Chapter

An Overview of THz Antenna Design for 5G/6G Wireless Communications

Haleh Jahanbakhsh Basherlou, Martins Odiamenhi,
Naser Ojaroudi Parchin, Chan Hwang See and Ming Shen

Abstract

The rapid evolution of wireless communication technologies has spurred significant interest in terahertz (THz) frequencies as a key enabler for next-generation 5G and 6G wireless communications and mobile networks. THz antennas are critical for leveraging these high-frequency bands, offering unprecedented data rates, ultra-low latency, and enhanced spectral efficiency. This chapter provides an overview of various types of THz antennas designed for wireless applications, with a focus on their unique design requirements, fabrication techniques, and performance characteristics. Key topics include advances in antenna design, miniaturization, fabrication methods, and integration with electronic components. Additionally, the chapter explores the role of THz antennas in enabling essential array technologies, underscoring their transformative potential in next-generation wireless communication systems. Furthermore, the design details and fundamental characteristics of new THz antennas are discussed extensively, complementing and reinforcing the insights presented.

Keywords: 5G/6G, antenna design and miniaturization, antenna arrays, THz communications, wireless networks

1. Introduction

The evolution of wireless communication systems, encompassing both 5G and 6G, has continually pushed technological boundaries, striving for increased data rates, reduced latency, and enhanced connectivity. While 5G has already brought transformative improvements in speed, capacity, and reliability, 6G technology is anticipated to extend far beyond these advancements. Building on the progress of 5G, 6G aims to revolutionize a multitude of domains, including mobile communication, spacecraft communication, aircraft communication, submarine communication, and illumination communication [1, 2]. The envisioned 6G network seeks to provide coordinated and integrated coverage, driving global network performance enhancements. Both 5G and 6G address escalating industrial demands for high connection density, increased network efficiency, enhanced spectrum efficiency, and minimized end-to-end latency. Notably, in May 2018, the International Telecommunication Union (ITU) took a pivotal step by establishing an International Mobile Telecommunications (IMT) standard for 6G, targeting a potential launch by 2030 [3]. In parallel, the United States Federal Communication Commission (FCC) proposed the integration of 6G technology in THz spectrum-based networks and spatial multiplexing technologies during the Mobile World Congress in September 2018, highlighting global efforts toward next-generation communication systems [4].

The upcoming wireless communication systems signify a substantial leap in this technological evolution, targeting operational frequencies in the terahertz (THz) bands ranging from 0.1 to 10 THz, as shown in **Figure 1**. These frequencies correspond to wavelengths spanning from 3 mm to 0.03 mm, positioning 6G at the pinnacle of high-frequency communication technologies [5]. However, the transition to THz frequencies introduces a series of significant challenges, primarily due to the intrinsic characteristics of terahertz waves. The THz band, which occupies a radio frequency (RF) spectrum from 0.1 to 10 THz, offers two substantial advantages: abundant spectrum availability and the potential for broadband communication with extremely high data transmission rates. Yet, the high-frequency nature of the THz band also brings considerable limitations, such as high propagation losses, absorption, and scattering by atmospheric molecules and particles [6]. These challenges are particularly pronounced over extended distances, necessitating solutions to enhance communication range and reliability. One of the primary challenges associated with THz frequency bands, crucial for 6G development, is the high propagation loss, path loss, and atmospheric absorption caused by molecules. While 5G operates at lower frequencies that mitigate these effects, 6G aims to extend the boundaries of wireless communication by utilizing THz waves, which are significantly impacted by atmospheric conditions. Substantial absorption by water vapor and oxygen molecules, whose dimensions are comparable to THz wavelengths, leads to pronounced attenuation, severely limiting the effective communication range and coverage area [7, 8]. Overcoming these obstacles is essential for realizing the full potential of 6G wireless communication systems, building upon the foundation laid by 5G.

Wireless technologies operate across a broad spectrum of frequencies, each optimized for specific communication needs. Lower-frequency systems like GSM and NB-Internet of Things (IoT) provide long-range coverage suitable for mobile and IoT applications, but with lower data rates. Mid-range technologies such as LTE and WiMAX offer faster data rates over moderate distances, supporting broadband access and mobile communication. Short-range technologies like Wi-Fi, Bluetooth, and ZigBee enable high-speed communication in local environments, with Wi-Fi offering some of the highest data rates in this category [9]. As we move to higher frequencies, technologies like UWB, mmWave, and SATCOM offer ultra-high-speed data transfer,

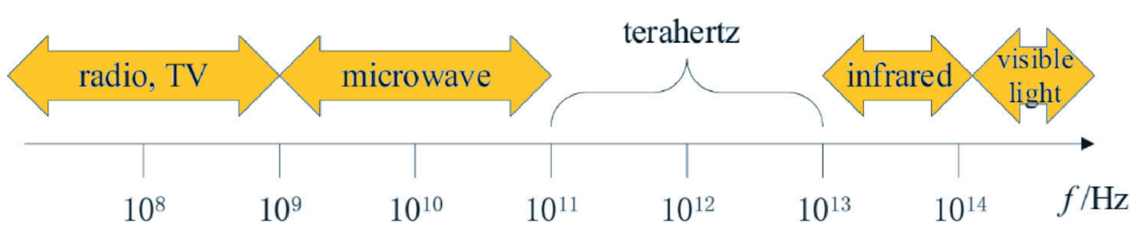

Figure 1.
The position of the THz wave in the electromagnetic spectrum.

with mmWave and Terahertz (THz) systems targeting even faster data rates for emerging applications. With the promise of speeds in the gigabit and terabit ranges, Terahertz communication, in particular, is poised to revolutionize wireless networks, requiring the development of advanced antenna designs capable of handling these ultra-high-frequency signals [10]. A detailed comparison of these technologies, including their frequency ranges, communication distances, and data rates, is provided in the **Table 1**.

The transition from 5G to 6G also introduces new complexities in antenna design and fabrication. While 5G technologies rely on advanced yet established antenna designs, the high frequencies and small wavelengths of the THz spectrum require entirely novel approaches. Conventional methodologies are inadequate for this spectrum, necessitating innovative solutions for efficient operation. Metamaterials, with their engineered electromagnetic properties, offer a promising avenue, enabling the creation of highly directional antennas with substantial gain to counteract the inherent limitations of THz communication. Addressing these challenges demands a multifaceted approach [11]. For both 5G and 6G systems, the development of antennas with high directionality or omnidirectionality and significant gain remains a critical focus. Research to optimize performance metrics—such as bandwidth, directivity, and gain—has resulted in advancements like the use of advanced substrate materials, corrosion-resistant designs, multi-element configurations, and dielectric lenses. Techniques to reduce mutual coupling, such as neutralization lines, decoupling networks, electromagnetic bandgap structures, defected ground structures, metamaterials, and slot elements, are increasingly vital for enhancing antenna performance in next-generation wireless systems [12].

