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Innovations and Progress in Terahertz Antenna: A Literature Review

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ABSTRACT

The terahertz (THz) frequency range, often overlooked in the past, is now gaining recognition for its unique properties and diverse applications. THz waves, positioned between microwave and infrared frequencies, offer safety, broad bandwidth, and low energy consumption. This review highlights the burgeoning importance of THz technology in communication systems, spectroscopy, biomedical imaging, and various industries. It emphasizes the significance of novel antenna designs in enhancing THz system performance and functionality, enabling rapid communication, data transmission, spectroscopic analysis, and sensor capabilities.

Keywords: terahertz; advances; review; antenna design; telecommunication

1. Introduction

The terahertz (THz) frequency range, spanning from 0.1 to 10 THz, lies between microwave and infrared frequencies, offering unique properties like safety, broadband capability, and low energy consumption [1,2]. Despite initial neglect resulting from challenges in component advancement, THz frequencies are now being increasingly recognized for their wide-ranging utility in areas such as communication systems, spectroscopy, biomedical imaging, and military applications [3,4]. The capacity of THz waves to permeate various materials along with their high temporal resolution makes them extremely valuable for applications in high-speed wireless communication systems. Novel methodologies are being investigated by researchers to effectively utilize THz frequencies, thereby surmounting existing constraints and opening up possibilities for groundbreaking applications in imaging, communication, and beyond. The significance of terahertz (THz) technology stems from its unparalleled attributes, playing a pivotal role in a multitude of applications. Within the realm of electromagnetic waves, THz systems present expansive bandwidths that facilitate highfidelity spectroscopic analyses and imaging [5]. THz imaging systems are effective in medical fields, notably in neurodiagnostics for investigating brain tissues and identifying conditions like neurodegenerative diseases and brain tumors [6,7]. Additionally, THz technology is essential in pharmaceutical environments, enabling molecular spectroscopy for diagnostics and imaging of minute molecules [8]. Apart from the healthcare sector, THz technology proves useful in industrial settings like semiconductor production and automotive assembly, demonstrating its versatility and influence across various industries.

Antenna design is an important aspect in the evolution of Terahertz (THz) technology by boosting performance and functionality. Numerous novel antenna designs have been suggested to address the requirements of THz applications. These designs encompass on-chip antennas for detectors and sources, metamaterial-based MIMO antennas, reconfigurable dipole antennas with compound capabilities, and graphene-based beam reconfigurable antennas. The antennas provide functionalities such as multi-band detection, miniaturization, high gain, ultra-broadband response, and beam re-configurability, significantly propelling THz communication systems. Antenna operation within the THz spectrum facilitates rapid communication, data transmission, spectroscopic analysis, and sensor functionalities, emphasizing the critical role of antenna design in unlocking the potential of THz technology [9–11].

1.1 Fundamentals of Terahertz Antennas

Terahertz radiation, located within the spectral region between the infrared and microwave frequencies, exhibits distinctive characteristics with a wide range of practical uses [12]. This type of radiation has the capability to pass through non-conductive materials, presenting significant value in domains like security, non-destructive testing, and imaging [13]. The impact of Terahertz radiation on living organisms varies from modifying protein behavior to triggering epigenetic alterations, potentially influencing sectors like agriculture and healthcare [14]. Technological progress in the field of Terahertz involves the development of emitters that utilize layered conducting transition metal oxides, facilitating efficient generation of Terahertz waves through the transverse thermoelectric phenomenon, thus holding promise as versatile sources for diverse applications [15]. Moreover, Terahertz quantum cascade lasers provide a means of precise manipulation over spectral properties, rendering them suitable for precise gas analysis in fields such as biomedicine and environmental science.

