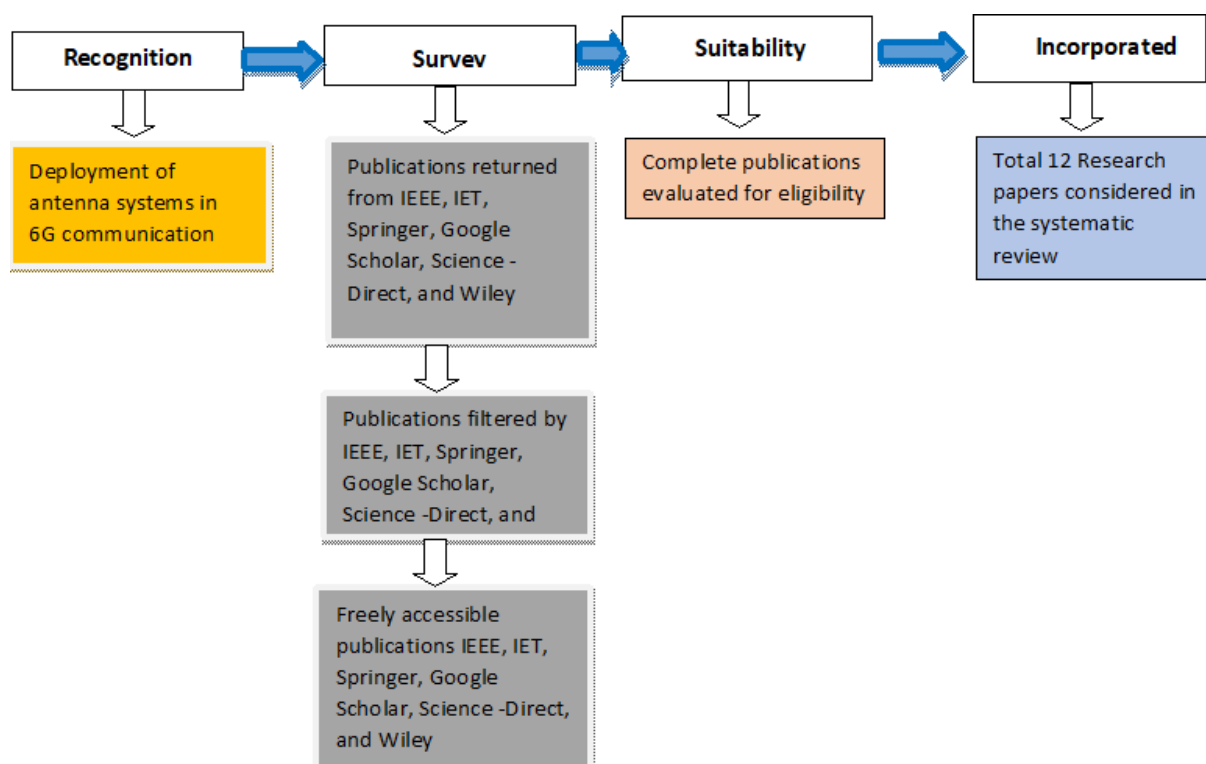


Figure 1: Outline of the Publication Selection Procedure

2. The Process of Retrieval of Metadata

To guarantee a complete and in-depth examination of relevant research on 6G antenna design, this systematic literature review focused on four key aspects during data extraction:

1. Antenna design methodologies utilized in the study.
2. Key features and technical specifications of the proposed designs.

3. Real-world applications referenced or validated in the research.

4. Performance metrics, including bandwidth and gain.

A structured and meticulous process was followed to extract essential details from each publication, capturing:

- Author(s) of the study.
- Year of publication to ensure relevance.

- Specific design techniques or methodologies applied.
- Practical applications where the antenna design was tested or implemented.

This systematic approach ensured that each study's contributions were accurately identified, facilitating a well-rounded review of advancements in 6G antenna technology and their potential real-world impact.

3.Results and Discussion

This section explores key research findings and trends in **THz band antenna performance**, with a focus on their suitability for **6G wireless communication systems**. The discussion is structured into five key areas:

- **III-A: Overview** – Summary of the search outcomes and the procedure for choosing publication.
- **III-B: Antenna Types** – Examination of various antenna types identified in the reviewed studies.
- **III-C: Design Analysis** – In-depth review of antenna design approaches presented in the literature.
- **III-D: Fabrication Technologies** – Assessment of fabrication techniques used in antenna development.
- **III-E: Performance Evaluation** – Summary of key performance metrics, including **bandwidth**, **gain**, **return loss**, and other relevant parameters.

