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Terahertz Antennas for Next-Generation Wireless Communication Systems: Advances, Challenges, Emerging Applications and Future Directions

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ABSTRACT

Due to the growing number of users, wireless communication has seen a considerable growth in data traffic exchange and the need for faster wireless networking in recent years. Within the next ten years, wireless data speeds are anticipated to reach 10 Gbps or more. With the spectrum's currently licensed bands, such high data rates are unlikely to be realized. Thus, it is evident that using greater bandwidth with cutting-edge technology is the only way to attain such high speeds. Given its enormous bandwidth (up to 100 GHz), massive data throughput (up to 1 Tbps), low latency and ability to enable a vast number of applications across a wide range of domains, the Terahertz (THz) band (0.1-10 THz) is regarded as one of the most potential choices for next-generation wireless networks. THz antennas play a central role in realizing these capabilities, yet their design and deployment face numerous challenges. A significant advancement in wireless communication, particularly in the Internet of Things (IoT) sector, can be seen through the incorporation of THz technology into 6th generation (6G) systems. The THz spectrum is essential for applications including streaming high-definition (HD) video, IoT security systems, and medical equipment. An overview of the recent advancements in THz communications research and the aspects of THz antennas for upcoming wireless communication is presented in this article, including target applications, and significant research issues. The paper also examines the current difficulties encountered in the development and utilization of THz antennas alongside potential solutions. Finally, future research prospects in the field are described, emphasizing the necessity for energy-efficient architectures, advanced materials, machine learning-based channel modeling, and seamless integration with existing networks.

***Keywords**: Terahertz Band, 6G Systems, THz Antennas, IoT, HD Video, Machine Learning.*

Introduction

The sixth generation (6G) aims to further enhance the features of the fifth generation (5G) technology since it can accomplish high-speed data rates, exceptionally low latency, incredibly reliable communication, and massive connectivity. The uplink speed of 5G is only 10 Gbps, but the downlink speed is 20 Gbps [1-2]. For rapidly growing applications like ultra-wideband THz space communication, secure high-speed short-range indoor communication, and the Internet of things (IoT), 5G technology in the millimeter-wave band will not be sufficient in the near future to meet the enormous demand for terabits/sec (Tbps) of data rate and large channel capacity. 6G technology is a potential future option to address the shortcomings of 5G [3]. The interconnection of everything (IoE), intelligent automation, and the capacity to support data rates approaching terabits per second with exceptionally low latency and excellent reliability are just a few of the anticipated benefits of its enhanced connectivity [4]. This is essentially achieved by exploiting the enormous potential offered by the Terahertz (THz) band. Even though the infrared and microwave/mmWaves bands above and below the THz band have been well studied in the past, the THz band remains one of the least studied areas of the electromagnetic spectrum. A potential solution to improve the channel capacity and transmission rate is to increase the carrier frequencies from millimetre wave to THz. Figure 1 displays the THz spectrum. This far-infrared region is important because it contains spectrographic imprints from a wide variety of physical and chemical processes. Examining the 300 GHz-30 THz band spectrum makes relevant given the recent success of mm-wave communications. Previously used only for image and sensing applications, the THz spectrum is now expected to play a bigger role in wireless communications in the future due to advancements in THz devices and the spectrum's noteworthy features [5]. For a number of applications, terahertz antennas are necessary for both sending and receiving terahertz signals. Because of the extremely short wavelength at THz frequencies, they are usually small and can be integrated into on-chip and miniaturized devices. Ultra-fast communication links are made possible by THz antennas' broad bandwidth and exceptionally high data transfer capacity. Although efficiency is frequently hampered by significant propagation and material losses at these frequencies, they can attain great directivity and gain. To improve its performance, reconfigurability, tunability, advanced materials including graphene, photonic crystals, and metamaterials are commonly used. At THz frequencies, antenna arrays can enhance directivity, gain, and overall performance. Nevertheless, there are a few major limitations and challenges, like the measurement techniques and the construction of THz antennas [6]. Furthermore, choosing the right substrates and materials is essential for THz antenna design since different materials might affect an antenna's performance [7].One of the disadvantages of its use is the high level of molecular absorption loss caused by the absorptive resonance of some molecules in the propagation environment [8]. Furthermore, in order to maintain an appropriate communication range, extremely directional antennas must be used due to the inherent substantial free space loss and power limitation at THz frequencies. 6G requires high-gain antenna arrays and Multiple-Input Multiple-Output (MIMO) antennas to mitigate the effects of atmospheric losses at high frequencies. THz waves' highly directed behaviour makes them perfect for short-range, high-speed wireless communications. In situations involving both indoor and outdoor communication, MIMO and THz-range technologies are especially crucial. In urban rich multipath situations, MIMO achieves diversity and significantly increases spectral efficiency. MIMO technology transmits and receives data simultaneously using multiple antennas. MIMO systems improve communication performance by increasing data throughput and reliability without requiring more bandwidth or transmission power. Furthermore, mutual coupling is evident in the proximity of the ports due to the antenna's miniaturization [9], which negatively affects the antenna's overall performance in terms of decreased radiation efficiency, channel capacity, and diversity gain. Therefore, orthogonal polarization, neutralization lines, periodic structures, defective ground structures (DGS), and metamaterials can all be used to improve the isolation [10-13]. Previous studies have investigated THz antennas, antenna arrays, and MIMO antennas on a variety of conducting materials, like copper and graphene. For 6G, Internet of Things (IoT), and high-speed wireless communication systems, graphene is used to create compact, tunable, and efficient THz antennas because of its distinctive properties, such as strength, flexibility, tunable conductivity, high carrier mobility, wide tuning range, and the capacity to support surface plasmon polaritons at THz frequencies [14]. Several dielectric substrates, such as polyimide, quartz, liquid crystalline polymer, and polytetrafluoroethylene, are used to develop these antennas. THz communications rely significantly on THz beamforming, metamaterial, photoconductive, and plasmonic antennas. IoT, communication systems, spectroscopy, biological imaging, sensing, security screening, and military applications are among their applications, where high resolution, compactness, and wideband operation are crucial [15]. For next-generation THz MIMO systems, a high-gain small dual-band MIMO antenna with exceptional isolation and efficiency is designed and optimized using RLC modelling and machine learning (ML) techniques [16].