The challenges in terahertz antenna design include high losses, low manufacturing accuracy due to small sizes, and the need for efficient broadband elements and arrays [16–18]. These challenges are crucial as terahertz (THz) frequencies offer vast bandwidths and high data rates, making them ideal for future wireless communication systems. Additionally, the integration of on-chip and off-chip antennas poses design trade-offs and interface technology limitations. To address these challenges, research focuses on improving THz antenna performance for 6G technology, emphasizing the importance of high-gain antenna arrays and MIMO systems to combat atmospheric losses at high frequencies [19]. Advanced antenna technologies like metamaterial, photoconductive, and plasmonic antennas, along with THz beamforming, play significant roles in enhancing THz communications.

1.2 Related Work

1.2.1. Metamaterial-Based Antennas

Metamaterials in THz antennas offer unique properties like perfect absorption and transmission, enhancing sensing, imaging, and communication systems. These artificially engineered materials are structured periodically to exhibit exceptional characteristics [20]. THz metamaterial-based sensors utilize pseudo-surface plasma effects to amplify incident THz waves, improving signal quality. By incorporating semiconductors in multilayer structures, design flexibility is increased while maintaining negative permittivity for metamaterial integrity [21]. Active meta devices and topological photonic crystals are advancing THz applications, enabling control over free-space propagation and on-chip waveguides. The future holds promise for reconfigurable topological waveguides and topologically-protected meta devices in advanced THz technologies. Developments in metamaterial antenna design have focused on enhancing performance and flexibility. Intelligent methods like machine learning and topology optimization are being employed for meta surface design, enabling precise control over electromagnetic wave fronts. Experimentally validated dipole frameworks are being utilized to describe the properties of tunable metamaterial radiators, paving the way for improved meta surface array antenna designs [22]. Additive manufacturing, particularly 3D printing, is revolutionizing the fabrication of RF devices, antennas, and metamaterials, offering new material properties and geometries for enhanced applications. Composite right/left-handed transmission line (CRLH-TL) metamaterials are providing extra design freedom for creating high-performance, multifunctional antennas with re-configurability, catering to various applications like MIMO systems and wireless power harvesting [23]. These advancements signify a shift towards more efficient, adaptable, and compact antenna solutions in modern wireless communication systems.

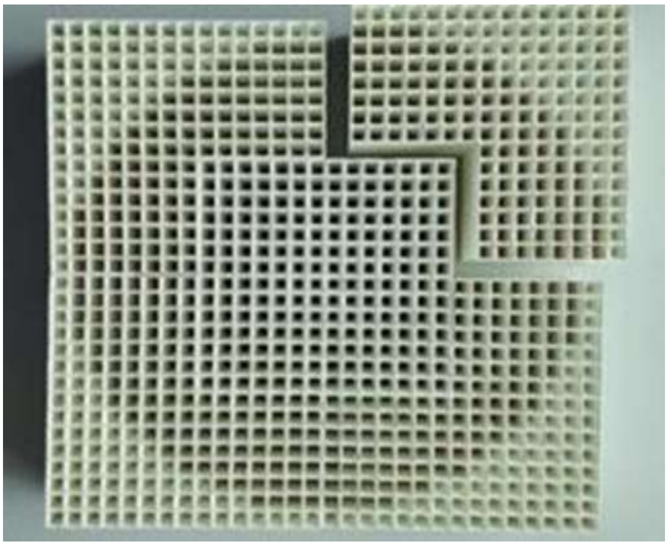

Figure 1. Whittaker et al. 3D-printed perorated dielectric transmitarray (TA) with total dimensions of 180 × 180 × 32 mm.

Metamaterial-based THz antennas offer advantages like high interaction impedance, compactness, and multi-band operation for diverse applications such as medical uses [24]. These antennas enable high-speed data rates up to 1 Tbps, massive bandwidth of up to 100 GHz, and low latency connectivity crucial for 6G systems [25]. Challenges include the impact of atmospheric losses at high frequencies, the need for high-gain antenna arrays, and mitigating performance degradation when placed near human body models [26]. Additionally, the design complexity and material selection for achieving desired properties pose challenges in developing efficient THz antennas. Despite these challenges, metamaterial-based THz antennas hold immense potential for advancing communication, imaging, and material analysis applications in the THz band.