This chapter provides an overview of the advancements in THz antenna design across both 5G and 6G wireless communication systems. It explores the unique issues posed by THz frequency bands for 6G and the latest innovations in design, fabrication, and measurement of antennas. This review covers both single-element and array

Technology	Frequency	Communication	Data rate
GSM	460 MHz–2 GHz	Up to 20 km	Up to 1 Mbps
NB-IoT	700–900 MHz	More than 10 km	Up to 200 Kbps
LoRaWAN	868 MHz–Sub-GHz	More than 10 km	Up to 50 Kbps
LTE Networks	1.9–2.1 GHz	Up to 5 km	Up to 100 Mbps
WiMAX Broadband	2.5–2.7 GHz	Up to 50 km	Up to 128 Mbps
Wireless Internet	2.4 GHz	Up to 30 m	Up to 150 Mbps
ZigBee IoT Protocol	868 MHz, 2.4 GHz	Up to 1 km	Up to 250 Kbps
Low-Energy Bluetooth	2.4 GHz	Up to 100 m	Up to 1 Mbps
WLAN	2.4 GHz, 5 GHz	Up to 100 meters	Up to 1.3 Gbps
UWB Systems	3.1–10.6 GHz	Up to 30 m	Up to 480 Mbps
mmWave Signals	24–100 GHz	Up to 100 meters	Up to 10 Gbps
SATCOM	1–40 GHz	More than 36 Mm	Up to 1 Gbps
Terahertz	100 GHz–10 THz	Up to 10 meters	10 to 160 Gbps

Table 1.
Comparison between various wireless technologies.

antennas reported for THz applications. In addition, two specific antenna designs including single-element and an array THz antenna are presented, along with a detailed discussion of their characteristics.

2. Development of THz antennas

The design and development of THz antennas are pivotal in advancing modern communication technologies, bridging the capabilities of 5G, and paving the way for 6G networks. THz antenna design is at the forefront of enabling cutting-edge applications such as ultra-HD streaming, immersive virtual and augmented reality, autonomous vehicle networks, advanced sensing, and IoT-based smart systems. This section provides an exploration of various THz antenna designs, their unique characteristics, and their transformative role in shaping the future of communication technologies. Each type of antenna, whether planar or 3D, single-element or array, carries unique design considerations tailored to specific applications, enabling diverse functionalities and efficiencies for present and future wireless networks [13].

2.1 Single-port/single-element THz antennas

The Single-port/single-element THz antennas represent a crucial frontier in the development of 6G networks, primarily due to their capability to harness the vast bandwidths available in the terahertz frequency spectrum (0.1 to 10 THz). Their compact size, enabled by the short wavelengths at THz frequencies, facilitates integration into small form factor devices, paving the way for ubiquitous connectivity on the Internet of Things (IoT) era. However, their deployment faces significant technical challenges, including precise fabrication to maintain performance at THz frequencies, mitigating losses associated with material characteristics, and overcoming integration hurdles with existing electronic systems [14]. Recent advancements leverage novel materials such as graphene and metamaterials, which offer unique properties like tunability and reduced signal loss, thereby enhancing antenna efficiency and performance. This sub-section discusses the various designs of single port and single element THz antennas along with their outcomes.

2.1.1 Microstrip/printed THz antennas

Microstrip-printed antennas, renowned for their compact form factor, ease of fabrication, and seamless integration with planar circuits, have become pivotal in leveraging this spectrum. One notable advancement in the realm of THz antennas is the development of a wideband substrate integrated waveguide (SIW) based slot antenna designed for D-band applications (0.11–0.17 THz) [15]. This antenna employs a two-step wideband WR6-SIW transition to ensure effective impedance matching and accurate measurement. The design achieves an impressive −10 dB impedance bandwidth of 42.86%, spanning from 0.11 to 0.17 THz, a significant bandwidth enhancement achieved by merging six closely spaced resonance frequencies. This intricate mode merging strategy not only broadens the bandwidth but also enhances the antenna's radiation characteristics, making it a viable candidate for future 6G applications. Another significant contribution is the use of microstrip patch antenna (MPA) operating at 0.835, 0.635, and 0.1 THz frequencies, designed on a liquid crystalline polymer substrate using a simple PCB etching process [16]. These antennas are targeted for THz spectroscopy in cancer detection and Doppler radar-based vital sign detection, demonstrating the versatility of THz applications beyond communication. The fabricated prototype array at 0.1 THz exhibited good agreement between measured and simulated results, showcasing the approach's potential for practical implementation. The study highlights the improved gain and fabrication tolerance achieved with the liquid crystalline polymer substrate. The development of a quasi-Yagi antenna designed for D-band frequencies (0.11–0.17 THz) integrated within a glass interposer represents another innovative approach to THz antenna design [17]. This antenna offers a wide impedance bandwidth and a peak gain of 4.78 dBi at 0.14 THz, making it highly suitable for 6G handset applications. The use of a glass interposer facilitates compact integration, leveraging advanced glass panel embedding techniques. One of the key challenges addressed is the measurement of end-fire antennas above 100 GHz, with a proposed probe-station-based setup for return loss and end-fire gain measurements. Additionally, an envelope detector circuit is utilized for characterizing the normalized radiation pattern, demonstrating consistency with simulation results. The integration of the quasi-Yagi antenna in a glass interposer provides a promising antenna-in-package solution, capitalizing on the beneficial properties of glass substrates, such as low loss and high integration density, critical for 6G applications., the photonic crystal (PC) structures for designing a microstrip patch antenna operating in the terahertz (THz) frequency range (0.1–1 THz) is investigated in [18]. An inset-feed rectangular microstrip antenna utilizing 1D, 2D, and 3D PC substrates has been proposed. The study evaluates various PC materials like air cavity, polyamide, paper, FR4, Arlon, and quartz, highlighting the superior efficiency of air cavity PBG structures. Antennas based on 2D PCs demonstrate impressive performance, achieving a minimum reflection coefficient of −63.22 dB, maximum directivity of 6.81 dBi, and radiation efficiency of 88.17% at 0.741 THz. Simulation using CST Microwave Studio includes analysis of scattering parameters and material properties, concluding that 2D PC antennas with air cavities are optimal for the 0.68–0.74 THz frequency band, suitable for applications in threat detection, homeland security, and wireless communication.