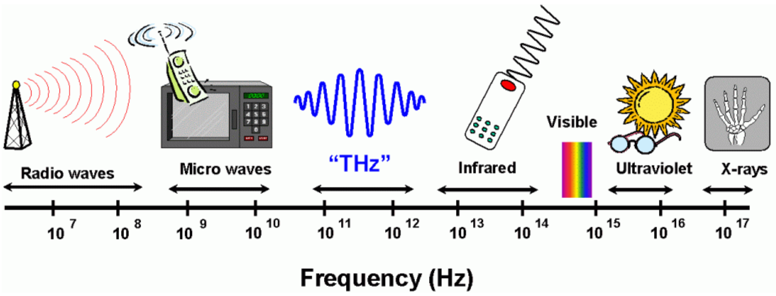

Fig. 1: THz band in the electromagnetic spectrum [17]

Features of the THz spectrum

Between the microwave and infrared bands, the Terahertz (THz) spectrum (0.1–10 THz) has unique properties that make it very appealing for scientific and technological usage. Compared to X-rays, THz waves are non-ionizing and have a very low photon energy of about 4 meV at 1 THz [18]. Therefore, it has a minor ionisation effect on biological tissues and other materials, making them appropriate for spectroscopy, security screening, and medical imaging [19, 20]. Ceramics, textiles, plastics, paper, wood, and a wide range of other materials can all be penetrated by them [21]. Therefore, it is possible to identify potentially hazardous substances using THz spectroscopy [22, 23]. Because the photon energy of THz radiation is similar to the excitation energy of the rotational transitions in molecules, the terahertz spectrum provides information about molecular vibration and rotation, allowing for extremely precise material characterization and chemical detection. Compared to the microwave region of the spectrum, this band offers a higher resolution. The terahertz spectrum has a limited dispersion compared to light waves. The propagation distance of THz waves in the atmosphere is limited due to their significant absorption by water molecules. The THz spectrum is notable for its high resolution, wide bandwidth, and special material interaction capabilities, which present promising prospects for communications, imaging, and sensing technologies despite its drawbacks, which include high atmospheric attenuation, limited power generation, and low detection sensitivity.