By organizing the analysis in this manner, this section provides a **comprehensive review** of THz band antenna advancements, emphasizing their potential to fulfil the demanding specifications of the upcoming 6G networks.

3.1 Data Collection Results

After eliminating duplicates and irrelevant studies, 17 publications were initially identified from eight different sources, including Foundations and Trends in Artificial Intelligence, Journal of the MDPI the International Electrical and Electronic Scholarly, Google Books, Science Direct, the scientific Springer Link, The publisher Wiley Digital Library, and The Institute of Engineering and Digital Library.

These publications were considered as candidates for inclusion in the review. Following a thorough screening of full-text publications and an evaluation against predefined eligibility criteria, 12 publications were ultimately selected based on their relevance to the study. A summary of the figure 1 shows the publication's selection procedure.

3.2 Types of Antennas

A study conducted [21, 22] systematically classified antennas based on their applications and performance attributes. The researchers identified six primary antenna categories: There are several types of antennas, including cable, travelling sound, reflection, micro Strip, logarithmic regular, and apertures. Additionally, they highlighted specialized types such as HUE [23], Grooved Micros strip Antennae [24], Mslot Folding Antennas [25] , and Multifunctional Antennas [26].

Wired Television antennas were further categorized into six subtypes, including antennas that are bi-conical, left handed, rolled $\lambda/2$ folded, half-wave, and L-loop are among the several types of dipole antennas. Reflective Antennas encompassed four main types: Helical Antennas, Yagi-Uda Antennas, Spiral Antennas, and Beverage Antennas, along with additional classifications for Reflector in the Corner antennas and Inclined Reflection Television antennas (Dish Network).

Micro-strip Antennas featured a specialized subset known as the Planar Antenna twisted F, Knot tie antennas, logs sequential antennas, logs sequential polar arrays antennas, and logs sequential hyperbolic Layout antennas were the four types of log periodic antennas that were identified antennas. Finally, three types of apertures antennas were distinguished: Vivaldi, Horn, and Inverted-F antennas.

The classification of these antenna types provides a solid framework for this literature review, ensuring that each antenna type is examined in detail, including its frequency range, material composition, fabrication methods, and performance metrics such as bandwidth and gain. This structured strategy will enable an extensive of the suitability of various antenna designs for 6G applications.

3.3 Design of the Antenna

This section reviews various antenna designs tailored for 6G applications, emphasizing advancements in performance metrics and innovative design methodologies.

1. Broadband G-Band Lens Antenna

In 2021, designed a G-band broadband lens [27] combined with a grid polarizer dielectric to optimize performance. This design achieved an impressive aperture efficiency of over 75% and maintained a 45% relative bandwidth with an axial ratio less than 2.99 dB. A quasi-analytical method based on the multiple-layer Spectrum Greens Functions (technique was used to optimize the lens system).

Operating at 180 GHz, the polarizer was fabricated from Topas material ($\epsilon_r = 2.3$) for its durability and ease of milling, while a low-loss HDPE (High-Density Polyethylene) lens ($\tan \delta = 3.4 \times 10^{-4}$) was used to further enhance efficiency (Campo et al., 2019).

2. PCB-Based Wideband Antenna

In 2020, author [28] presented a wideband antenna designed using PCB technology, incorporating a high-efficiency electromagnetic structure that is grounded and has a radiating choke and backing cavity. For structural stability, the antenna used grounded vias and connected grounded vias and was constructed on two layers of Rogers 3003 PCB ($\epsilon_r = 3.0$).

The substrate layers (S1 and S2) were 0.7652 mm and 0.5028 mm thick, respectively. This design delivered a well-balanced structure, high gain, and broad bandwidth, making it particularly suitable for low-frequency applications.

3. LCP-Based Antenna for D-Band Applications

Author [29] designed a liquid crystal polymer (LCP) antenna tailored for D-band antenna-in-package applications. LCP was chosen for its cost-effectiveness, stability, and large-scale processing capabilities, though its low laminating temperature introduced heat stability challenges. Further discussed the limitations of gain enhancement in LCP antennas [30], noting the impact of rod length constraints and the necessity of considering

environmental temperature variations during design.