2.1.2 3D/non-planar THz antennas

The advancements in 3D and non-planar THz antennas highlight significant strides in achieving the performance metrics required for 6G networks. These innovations are poised to facilitate the integration of THz technologies into future 6G communication systems, supporting a wide array of applications from high-speed data transmission to advanced sensing. One notable advancement in this field is the development of 0.3-THz step-profiled corrugated horn antennas designed for integration into low-temperature co-fired ceramic (LTCC) packages [19]. These antennas utilize substrate-integrated waveguide technology to form a hollow waveguide and horn structure within a multilayer LTCC substrate, surrounded by a *via* fence, for enhanced performance. Experimental results show the LTCC waveguide demonstrating low insertion loss of 0.6 dB/mm, while the LTCC horn antenna achieves an 18-dBi peak gain with a 0.1-THz bandwidth and over 10-dB return loss. The compact design facilitates seamless integration into LTCC transceiver modules, with experimental results aligning closely with simulations. Another significant contribution is the introduction of a dielectric rod waveguide (DRW) antenna designed for frequencies ranging from 0.075 to 0.325 THz [20]. The antenna's broadband geometry is optimized through numerical simulations and is matched with metal waveguides of varying sizes across different frequency bands. Measurements confirm close agreement with simulations up to 0.325 THz, maintaining nearly constant gain across the entire frequency range with a relative bandwidth of 160%. However, sharp antenna tips limit performance beyond 0.325 THz due to manufacturing constraints. The antenna demonstrates better than 15 dB return loss, with radiation patterns nearly independent of frequency. The development of a suspended SOG tapered antenna operating in the frequency band of 0.11–0.13 THz represents another innovative approach in THz antenna design [21]. This antenna, fabricated using deep reactive ion etching (DRIE) of the Si layer and selective etching of the glass substrate, radiates both Ex- and Ey-polarizations. Key features include linear polarization, high directivity, integrability, and low-cost fabrication. Experimental results validate its performance, showing gains of 17.5 dBi at 0.115 THz for Ex-polarization and 18.3 dBi at 0.128 THz for Ey-polarization, with measured efficiencies of 94% and 99%, respectively. The suspended SOG tapered antenna enhances radiation efficiency and gain in mmW applications, designed, fabricated, and measured using precise photolithography and DRIE processes. This configuration achieves high directivity and efficiency, making it suitable for transceiver applications in the 0.11–0.13 THz range. In [22], the use of metallic 3D printing for antennas operating up to 0.325 THz is discussed which compares binder jetting/sintering on stainless steel and selective laser melting on Cu–15Sn, ultimately selecting Cu–15Sn for its cost-performance balance. This led to the development of conical horn antennas for the E-, D-, and H-bands, which demonstrated strong agreement between simulated and measured performance, covering the entire operational band with gains over 21.5 dBi. The study highlights that compared to traditional methods, 3D printed antennas offer environmental benefits, lower costs, and faster production times. Additionally, these metallic 3D printed antennas provide greater simplicity and robustness than their non-metallic counterparts, underscoring the potential of metallic 3D printing for both industrial mass production and prototyping.

2.1.3 On-chip THz antennas

The development of on-chip antennas is critical for the miniaturization and integration of THz technologies in 6G wireless systems. On-chip antennas offer the potential for high performance and compact size, essential for advanced communication and sensing applications. The advancements in on-chip THz antennas highlight significant strides in achieving the performance metrics required for 6G networks. These innovations are poised to facilitate the integration of THz technologies into future 6G communication systems, supporting a wide array of applications from high-speed data transmission to advanced sensing [23]. This section explores recent progress in on-chip THz antennas, focusing on their innovative designs, fabrication techniques, and potential impact on future 6G networks. A significant advancement in on-chip THz antennas is the development of antennas operating at 0.165 THz, designed using a standard silicon-Germanium BiCMOS process with localized backside etching (LBE) to create air trenches in silicon [24]. This study developed and characterized three antennas in the D-band (0.11–0.17 THz): a dipole antenna optimized for a tilted beam achieving 1 dBi gain, an LBE-based folded dipole achieving 5 dBi gain at 0.165 THz over 1.88 mm^2, and an LBE-patch antenna attaining 6 dBi gain at 0.16 THz over 1 mm^2. The study emphasizes optimizing antenna geometry for process reliability and examines the effects of metal fillings on radiation patterns and matching. Another notable development is the introduction of a 0.45-THz on-chip antenna designed for wide bandwidth and an exceptionally low profile [25]. Utilizing a dual-patch structure, this antenna achieves an impedance bandwidth exceeding 15% at a profile height of just 0.013 $\lambda 0$. Simulation results indicate a peak gain of 2.7 dBi and a radiation efficiency of 31.7%. Fabricated using 65-nm CMOS technology, preliminary measurements confirm an impressive 15.9% impedance bandwidth, consistent with simulations. The antenna's characteristics, including its low profile and wide bandwidth, make it suitable for future applications in 6G wireless systems, short-range communications, and terahertz detection. Enhancing the performance of a 0.3-THz on-chip patch antenna by placing it in a low-cost quad-flat no-lead (QFN) package using silica-based materials represents another significant advancement [26]. Full-wave simulations for a rectangular patch antenna, designed to match a 65 nm CMOS process, reveal that when the packaging material thickness over the antenna is approximately $\lambda/3$, radiation efficiency improves from 46–60% at 0.3 THz, with a 7 GHz bandwidth increase and 1 dB peak gain. Practical tests with a 0.276-THz CMOS signal generator equipped with the on-chip antenna in a QFN package show an effective isotropic radiated power (EIRP) about 6 dB higher than unpackaged versions. This improvement is attributed to enhanced antenna performance due to the packaging. A THz CMOS on-chip patch antenna with a defected ground structure (DGS), designed to achieve broadband and high gain is proposed in Ref. [27]. Simulation results show that the DGS enhances the antenna element's gain, bandwidth, and isolation. The antenna is fabricated using a commercial 65 nm CMOS process and measured on-wafer. They exhibit gains of 3.1 dBi, with bandwidths of 14.0%, for a reflection coefficient less than −10 dB at 0.3 THz. The CMOS on-chip antenna designed in this work promises low-cost and high-performance integration into THz systems using standard CMOS processes without additional manufacturing techniques.