1.2.2. Printed and Flexible THz Antennas

Printed antenna technologies for THz frequencies offer innovative solutions for high-gain, lowcost antennas. Li and Luk proposed an open resonator antenna design at 0.1 THz, utilizing a planar cavity with a loaded phase-shifting periodic structure to achieve high gain and wide bandwidth. Wu et al.

introduced a near-field focus lens antenna operating at THz frequencies, utilizing 3D printing for fabrication, showcasing 3D focus-scanning capabilities [27]. The integration of printed circuit boards and flexible printed circuits for efficient broadband antennas is discussed, highlighting the benefits and limitations of on-chip and off-chip designs [28]. These advancements in printed antenna technologies at THz frequencies demonstrate the potential for cost-effective, high-performance antennas suitable for various applications.

THz antenna design have shown promising developments in printed and flexible structures. Studies have explored hybrid designs incorporating materials like graphene and gold to enhance efficiency and flexibility [29]. Additionally, open resonator antennas with phase-shifting periodic structures have been proposed to achieve high gain and cost-effectiveness, utilizing threedimensional printing technology for manufacturing [30]. Furthermore, the use of innovative materials like Gallium-indium alloy (EGaIn) and Polyethylene naphthalate two formic acid glycol ester (PEN) has enabled the creation of flexible microstrip antenna arrays with superior mechanical properties and efficiency, catering to the demands of microwave energy transmission systems [31]. These collective efforts signify a significant stride towards enhancing the performance and applicability of THz antennas in modern communication systems.

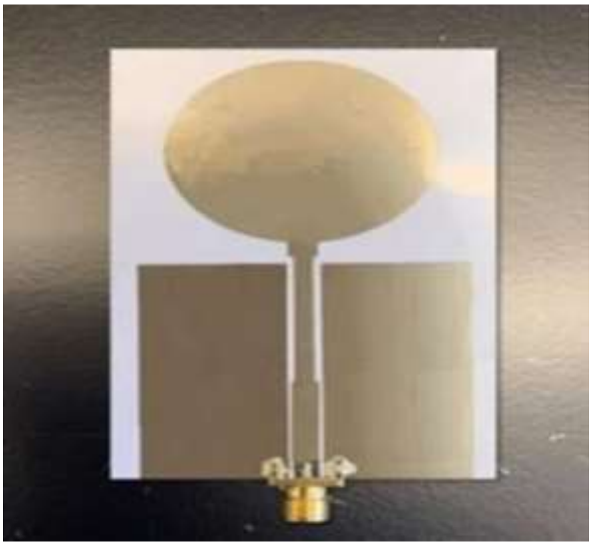

Figure 2. Chen et al. Inkjet-printed UWB antenna.

There are several uses and advantages for printed and flexible antennas in THz systems. Highspeed wireless communications are a good fit for hybrid antenna designs that use materials like gold and graphene, which exhibit increased efficiency [32]. Furthermore, in one-dimensional THz applications, 3D-printed lens antennas can enhance beam-scanning and gain performance. Further, low transmission loss and single-mode properties of 3D printed flexible and stretchy terahertz waveguides allow for a wide range of applications in ultra-flexible and stretchable THz devices [33]. These developments show that extremely efficient THz antennas have broad potential for use, particularly in wearable technology and body-centric wireless communication.1.3 Reconfigurable and Smart Antennas

Terahertz (THz) applications benefit from reconfigurable antennas because they provide wireless communication systems with flexibility and adaptability. Because of their special qualities, graphene-based antennas have potential for reconfigurability. Beam reconfigurable directional antennas using graphene components, reconfigurable structured light for augmenting THz production, and multi-band patch antennas based on graphene have all been suggested [34,35]. Moreover, printed ridge gap waveguides with programmable capabilities for flexible terahertz systems have been implemented using graphene. Moreover, Substrate-Integrated Waveguide (SIW) filters that use graphene have been made tunable in the THz range [36]. The aforementioned developments underscore the possibility of reconfigurable graphene-based antennas to augment efficiency and usefulness inside THz wireless systems.