4. Circularly Polarized Conical Horn Antenna

In 2020, author [31] introduced a 0.3 THz circularly polarized conical horn antenna aimed at 6G wireless applications. The design incorporated a waveguide feed, a circular polarizer disk, and a conical horn, all crafted with high precision through Wire Electrical Discharge Machining (EDM). Key design parameters included unequal sub-wavelength slot lengths ($L_{s1} = 0.51$ mm, $L_{s2} = 0.46$ mm), a horn throat radius ($a_i = 0.4$ mm), and a horn aperture radius ($a_o = 1.9$ mm).

5. High-Gain Lens Antenna

In 2019, author [32] a high-gain circularly polarized lens antenna, which is excited by a linearly polarized pyramidal horn. Functioning within the 0.24–0.32 THz range, the design minimized feeding network losses by utilizing a space-fed approach, enhancing overall efficiency and performance for high-frequency applications.

6. SIW Quasi Yagi-Uda Antenna

In 2021, author [33] presented a substrate-integrated waveguide (SIW) Quasi Yagi-Uda antenna [34] designed for 6G satellite communication. The study explored the impact of photonic band gap (PBG) structures and graphene layers on critical performance metrics such as gain, return loss, and Q-factor. These advancements highlight the potential of THz-band antenna technologies in next-generation satellite communication systems.

7. Wide-Band Antenna Array for D-Band Applications

In 2020, author [35] presented a 16-element antenna array that includes a wideband cavity-backed aperture-coupled patch antenna specifically designed for the D-band (135–155 GHz). This design made use of Megtron 7N PCB material ($\epsilon_r = 3.20$, $\tan \delta = 0.003$ at 50 GHz) and featured both microstrip and grounded coplanar waveguide (GCPW) transmission lines.

8. All-Dielectric Huygens' Transmit Array

Demonstrated a 120 GHz all-dielectric Huygens' transmit array [36] fabricated using laser drilling

technology. The study focused on gain optimization and tolerance analysis in uniform arrays, offering comparative insights into related antenna designs.

9. Vivaldi Antennas for THz Bands

In 2019, author [37] explored Vivaldi antenna designs suitable for millimeter-wave and terahertz (THz) frequency bands, specifically targeting 0.06–0.065 THz and 0.56–0.74 THz. Their research focused on optimizing antenna dimensions and analyzing four distinct structural configurations, demonstrating the antennas' potential for efficient operation within these frequency ranges.

Author[38] presented a split ring resonator (SRR) slotted waveguide array antenna that achieved an impressive 10 dB impedance bandwidth of 88 GHz (0.244 THz–0.332 THz) and an axial ratio bandwidth of 35.71 GHz (0.25172 THz–0.28751 THz). Their research explored how variations in slot width and split gap affected return loss and gain. The results highlighted the significance of optimizing slot geometry and split configurations to improve impedance bandwidth and axial ratio for THz applications.

Authors [39–41] conducted a comprehensive review of wideband, high-gain antennas tailored for sub-millimeter wave and low-THz frequencies. Their performance analysis included an all-metal model based on Fabry-Perot cavity (FPC) theory [42] for THz communication. A notable contribution of the study was the creation of a wideband, high-gain resonant cavity antenna (RCA) operating at 300 GHz, which was fabricated at a scaled-up frequency of 30 GHz using metal binder jetting, an advanced 3D printing technique.

Authors [43–47] developed a Sub-THz offset Cassegrain antenna for multi-Gbps point-to-point radio communication, functioning within the 0.22–0.3 THz (220–300 GHz) range. Their research examined the practicality of employing an offset dual-reflector configuration to achieve high gain and broad performance. The design featured a conical horn[48–50] feed with a rectangular waveguide section, a smooth E-plane bend of 35.6°, and was set up for linear (vertical) polarization. Additionally, the antenna was specified to weigh 640 grams.

Table 1 provides a summary of the 12 reviewed publications, detailing the antenna types, frequency ranges, materials used, fabrication technologies, and key performance results.