2.1.4 Summary and comparison

Table 2 provides a summary and comparative overview of single-port/single-element THz antenna designs, focusing on their fabrication methods, operational frequency ranges, and unique characteristics. Each design showcases innovations aimed at overcoming the technical challenges of THz antenna deployment, such as precise fabrication, efficient material utilization, and integration compatibility. For instance, microstrip antennas demonstrate advancements in substrate technologies, like liquid crystalline polymers and photonic crystals, to enhance bandwidth and efficiency. Similarly, 3D and non-planar antennas leverage cutting-edge methods such as LTCC and metallic 3D printing to achieve high gain and compactness, essential for integration into transceiver modules. On-chip antennas highlight the potential for miniaturization, employing advanced CMOS and BiCMOS processes to enable compact and high-performance designs suitable for 6G systems. The diversity of these designs underscores the ongoing efforts to address specific requirements, including wide bandwidth, high efficiency, and cost-effective manufacturing, paving the way for practical THz communication and sensing applications.

2.1.5 Simulations and design example of a single-element THz antenna

In this sub-section simulation and design details and radiation characteristics of a single-element THz antenna are discussed. The properties of the design were examined using CST 2022 [28]. **Table 2** provides the specific parameter values for

References	Antenna type	Fabrication method	Frequency (THz)	Main characteristics
[15]	SIW Slot Antenna	Substrate Integrated Waveguide (SIW)	0.11–0.17	Wide bandwidth; merges six modes.
[16]	Liquid Crystal Polymer MPA	PCB etching on liquid crystalline polymer	0.1, 0.635, 0.835	High fabrication tolerance; versatile for spectroscopy and radar.
[17]	Quasi-Yagi Antenna	Glass interposer with panel embedding	0.11–0.17	Compact integration; probe-based end-fire.
[18]	Photonic Crystal MPA	Inset-feed with PC substrates	0.68–0.74	Air cavity PC substrates; high efficiency.
[19]	Corrugated Horn Antenna	LTCC with hollow waveguide	0.1–0.3	High gain; compact integration modules.
[20]	Dielectric Rod Waveguide	Metal waveguide with optimized geometry	0.075–0.325	Broadband with stable gain across frequencies.
[21]	Suspended SOG Tapered	Photolithography and DRIE	0.11–0.13	Dual polarization; high efficiency.
[22]	3D Printed Conical Horn	Metallic 3D printing (Cu–15Sn)	Up to 0.325	Cost-effective and eco-friendly fabrication.
[24]	On-Chip Dipole	LBE in SiGe BiCMOS	0.11–0.17	Compact size; optimized for process reliability.
[25]	On-Chip Dual-Patch Antenna	CMOS 65-nm	0.45	Low profile; wide impedance bandwidth.
[26]	Packaged Patch Antenna	CMOS in QFN package	0.276–0.3	Enhanced efficiency and gain with packaging.
[27]	On-Chip Patch	CMOS 65-nm with DGS	0.3	Improved isolation, bandwidth, and gain.

Table 2.
Summary of the discussed single-element THz antennas.

Parameter	W_X	L_X	W_1	L_1	W_2	L_2
Value (μm)	70	60	12	5	5	10
Parameter	L_3	W_4	L_5	W_5	W_6	W_3
Value (μm)	5	25	15	5	25	7.5

Table 3.
Parameter values of the designed THz antenna.

the suggested antenna design. **Figure 2(a)** illustrates the configuration and design details of the single element S-shaped monopole resonator which characterized by its compact dimensions, printed in a 5 μm thick Rogers RO3003 material. The choice of the S-shaped monopole design is driven by its compact size, dual-band functionality, make it suitable for modern devices of the next-generation wireless communication systems. **Figure 2(b)** presents the S_{11} (reflection coefficient) result showing that the antenna impedance bandwidth spanning from 2.45 to 2.55 THz and 3.3 to 3.75 THz at a − 10 dB threshold within the 6G spectra.

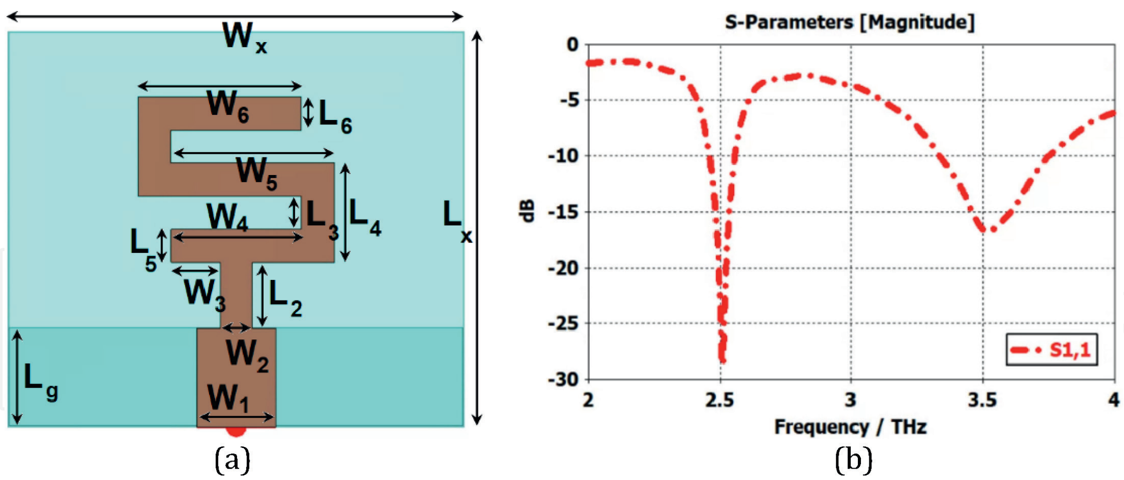

Figure 2.
(a) Single-element design details and (b) its S_{11} result.

To theoretically discuss and validate the dual-band functionality of the proposed antenna, the simulated current distributions at the resonance frequencies of 2.5 THz and 3.5 THz are presented in **Figure 3**. Notably, during the first resonance at 2.5 THz, the longer section of the S-shaped structure exhibits significant current flow. Conversely, in the second resonance at the higher frequency of 3.5 THz, it is primarily the lower (or half) section of the S-shaped antenna that demonstrates considerable current densities. This behavior underscores the inverse relationship between antenna size and frequency, where shorter dimensions correspond to higher frequencies [29].

Figure 4 illustrates the efficiency results across the resonance frequencies. As depicted, the element exhibits high-efficiency rates throughout its operational bandwidth. Radiation efficiencies exceed 95%, while total efficiencies remain above 85% across the two frequency bands. Notably, within the mid-frequency range, both values surpass 95%, demonstrating that the proposed design is suitable and reliable for 6G communications. Furthermore, the gain results presented in **Figure 5** indicate that the suggested monopole design achieves significant gain levels, enhancing its performance.