Smart and reconfigurable THz antenna designs have demonstrated creative methods for improving performance with graphene-based materials. Compact graphene-based MIMO antennas with good isolation and wideband capabilities are among these designs; they provide effective and reversible solutions for THz applications [37]. Furthermore, with the use of graphene-based components, terahertz dipole antennas with compound reconfigurability have been created, providing control over radiation pattern, frequency, and polarization state [38]. Additionally, a reconfigurable graphene antipodal Vivaldi antenna with increased gain has been shown [39]. This antenna employs frequency selective surfaces in addition to reconfigurability by modification of the graphene chemical potential. These developments demonstrate how graphene-based materials may be used to create smart, programmable THz antennas for a range of uses.

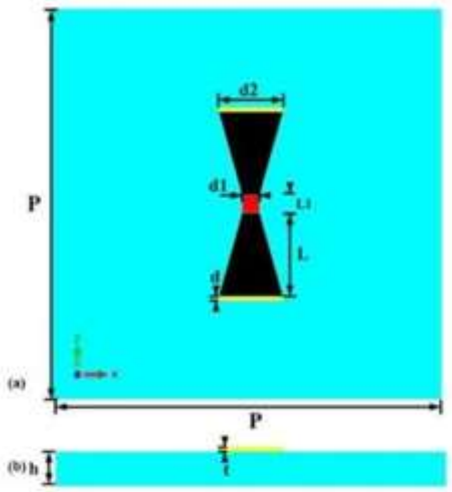

Figure 3. Jin et al. The structure of the graphene-based dipole antenna. (a) top view, (b) side view.

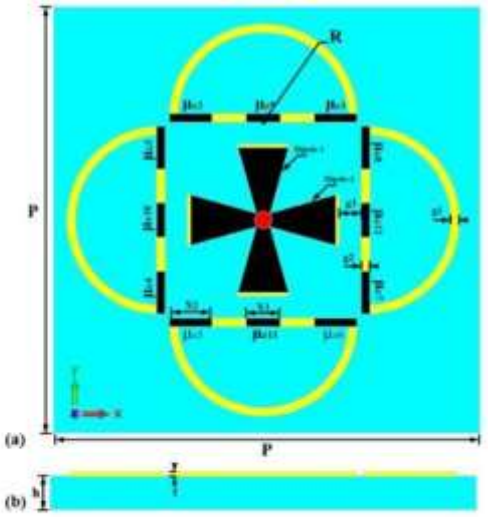

Figure 4. Jin et al. Structure of the CRTA. a) Top view. b) Side view.

Through the adjustment of antenna array weights, adaptive beamforming techniques are essential in improving signal reception. Challenges such as unexplained mismatches and problems with the signal-to-noise ratio (SNR) are tackled in different ways. Improving resilience against mismatches may be achieved by using steering vector (SV) estimates in an interference-plus-noise covariance matrix (INCM) reconstruction method [40]. An alternative technique efficiently suppresses interferences under system defects by using Gauss–Legendre quadrature (GLQ) for INCM reconstruction and SV estimation. Furthermore, in non-ideal conditions, a unique robust beamforming approach achieves good performance and resilience against multiple mismatches by combining steering vector estimation with interference estimates [41]. These methods demonstrate developments in adaptive beamforming and address issues to maximize signal reception while reducing interference.

Improving smart THz antenna systems requires a significant contribution from machine learning. These technologies enable adaptive learning by quickly analyzing large volumes of data from different antenna configurations with the use of machine learning algorithms [42]. Furthermore, in order to optimize geometric parameters and suggest appropriate antennas, intelligent antenna synthesis techniques make use of ensemble models and support vector machines [43]. This results in excellent classification and parameter prediction accuracy. Real-time self-adaptive beamforming for 6G terahertz wireless communications in huge MIMO systems is made possible by deep reinforcement learning, which also predicts spatial phase profiles for desired radiation patterns. Furthermore, antenna designs may be optimized with the use of machine learning models like Extra Tree Regression, which drastically cut down on simulation time and resource needs [44].