Antenna Type	Operational Band	Construction Material	Fabrication Method	Bandwidth	Gain (dBi)
Patch Antenna & Array	135–155 GHz	High-Performance Substrate	PCB-Based Manufacturing	20 GHz	14 dBi
Transmit Array	120–130 GHz	All-Dielectric Structure	Laser-Based Fabrication	10 GHz	32–34 dBi
Vivaldi Antenna	61.25–62.15 GHz	Low-Loss Dielectric Substrate	PCB Technology	180 GHz	11.77–11.89 dBi
SRR-Based Waveguide Antenna	244–332 GHz	Waveguide made of metal	Not Specified	88 GHz	15.2 dBi
Wideband High-Efficiency Antenna (WHEMS)	60–75 GHz	High-Frequency PCB Material	PCB Fabrication	11 GHz	8–10 dBi
Grid Array Antenna	136–157 GHz	Copper Core with LCP	LCP-Based Fabrication	21 GHz	14.5 dBi

Circularly Polarized Conical Horn	270–330 GHz	Precision-Machined Brass	Wire-Cut EDM Manufacturing	60 GHz	18.3 dBi
Circularly Polarized Lens Antenna	240–320 GHz	Heat-Resistant Resin	3D Printing	80 GHz	30.8 dBi
Yagi-Uda Antenna(Quasi)	455–530 GHz	Graphene-Enhanced Material	CMOS Processing with TSV	75 GHz	9 dBi
Resonant Cavity Antenna	26.5–40 GHz	Metallic Components	3D Printed Manufacturing	13.5 GHz	13–16 dBi
Cassegrain Offset Antenna	220–310 GHz	Gold-Coated Brass	CNC Machining	80 GHz	48 dBi

3.4 Fabrication Techniques for Antenna Designs

LCP Technology Liquid Crystal Polymer (LCP) technology is recognized for its cost-effectiveness and compatibility with economical fabrication techniques such as wet etching. LCP, a thermoplastic material, exhibits excellent thermal stability, low moisture absorption, and strong mechanical properties, making it a preferred choice for millimeter-wave device manufacturing. Its application in terahertz (THz) technology is notable due to its high flame resistance, stable dielectric properties, and compatibility with photolithographic methods when combined with copper cladding. Compared to materials like silica glass and PTFE, LCP is easier to process, especially for multilayer RF and THz applications, providing enhanced flexibility and performance.

PCB Technology Printed Circuit Board (PCB) technology plays a crucial role in antenna fabrication, allowing electrical connections are established through surface metal etching and plating vias. More advanced designs include grounded vias (GV) and connected grounded vias (CGV).to optimize performance. For instance, semi-additive processing of conductors has been used to develop antennas for D-band applications. Traditional PCB etching methods have also proven effective for fabricating antennas designed for 6G and THz communications. Recent advancements continue to enhance the efficiency and adaptability of PCB technology for high-frequency applications.

Topas Fabrication Topas polymers are frequently utilized alongside High-Density Polyethylene (HDPE) for antenna enclosures. This fabrication process often includes the integration of an HDPE lens to enhance performance. The widespread adoption of HDPE in structural applications underscores its robustness and reliability in antenna design.

CNC Machining Computer Numerical Control (CNC) machining is renowned for its precision in shaping complex structures. It has been employed to develop paraboloidal and hyperboloidal reflector profiles. This technique offers benefits such as high efficiency, cost-effectiveness, and minimal surface roughness, particularly when enhanced by nano-CNC methods. The adaptability of CNC machining makes it a reliable approach for producing intricate antenna components.

3D Printing Technology 3D printing has emerged as a transformative technology in antenna fabrication. Studies have utilized laser-based photopolymerization to create circularly polarized lenses, while additive manufacturing techniques have been employed to construct complex antenna structures with precision and cost efficiency. Research continues to demonstrate the versatility of 3D printing in the development of innovative antenna designs.

Wire-cutting Electric Discharge Machining (EDM) is a thermal-based method employed to shape tough materials like ceramics and superalloys. It has been

applied to fabricate compact and efficient circularly polarized conical horn antennas. EDM's precision and suitability for challenging materials make it an excellent choice for advanced antenna fabrication.

Laser-Drilling Laser-drilling technology has been employed to fabricate bridge-connected dielectric resonators with high precision. This method ensures accurate prototyping with minimal mechanical vibrations and low fabrication tolerances. The technique is increasingly utilized in 6G technologies, offering cost-effective solutions for high-frequency and wireless communication applications.