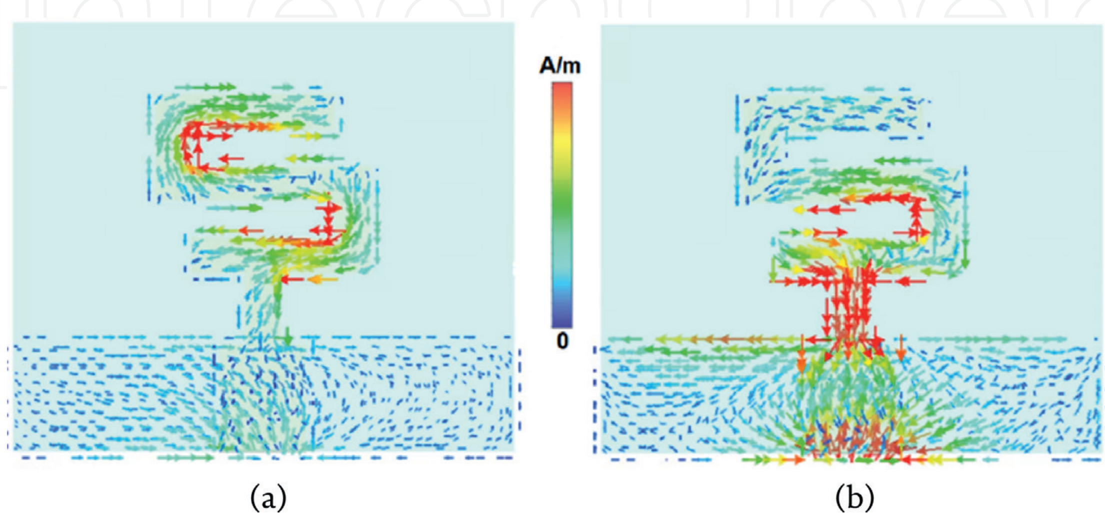

Figure 3.
Current distributions at (a) 2.5 and (b) 3.5 THz.

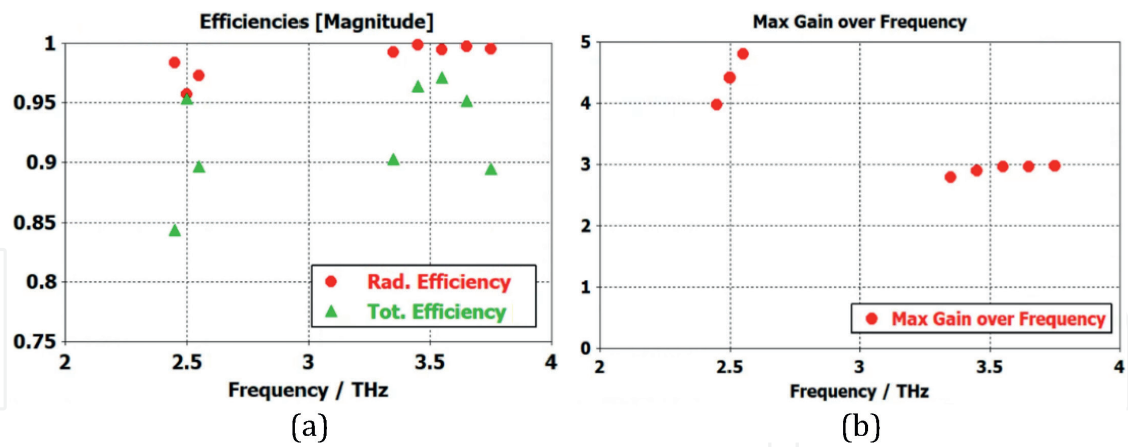

Figure 4.
(a) Efficiencies and maximum gain results of the designed THz antenna.

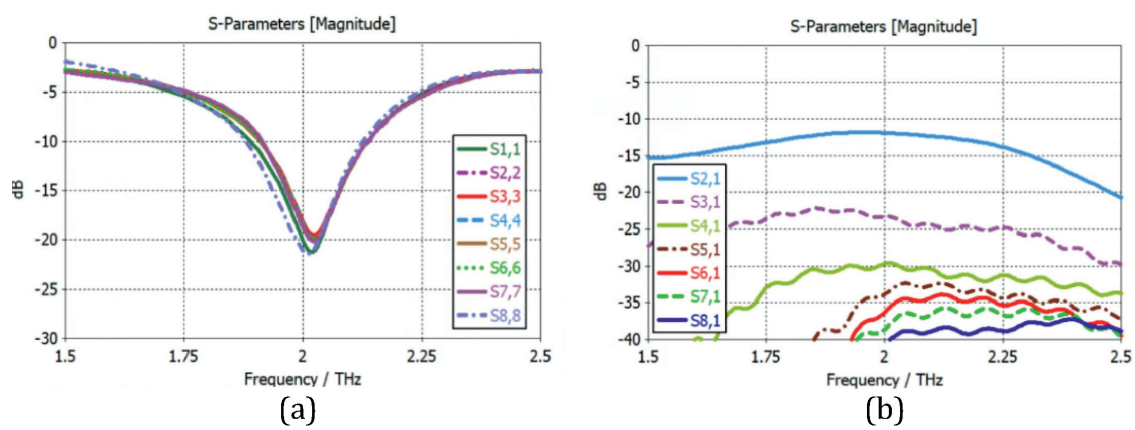

Figure 5.
Scattering parameters: (a) S_{nn} and (b) S_{n1}.

2.2 Multi-prot/array THz antennas

Multi-port and array THz antennas are pivotal in addressing the growing demands of high-capacity, high-speed communication networks, especially for 6G systems. These antennas leverage array configurations and multi-port designs to achieve high gain, precise beam control, and enhanced efficiency, making them essential for a wide range of applications, including wireless backhaul, radar systems, and advanced sensing. Furthermore, the integration of THz antennas into multi-element arrays allows for the development of features such as beam steering, frequency-dependent beam shaping, and polarization diversity, which are critical for reliable and adaptable communication in dynamic environments [30]. This sub-section delves into the design of multi-port and array THz antennas, highlighting innovations such as phased arrays for beam steering and frequency-scanning arrays for fixed beam designs.