1.2.3. Terahertz Antenna Arrays and MIMO Systems

A key component of Terahertz (THz) technology are antenna arrays. They are necessary to prevent air losses at high frequencies, achieve large data speeds, and provide dependable communication. In order to construct 6G wireless communication systems, THz antennas, antenna arrays, and Multiple Input Multiple Output (MIMO) systems are popular research subjects [19]. Researchers have been working on improving THz antennas employing a variety of substrates and materials, including polyimide, quartz, copper, graphene, and more, for Internet-of-things, imaging, and sensing applications [45]. THz antenna technology has also been used with reflector antennas, horn array antennas, and metamaterial substrates in radio astronomy, deep space exploration, and atmospheric remote sensing. For space communication, high-gain THz antenna arrays with notable gains and efficiency at particular frequencies have been developed.

Novel designs such as a patch antenna array with via and slot loading for D-band applications are examples of terahertz antenna arrays that offer high radiation gain and broad impedance matching. Furthermore, the creation of improved terahertz pulses with scalable directional gain and low-profile assembly has been made possible by the combination of InP/InGaAs unitraveling-carrier photodiodes (UTC-PDs) with planar bowtie antennas [46]. Additionally, a high-power, compact surface-emitting terahertz source with resonant-tunneling diodes (RTDs)-based active antenna has been presented [47]. It exhibits increased directivity via coherent oscillation and has promise for use in 6G communication and THz imaging. These innovations demonstrate how terahertz antenna technology is developing in order to achieve improved functionality and performance.

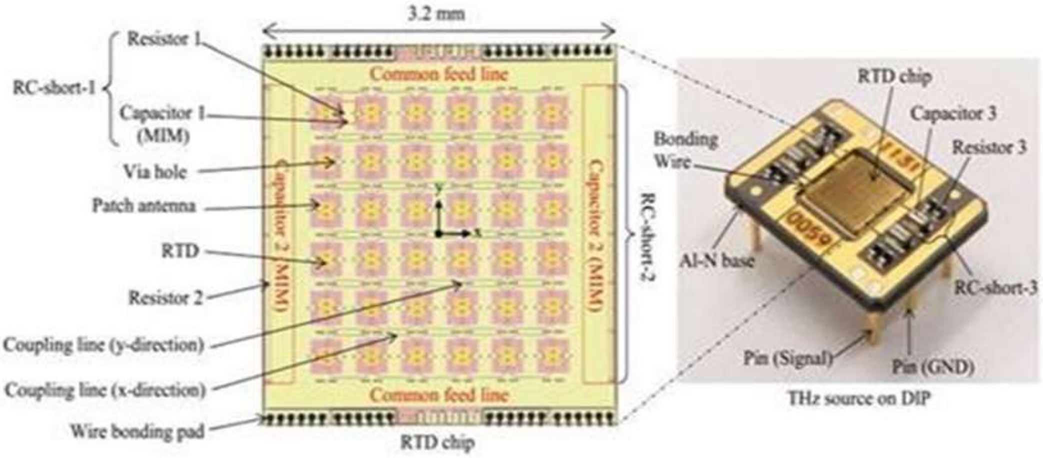

Figure 6. Koyama et al. The THz source chip prototype features an RTD chip measuring 3.2 × 3.2 mm², housing 36 active antennas, coupling lines, a common feed line, and wire bonding pads. Each antenna integrates a 170 × 170 μm² square patch antenna with two RTDs buried within a 7 μm-thick dielectric layer of benzocyclobutene (BCB) and silicon dioxide (SiO2). Metal vias establish electrical connections between the RTDs and the upper and lower electrodes of the patch antennas, enabling bias power feeding to the diodes and facilitating THz oscillation of the antennas.