CMOS Technology CMOS (Complementary Metal-Oxide-Semiconductor) technology, in conjunction with Through-Silicon Via (TSV) processes, has been instrumental in fabricating compact antenna structures. These methods enable precise control over the cylindrical antenna's diameter and pitch. The integration of CMOS and TSV technologies has also facilitated the development of miniaturized waveguide filters for THz applications, highlighting their significance in millimeter-wave and terahertz integrated circuits.

3.5 Evaluations and Outcomes

Circularly Polarized Antenna

This antenna showed a relative bandwidth of over 43%, an axial ratio of less than 3.3 dB, an aperture efficiency of over 75%, and a bandwidth of more than 36%. Its ability to produce several directional circularly polarized beams while keeping a steady axial ratio bandwidth is demonstrated by the measured gain, which was 34 dB.

Wideband High-Efficiency Electromagnetic Structure Antenna This antenna demonstrated a gain bandwidth of 25%, which translates to 11 GHz (0.011 THz) within the frequency range of 0.06–0.075 THz. It consistently achieved a relative gain between 8 and 10 dBi, featuring a radiation aperture size of $4.7 \times 4.7 \text{ mm}^2$.

Grid Array Antenna This design offered an impedance bandwidth from 0.14–0.16 THz, achieving a peak gain of 16.5 dBi at 0.15 THz. Vertical beams in the broadside direction were observed between 0.140–0.148 THz.

Conical Horn Antenna with Circular Polarization

With a measured directivity of 19.3 dBic at 0.33 THz, this antenna offered a 61 GHz bandwidth while operating in the 0.28–0.34 THz range. The manufacture of Wire-EDM increased the radiation patterns' accuracy.

Antenna with Circular Polarization of the Lens

With a 1.05-dB gain bandwidth of 14.4% and a 2.99-decibal axial ratio bandwidth of 19.8%, this antenna, which was designed to produce right-hand circular polarization (RHCP) radiation with a low-frequency feed, attained a gain of 31.8 dBic at 0.35 THz.

Yagi-Uda Array Quasi

With a Q-factor of 675 at 0.49 THz, this design incorporated a graphene-loaded THz filter to enhance the bandwidth to 15.2%. It achieved a total gain of 9.15 dB and maintained a directive radiation pattern with a side-lobe level of -4.99dB.

Antennas arrays and patches of antennas

For D-band applications, a 16-element array linked with a cavity-backed aperture antenna patch were created. Measured at 0.17 THz, insertion losses for microstrip lines were 1.89 dB/cm and for coplanar waveguide lines, they were 1.9 dB/cm. The maximum gains were 7 dBi (single antenna) and 14 dBi (array) at 0.143 THz.

Transmit Array

An all-dielectric Huygens' transmit array, operating between 0.12–0.13 THz, achieved gains ranging from 32–34 dB with a minimal gain reduction of approximately 2 dB.

Vivaldi Antenna

This antenna demonstrated a simulated gain of -10 dB and an impedance bandwidth of 0.076 THz, achieving a peak gain of 11.77 dB and a return loss of -58.83 dB. The measured radiation efficiency was 97.4%, with a directivity of 11.89 dBi at a resonant frequency of 0.603 THz.

5. Conclusion

This research provides an extensive evaluation of different antenna designs tailored for 6G and THz communication systems. It explores different types of antennas, such as elliptical lens antennas, grid arrays, circularly polarized horn antennas, Quasi

Yagi-Uda antennas, patch antennas, and transmit arrays. Furthermore, it evaluates various fabrication methods such as 3-D printing, lasers drilling, CNC-machining, Printed Circuit Boards etc., to determine their effectiveness.

The findings highlight that PCB technology effectively supports WHEMS, patch, and Vivaldi antennas, while LCP is well-suited for grid arrays. Wire-EDM and Topas fabrication enhance circularly polarized antenna performance, whereas 3D printing and TSV processes facilitate advanced designs such as resonant cavity and Quasi Yagi-Uda antennas. CNC machining has been instrumental in offset Cassegrain antenna production.

While substantial advancements have been achieved in 6G antenna design, further exploration of novel fabrication techniques and intelligent, high-gain antennas is necessary to meet future wireless communication demands.

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