2.2.1 High-gain THz antenna arrays: Beam-steerable phased arrays

Phased array antennas with beam-steerable capabilities at THz frequencies are critical for achieving high data rates, precise radiation steering, and enhanced connectivity required for 6G wireless networks. A notable development in phased array THz antennas is the 0.37–0.41 THz phased-array transmitter utilizing W-band components and an eight-element quadrupler array connected to high-efficiency microstrip antennas built with CMOS technology [31]. The design's scalability, leveraging W-band frequencies, avoids high transmission-line loss at 0.4 THz. This represents one of the first demonstrations of a CMOS-based phased array operating at such high frequencies with a wide bandwidth, highlighting its potential for scalable and efficient THz communications in 6G networks. Another contribution is the 0.14-THz wideband array antenna-in-package (AiP) designed for compatibility with flip-chip technology and integrated transceivers [32]. Utilizing multimode resonance on a low-profile multilayer PCB, this design incorporates multiple resonances from a patch and $\lambda/4$ monopole-type feeder, achieving a simulated impedance bandwidth of 53% with stable radiation performance. A 4 × 4 antenna array demonstrates up to 18.1 dBi gain, 80% radiation efficiency, and over 20 dB cross-polarization discrimination (XPD). Experimental results show a measured −10 dB impedance bandwidth of 31%, making this AiP solution a promising candidate for high-performance 6G applications, balancing wide bandwidth and compact form factor. The development of a phased array solution for ultra-sharp beam forming and high-angular-resolution steering at 0.265 THz represents another breakthrough [33]. This approach reduces the required aperture size for a 1° beamwidth, facilitating implementation with CMOS microelectronic chips. A 98 × 98 antenna element array demonstrates the formation and electronic steering of a THz pencil beam with approximately 1° beamwidth in two dimensions. Using a 1-bit phase-shifting reflective antenna with cross-polarization backscattering, the design achieves precise 0°/180° phase inversion and maintains performance despite quantization errors. This method effectively reduces sidelobe and squint, supporting monolithic integration for advanced THz applications. The high-angular-resolution steering and ultra-sharp beam forming capabilities make this design highly suitable for precise and high-capacity 6G wireless systems. Additionally, a 0.28-THz phased array transmitter featuring an integrated silicon-based antenna offers another innovative solution for THz applications [34]. Developed using a 65-nm CMOS process, this transmitter achieves a peak EIRP of 9.3 dBm with a 3-dB bandwidth of 20 GHz. The design integrates a 4 × 4 phased array, employing phase shifters and power amplifiers to enhance beam steering and signal amplification. The antenna array demonstrates a beam-steering range of ±30°, with measured results closely aligning with simulations. A promising approach for THz photonic circuits involves micro-scale silicon photonic crystal waveguides enhanced by monolithically integrated gradient-index (GRIN) optics [35]. Integrating gradient-index (GRIN) optics with silicon photonic crystal waveguides, recent research presents two innovative devices: a Luneburg lens-based multi-beam antenna and a Maxwell fisheye lens-based slab-mode beam launcher [36]. These lenses show great potential for THz antennas, multiplexers, and power-combining devices. Furthermore, a seven-port multi-beam antenna, implemented with a GRIN Luneburg lens coupled to an array of photonic crystal waveguides, demonstrates significant potential for dense communication networks and directionally aware short-range radar.

2.2.2 High-gain THz antenna arrays: Fixed and frequency-dependent beam angles

THz antenna arrays designed for fixed beams or with frequency-dependent beam angles are crucial for high-gain applications in 6G wireless networks, offering robust performance without the complexity of active phase shifting or beam steering mechanisms. This sub-section reviews recent advancements in such antenna arrays, emphasizing their fabrication techniques, gain characteristics, and potential for 6G applications. A significant advancement in high-gain THz antennas is the development of high-gain antennas with broad bandwidth for the 0.12 THz band, fabricated by diffusion bonding of laminated thin copper plates [37]. This approach offers high precision and low loss at high frequencies. The design includes a double-layer feeding structure ensuring stable fabrication. A 32 × 32-element array antenna achieves a 38 dBi gain with 60% efficiency over a 0.015 THz bandwidth (0.119–0.134 THz), while a 64 × 64-element array achieves a 43 dBi gain with 50% efficiency over a 0.0145 THz bandwidth (0.1185–0.133 THz). These low-profile antennas could serve as alternatives to conventional high-gain antennas like reflector and lens antennas, making them suitable for 6G applications that require high efficiency and compact design. Innovative design techniques for terahertz antenna-in-package (AiP) systems have been proposed to address challenges in integration, fabrication, and measurement of multilayer PCB-based antenna arrays [38]. Key innovations include a wideband dual-polarized stub-loaded proximity-coupled stacked patch antenna and a compact vertical power divider. These solutions were validated through circuit analysis and demonstrated with a 4 × 1 subarray, paving the way for an 8 × 8 AiP for future 6G communications. The stub-loaded antenna enhances bandwidth using open and short stubs *via* transitions, while the vertical power divider simplifies the feeding network. Measurement of the 8 × 8 antenna array package showed a boresight gain exceeding 17.1 dBi across the 0.136–0.148 THz bandwidth, highlighting its potential for robust and efficient 6G communication systems. Another significant contribution is the development of frequency scanning slot arrays operating from 0.13 to 0.18 THz, micro-fabricated using the PolyStrata sequential copper deposition process [39]. The voltage standing wave ratio is less than 1.75:1 over the entire range, with measured scanning of 0.00104 THz from 0.13 to 0.15 THz and 32.5° over the full range. A 10-element array achieves a gain of 15.5 dBi at 0.15 THz, and a 20-element array achieves 18.9 dBi at 0.15 THz, with about 3 dB variation over the scan range. The results align with HFSS full-wave simulations, demonstrating effective beam scanning and gain performance. These slot arrays are well-suited for applications requiring high-gain and frequency-dependent beam angles in the THz range. A novel architecture for a sub-THz antenna-in-package (AiP) enhances isolation between ports in a dual-polarized stacked patch antenna [40]. It integrates orthogonal fan-out lines from a vertical *via* for probe feeding, augmented with grounded shielding structures. This design achieves up to 10 dB isolation improvement per polarization. Validation through simulations and measurements of a 4 × 1 subarray shows an S21 value of −20 dB at 0.145 THz, with a measured S11 bandwidth exceeding 0.01 THz and return loss of 10 dB. The proposed structure enhances AiP performance for sub-THz applications, ensuring stable communication systems with improved port isolation, essential for high-performance 6G networks. The design and development of a novel frequency beam-scanning array antenna operating in the Y-band (0.22–0.325 THz) represent another innovative approach [41]. The antenna features a traveling-wave structure with a meandered rectangular waveguide and a slot-coupled cavity-backed patch array for elevation. It achieves a narrow beamwidth of ~2.5° and ± 25° beam steering from 0.23 to 0.245 THz, with a 10° elevation beamwidth. The array, consisting of over 600 patch elements, provides a gain of over 29 dBi and radiation efficiency above 55%, all within a compact 45 mm × 8.5 mm × 1.25 mm, 4.5 g structure. Fabricated using silicon micromachining, the prototype demonstrates a measured scanning range of over 48° and gain over 28.5 dBi, aligning well with simulations. This design is ideal for low-mass, compact Y-band radar applications, offering high gain and precise beam control. A corporate-feed slotted waveguide