Multiple-Input Multiple-Output (MIMO) systems provide huge connectivity and good spectrum efficiency. Higher data rates and greater connection are made possible by THz-band NOMA communications, which use MIMO systems for antenna arrays [48]. Furthermore, the use of MIMO technology to Quantum Key Distribution (QKD) systems operating at THz frequencies is discussed. In these systems, the use of multiple antennas improves security and secret key rates are improved in situations when eavesdropping is restricted. Moreover, channel sparsity and channel estimation issues are addressed by combining ultra-massive MIMO with intelligent reflecting surfaces in THz communications, which improves system capacity and performance [49]. MIMO systems have a great deal of promise to enhance system performance in terms of spectrum efficiency, connection, security, and overall THz communication scenarios.

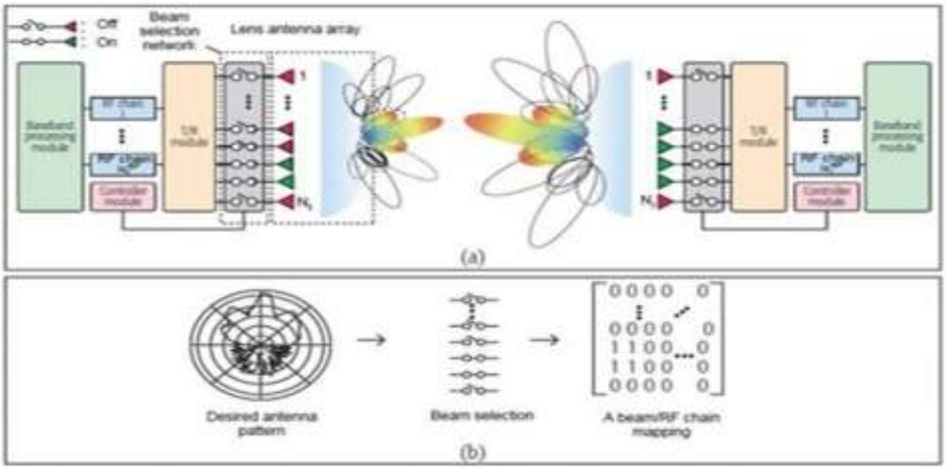

Figure 7. Zarini et al. Schematic of beamspace technology: (a) architectural components; (b) analog beam selection.

Terahertz (THz) MIMO systems face challenges and offer performance enhancements. Challenges include the impact of antenna element directivity and self-induced inter-symbol interference on THz MIMO system performance [50]. Innovative techniques such as tailored photonic crystal substrates and graphene-based patch antenna arrays have been proposed to increase performance, leading to notable reductions in total path loss and significant capacity improvements in THz MIMO systems [51]. Furthermore, difficulties like near-field region enlargement and channel sparsity must be controlled, however integrating ultramassive MIMO and intelligent reflecting surface systems can successfully overcome coverage restrictions and line-of-sight obstructions in THz communications [52]. THz MIMO systems can greatly increase capacity and open the door for upcoming ultra-high-speed wireless networks by utilizing these developments and resolving related difficulties.

1.3 Applications of Terahertz Antennas

Terahertz (THz) technology have diverse applications in imaging and sensing. Metasurfaces play a crucial role in enhancing THz sensor performance by engineering subwavelength resonators. High-temperature superconducting Josephson plasma emitters enable non-destructive imaging of various objects with high contrast differentiation, making them suitable for security, medical, and material evaluation applications [53]. THz imaging, coupled with image processing algorithms, simplifies non-destructive evaluation processes for fault detection in aircraft composites, including air cavities, debonding, and mechanical damage. Additionally, polarimetric imaging using anisotropic metasurfaces shows promise in NDT and 3-D profiling of reflective surfaces, offering potential applications in polymer composite imaging and refractive index measurements [54]. These advancements highlight the versatility and potential of THz technology in various industries. Terahertz communication systems offer high-speed wireless transmission capabilities, with research focusing on frequencies above 1 THz for short-range applications [55]. These systems address the need for very high-speed radio systems in wireless multimedia applications, utilizing the unique characteristics of the terahertz frequency band, such as high temporal resolution and low absorption. The terahertz band, spanning from 0.1 to 10 THz, is being explored to achieve transmission rates of several Terabits per second (Tbps) for applications like autonomous vehicles, 5G/6G networks, and HD holographic video conferencing. To meet the Quality of Experience (QoE) requirements of emerging cellular systems like wireless virtual reality, terahertz frequencies are crucial for providing high-rate, high-reliability, low-latency communications, necessitating abundant bandwidth and line of sight for improved reliability [56].

THz antennas are essential for applications in industry and biomedicine. THz antennas are used in industrial environments for material characterization, explosive detection, weapons detection, and high-speed short-range indoor wireless communication. THz antennas, on the other hand, are useful in biomedical applications for monitoring blood supply and tissue water levels, which aids in medical imaging, pharmacological analysis, and cancer diagnosis. These antennas are made to satisfy the unique needs of the industrial and biomedical domains by having features including high bandwidth, high gain, and circular polarized radiations [57]. The variety of uses for THz antennas demonstrates their adaptability and significance in the advancement of science and medicine. Research in a broad range of fields is being addressed by emerging trends and future directions in THz antenna applications. The wide bandwidth and fast data rates that Terahertz (THz) frequencies offer make them attractive candidates for use in wireless communication systems, including 6G technology [58]. Applications including radio astronomy, atmospheric remote sensing, and deep space exploration depend heavily on THz antennas, of which horn array and reflector antenna designs are two common uses [59]. The THz Science and Technology Roadmap highlights the technological obstacles as well as opportunities that the THz spectrum, which spans from microwaves to far-infrared, brings for breakthroughs in domains including medical imaging, climate monitoring, and 6G communications. Future THz applications such as wireless communication, industrial inspections, and medical imaging will require antenna designs with improved gain, bandwidth, and performance.

1.4 Conclusion

A. Summary of Key Findings

Metamaterial-based THz antennas offer significant advantages, including high interaction impedance, compactness, and multi-band operation, making them ideal for diverse applications such as medical uses [20]. These antennas facilitate high-speed data rates of up to 1 Tbps, massive bandwidth reaching up to 100 GHz, and low-latency connectivity crucial for 6G systems. However, challenges persist, including the impact of atmospheric losses at high frequencies, the necessity for high-gain antenna arrays, and the need to mitigate performance degradation when placed near human body models [21]. Additionally, the design complexity and material selection required to achieve desired properties pose hurdles in developing efficient THz antennas. Despite these challenges, metamaterial-based THz antennas hold immense potential for advancing communication, imaging, and material analysis applications within the THz band [22]. Printed antenna technologies tailored for THz frequencies offer groundbreaking solutions, delivering highgain capabilities at a low cost. Li and Luk's proposal of an open resonator antenna design at 0.1 THz, incorporating a planar cavity with a loaded phase-shifting periodic structure, promises both high gain and wide bandwidth.