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array antenna for the 0.35-THz band has been designed and fabricated using the DRIE process to achieve high fabrication accuracy [42]. The thin laminated plates forming the antenna were etched with tolerances lower than ±5 μm and bonded using diffusion bonding. The gold-plated silicon wafer showed an effective conductivity of 1.6×10^7 S/m and a loss per unit length of 1.1 dB/cm. The 16 × 16 element array antenna demonstrated a gain of 29.5 dBi at 0.35 THz, with a 3-dB bandwidth of 0.0508 THz in simulations and 0.0446 THz in measurements. This is the first demonstration of a broadband antenna in this frequency band, suitable for applications such as short-range broadband wireless communication, highlighting its potential for high-frequency, high-gain 6G networks.

2.2.3 Summary and comparison

Table 4 provides a comprehensive overview of advancements in multi-port and array THz antennas, highlighting their diverse fabrication methods, frequency ranges, and unique characteristics tailored for 6G applications. CMOS-based phased-array transmitters offer scalability and low loss with wide bandwidths, while AiP solutions utilizing multimode resonance provide high gain and wide impedance bandwidth. Ultra-sharp beamforming antennas and integrated silicon-based phased arrays enhance angular resolution and beam control. GRIN optics-based antennas are suited for multi-beam applications, while laminated copper plate antennas excel in compact, high-precision designs. Frequency-scan slot arrays and stub-loaded AiP antennas cater to frequency-dependent beam steering, and novel sub-THz AiP and meandered waveguide antennas offer compact, high-gain solutions. Corporate-feed slotted waveguide arrays provide high accuracy and broadband performance. These designs reflect the diverse approaches to meeting the advanced requirements of emerging 6G networks.

2.2.4 Simulation and design details of phased array THz antenna

This sub-section explores the characteristics of a linear phased array designed to provide high gain and steerable radiation patterns, tailored to meet the demands of upcoming 6G networks. **Figure 6** displays the configuration of an 8-element array, arranged in a 1 × 8 layout with an element spacing of d = 80 μm. The array features a schematic with eight modified dipole elements arranged in a 1 × 8 linear format with overall dimension of $W_a \times L_a = 480 \times 70\ \mu m^2$. To improve the radiation efficiency of the dipole resonators, rectangular directors are strategically placed adjacent to each resonator. These compact resonators utilize microstrip-line feeds, optimizing their design.

The S-parameter results (S_{nn}/S_{n1}) for this array are shown in **Figure 5**, highlighting its operational coverage from 1.9 to 2.1 THz, encompassing critical frequencies within the emerging 6G and beyond spectrum. The results illustrate that the resonators exhibit low mutual coupling, consistently below −12 dB across the entire bandwidth. When evaluating the gain levels, as shown in **Figure 7(a)**, the single antenna achieves a gain ranging from 4.5 to 5.5 dBi. In contrast, the linear array shows significantly higher gain levels, varying between 12.5 and 14.5 dBi. Notably, the array exhibits a clear trend of increasing gain as the operating frequency rises, which highlights the array's capability to enhance performance at higher frequencies. This gain improvement, coupled with the consistent end-fire radiation, underscores the array's suitability for high-frequency THz applications, offering robust signal strength and wide-area coverage necessary for next-generation systems.

References	Type of antenna	Fabrication method	Frequency (THz)	Main characteristic
[31]	CMOS-based phased-array transmitter	CMOS technology	0.370–0.410	Scalability, wide bandwidth, low transmission-line loss
[32]	AiP with multimode	Flip-chip, multilayer PCB	0.140	High gain, wide bandwidth (53%)
[33]	Ultra-sharp beamforming	CMOS microelectronic chips	0.265	High-angular-resolution, sharp beam forming, reduced sidelobe/ squint
[34]	Integrated silicon-based antenna	65-nm CMOS process	0.280	Peak EIRP, ±30° beam-steering, amplification
[35]	GRIN optics-based	integration of gradient-index (GRIN) optics	Various (THz range)	Multi-beam formation, potential for dense and radar applications
[36]	Laminated copper plates	Diffusion bonding of laminated thin copper plates	0.119–0.134	High precision, low-loss, high gain up to 43 dBi, compact design
[37]	Stub-loaded AiP antenna	multilayer PCB, compact divider	0.136–0.148	Improved port isolation, wide bandwidth, high gain
[38]	Frequency-scan slot array	PolyStrata sequential copper deposition	0.130–0.180	Effective scanning, high gain, compact and efficient design
[39]	Sub-THz AiP with enhanced isolation	Stacked antenna orthogonal fan-out and shielding	0.145	Improved isolation, stable performance, robust for sub-THz
[40]	Meandered rectangular waveguide	slot-coupled cavity-backed array	0.230–0.245	High gain, low mass, compact for radar applications
[41]	Corporate-feed slotted waveguide	DRIE process, laminated thin copper plates	0.350	High fabrication accuracy, broadband performance, high gain
[42]	Frequency-scan slot array	PolyStrata sequential copper deposition	0.130–0.180	Efficient beam scanning, High gain, suitable for frequency-dependent beam angle applications

Table 4.
Summary of the discussed THz array antennas.

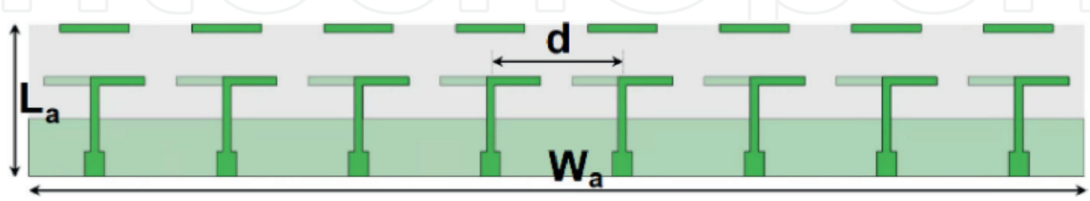

Figure 6.
Schematic of the designed THz phased array.

Moreover, the antenna resonators maintain high total efficiencies across their operational band, as evidenced in **Figure 7(b)**, which is crucial for maximizing signal strength and minimizing losses in high-frequency THz applications. These characteristics, wide bandwidth, low mutual coupling, and high efficiency, demonstrate the array's potential for point-to-point communications. **Figure 8** demonstrates the

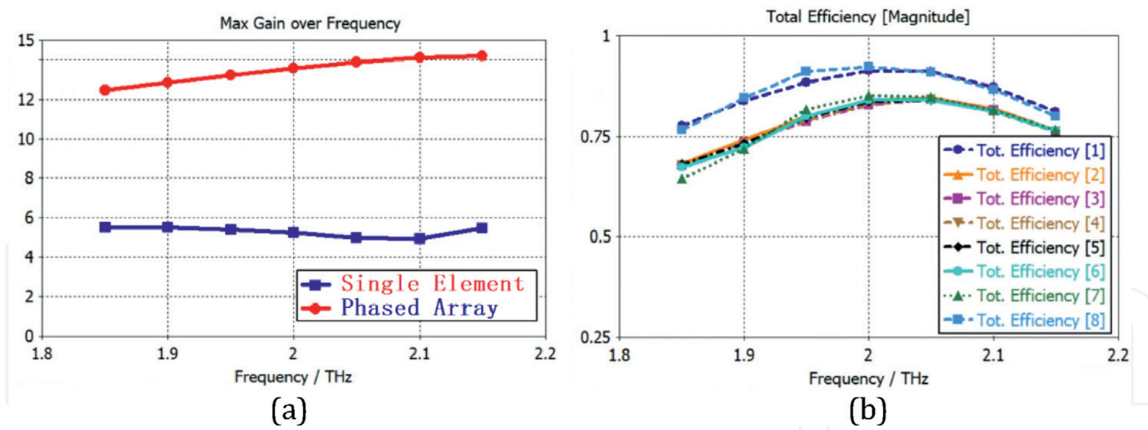

Figure 7.
(a) Gain level comparison and (b) total efficiency results.

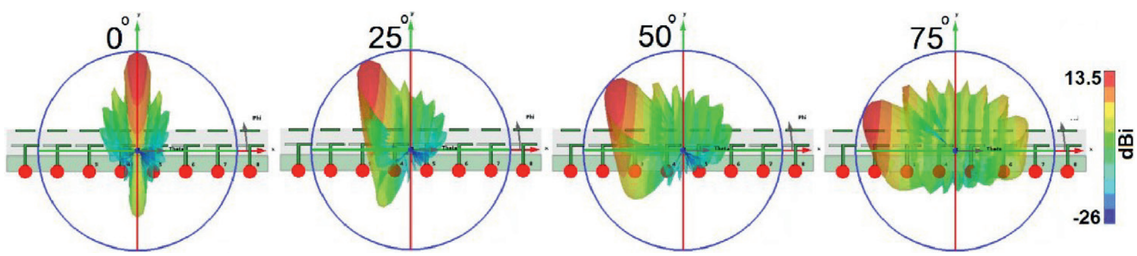

Figure 8.
3D beam-scanning at different scanning degrees (0 ~ 75).

beam-steering capabilities of the proposed array at the mid-frequency of 2 THz, showcasing a wide scanning range. This feature significantly enhances the array's versatility and adaptability for various communication scenarios [43]. Additionally, the antenna resonators exhibit high gain across multiple scanning angles from 0 to 60 degrees.

3. Conclusion

The review of THz antennas for future 5G and 6G networks highlights substantial advancements in design, materials, and integration techniques, addressing the unique challenges of terahertz frequencies. As the demand for ultra-high data rates, minimal latency, and improved spectral efficiency grows, THz antennas have emerged as key enablers, offering extensive bandwidth within the 0.1–10 THz range. Their diverse configurations—including single-port microstrip designs, 3D/non-planar structures, on-chip solutions, and multi-port arrays—demonstrate ongoing innovation tailored to next-generation wireless communication systems [44].

Microstrip antennas, valued for their compactness and integration potential, have been enhanced with advanced materials such as graphene and liquid crystal-line polymers, reducing signal losses and improving efficiency. In parallel, 3D and non-planar structures, such as dielectric rod waveguides and corrugated horn antennas, provide high gain and directivity, making them ideal for THz imaging, sensing, and radar applications. On-chip antennas, leveraging CMOS and other silicon-based technologies, support miniaturized, high-performance, and cost-effective THz systems. Additionally, packaging techniques, including quad-flat no-lead (QFN) solutions and dielectric substrates, are improving performance and facilitating mass production. Multi-port and array THz antennas play a crucial role in high-capacity, high-speed 6G communication networks. These designs utilize array configurations and multi-port architectures to enhance gain, beam control, and polarization diversity, enabling applications such as wireless backhaul, radar, and advanced sensing. Phased-array antennas facilitate precise beam steering with high angular resolution, while frequency-dependent beam-scanning arrays offer high-gain solutions without complex active phase shifting. The continuous development of materials, micromachining techniques, and innovative feed structures is driving the next generation of THz antenna solutions. In addition to reviewing existing advancements, this chapter also explored the simulation and design of both single-element and array THz antennas, providing practical insights into their performance and implementation challenges. These simulations demonstrated key trade-offs between gain, bandwidth, efficiency, and integration, offering valuable perspectives on optimizing antenna designs for real-world applications. The design examples illustrated how different approaches—ranging from individual radiating elements to complex phased arrays—can be tailored to meet the stringent requirements of 6G systems, further emphasizing the critical role of THz antennas in future networks.

Despite these advancements, challenges remain, particularly in precision fabrication, material losses at THz frequencies, and seamless integration with existing communication systems. Designing compact, high-frequency antennas with efficient beam control and high radiation efficiency continues to be a focal area of research. Looking ahead, THz antennas will play a transformative role in shaping the future of 6G technology. With ongoing innovations in materials, fabrication techniques, and integration strategies, scalable and high-performance antenna solutions will become increasingly viable. These advancements will not only enable ultra-fast data transmission and low-latency communication but will also support emerging applications in high-resolution sensing, imaging, and next-generation radar systems. As research progresses, the focus will be on achieving seamless system integration, improved efficiency, and enhanced reliability, ensuring that THz antennas unlock the full potential of 6G networks across diverse real-world applications [45].

Author details

Haleh Jahanbakhsh Basherlou[1], Martins Odiamenhi[1], Naser Ojaroudi Parchin[1*], Chan Hwang See[1] and Ming Shen[2]

1 School of Computing, Engineering and the Built Environment, Edinburgh Napier University, Edinburgh, UK

2 Department of Electronic Systems, Aalborg University, Aalborg, Denmark

*Address all correspondence to: n.ojaroudiparchin@napier.ac.uk

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