Meanwhile, Wu et al. showcased a near-field focus lens antenna operating at THz frequencies, leveraging 3D printing to exhibit remarkable 3D focus-scanning capabilities [27]. Further discussions explore the integration of printed circuit boards and flexible printed circuits, underscoring the advantages and limitations of on-chip versus off-chip designs for broadband antennas. These advancements underscore the potential of printed antenna technologies at THz frequencies to offer cost-effective, high-performance solutions applicable across diverse fields. Notably, studies have demonstrated promising developments in printed and flexible structures, including hybrid designs integrating materials like graphene and gold to boost efficiency and flexibility [28]. Open resonator antennas with phase-shifting periodic structures, manufactured through three-dimensional printing, offer avenues for achieving high gain and cost-effectiveness. Additionally, innovative materials such as Gallium-indium alloy (EGaIn) and Polyethylene naphthalate two formic acid glycol ester (PEN) have enabled the creation of flexible microstrip antenna arrays, meeting the demands of microwave energy transmission systems [29]. These collective endeavors signify significant progress toward enhancing THz antenna performance and versatility in modern communication systems [30]. Printed and flexible antennas within THz systems present myriad applications and benefits, with hybrid designs facilitating high-speed wireless communications through enhanced efficiency. Further, 3Dprinted lens antennas promise improved gain and beam-scanning capabilities in one-dimensional THz applications. Additionally, flexible and stretchable terahertz waveguides, produced via 3D printing, exhibit low transmission loss and single-mode characteristics, paving the way for diverse applications in stretchable and ultra-flexible THz devices. These advancements underscore the potential for highly efficient THz antennas to find widespread use, including in body-centric wireless communication and wearable applications. Reconfigurable THz antennas, particularly those using graphene, offer adaptability in wireless systems [36]. They enable multi-band patch antennas, beamreconfigurable directional antennas, and smart designs like compact MIMO antennas. Graphenebased Vivaldi antennas with improved gain also showcase flexibility [40]. Adaptive beamforming techniques, including INCM reconstruction and robust methods, enhance signal reception. Machine learning aids in efficient data analysis, adaptive learning, and antenna synthesis, improving overall performance and adaptability [43]. Terahertz (THz) antenna arrays feature novel designs like via and slot-loaded patch antennas for D-band applications, offering wideband impedance matching and high radiation gain [47]. Integration of InP/InGaAs photodiodes with planar bowtie antennas enables enhanced terahertz pulse generation, while a compact, high-power surface-emitting terahertz source based on active antennas with resonant-tunneling diodes (RTDs) promises improved directivity for applications in THz imaging and 6G communication [48]. Multiple-Input-Multiple-Output (MIMO) systems are integral to THz communications, enhancing spectral efficiency and connectivity, with applications in NOMA communications and Quantum Key Distribution (QKD) systems [50].

Challenges faced by THz MIMO systems include antenna directivity and inter-symbol interference, which are addressed through solutions like graphene-based patch antennas and optimized photonic crystals substrates [51]. Integration of ultramassive MIMO and intelligent reflecting surfaces mitigates coverage limitations and line-of-sight blockages, enhancing THz system capacity for ultra-high-speed wireless networks [52]. Terahertz (THz) technology finds diverse applications in imaging, sensing, and communication. Metasurfaces enhance THz sensor performance for security, medical, and material evaluation [54]. THz imaging, coupled with image processing, simplifies non-destructive evaluation processes, while polarimetric imaging offers promise in polymer composite imaging and refractive index measurements [55]. In communication, THz systems explore frequencies above 1 THz for high-speed wireless transmission, crucial for applications like autonomous vehicles and HD holographic video conferencing [57]. THz antennas play vital roles in industrial communication, biomedical imaging, and future technologies like 6G communication and atmospheric remote sensing [59]. Antenna designs with enhanced bandwidth, gain, and performance are essential for advancing THz applications in various fields [60].

Future wireless communication technologies will be significantly impacted by recent developments in THz antenna design. In order to mitigate route loss and improve coverage in THz communication, these improvements include the creation of high-gain antenna arrays and MIMO systems, as well as the application of precoding techniques including hybrid precoding, delay-phase precoding, and analogue beamforming [58]. Furthermore, the utilization of plasmonic gratings in photoconductive antenna design has demonstrated encouraging outcomes in relation to enhanced THz power output and efficiency [60]. Slot antennas have also been investigated; by varying the slot position, better performance has been shown. Additionally, optimized PBG MIMO antennas with a large bandwidth for THz applications have been presented using polyimide substrates [61]. These antennas offer good isolation. All of these developments open the door for future 6G systems to have high data speeds, dependable communication, huge connection, and low latency.

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