Technical challenges with THz communication

Despite THz communication's immense potential for ultra-high-speed data transfer rate, a number of technological obstacles prevent it from being used in practice. The THz antenna structures' primary problems are their intricate design, higher production costs, larger size, and difficult integration with planar circuits. Because of their many advantages, including as their affordability, portability, ease of manufacture, and tiny size, microstrip antennas have become more and more popular for terahertz short-range wireless applications. However, its narrow bandwidth limits its application in the wide THz range. Using photonic crystal structures, photonic crystal-based frequency selective surfaces, and electromagnetic crystal substrates, researchers have suggested several design approaches to enhance the bandwidth of the microstrip antenna in the THz regime. Wideband single element THz antennas suffer from fading in high-speed, short-range wireless applications. Using MIMO technology is an easy way to solve this issue. Surface treatment, micro assembling, precision machining, and thickness reduction of quartz substrates are the main techniques used in the development of THz devices. These techniques are constrained by the devices' small size, high accuracy requirements, and sensitivity to machining errors. It is challenging to construct precise THz devices and antennas with good efficiency due to nanoscale fabrication restrictions. The tolerance analysis of each dimension should be emphasized from the perspective of the simulation results in order to ensure the exceptional performance of the THz hardware circuits. Reliable communications necessitate highly directed antennas and sophisticated beamforming algorithms due to substantial route loss and material penetration loss, which further diminish signal strength [24]. THz signals are impacted by high molecular absorption and free-space path loss, particularly in the presence of oxygen and water vapor molecules. These signals need precise channel modelling due to their high sensitivity to obstacles. Compactness without performance deterioration is crucial for the practical utilization of THz devices. Efficient methods are necessary for fast and accurate channel estimation in order to provide reliable communication networks. Conventional metals are not suitable in the THz range due to the decrease in conductivity and skin depth. Nonetheless, graphene's inherent high conductivity may be tuned, which makes it a desirable material for THz miniaturized and reconfigurable antennas [7, 25, 26]. Unless assisted by spectrally effective modulation techniques, beam steering, high-gain lens-integrated leaky-wave antennas, intelligent beamforming, and powerful optoelectronic transmitters, THz waves are best suited for short-range communication [27]. Designing effective THz sources and detectors is challenging. While optical devices require costly photonic technologies, conventional electronic devices are limited in speed. A metallic bull's-eye plasmonic antenna is integrated into a nonlinear THz detection system that is presented in [28]. Compact, alignment-tolerant, and extremely sensitive THz detectors are made possible by the design, which makes them very beneficial for wireless communication applications. In order to overcome these difficulties and enhance the resilience and effectiveness of THz antennas, research and development efforts are required. beam alignment techniques. Addressing these issues, improving performance, and making deployment easier are the goals of ongoing research and developments in this area.Addressing these issues, improving performance, and making deployment easier are the goals of ongoing research and developments in this area.

Recent advancements in the development of THz antennas

In order to fully realise the potential of THz communication in 6G and beyond, researchers are addressing the aforementioned technological obstacles through advancements in materials (such as graphene and metamaterials), device engineering, and signal processing. To reduce path loss and increase coverage, reconfigurable intelligent surfaces (RIS) are being developed to dynamically control and redirect THz signals. By utilising optical technologies for effective signal processing, photonic-assisted THz generation and detection offer a viable solution for bridging the THz gap. In order to create tunable, compact, and high-performing THz antennas and transceivers, advancements have been made in photonic and graphene-based THz devices as well as other 2D materials. As additive manufacturing (AM) and 3D printing (3DP) technologies continue to progress, it is now possible to manufacture antennas with complicated designs with ease, high precision, and reasonable cost. These technologies provide emerging THz applications with a reliable and economical solution. Companies including Huawei, Samsung, and NEC have demonstrated THz communication prototypes integrated into 6G testbeds. THz antenna developments that have been observed to improve beamforming and gain include metasurfaces and lens-based designs. THz spectrum policies and regulations are being actively influenced by international 6G initiatives as well as the International Telecommunication Union’s (ITU) contributions. Spectrum allocation and regulation have been advanced by the European Telecommunications Standards Institute (ETSI) and the Federal Communications Commission (FCC). The preliminary spectrum allocation and IEEE 802.15.3d standard have been developed by the FCC and ITU. To improve system performance in complex propagation environments, forecast channel conditions, and optimize beam alignment, machine learning-based channel modelling and resource allocation are being used. Machine learning regression approaches are the most effective way to build and optimize antenna performance since they are faster than numerically solving a physical simulation model. For dynamic THz wireless applications, a graphene-silicon-based two-port array antenna with good gain performance and circular polarization allows for frequency reconfigurability [25].

Table 1: Comparative study of various THz antenna designs

Ref.	Antenna Design	Key characteristics	Technology/ materials used	Applications	Challenges
[14]	**THz MIMO antenna**	Compact size, multiband operation	Graphene, machine learning technique	6G wireless communication, indoor THz links	fabrication challenges, bandwidth limitations
[25]	**Graphene-silicon based array antenna**	Circular polarization	Hybrid radiator, frequency reconfigurability by varying the chemical potential of graphene	THz wireless communications, MIMO applications	Moderate gain, fabrication precision required
[29]	**Dielectric resonator antenna (DRA)**	High-gain directional pattern, dual-band operation	Coplanar waveguide (CPW) feeding	spectroscopy or photonics applications	Moderate efficiency, dielectric losses, fabrication tolerances
[30]	**Decagonal patch antenna**	decagonal patch with graphene strip	Polyimide substrate, hybrid patch	medical THz sensing and imaging (breast cancer detection)	Material losses, thermal effects
[31]	**High-gain planar arrays**	high gain and narrow beams to compensate path loss, simple feeder structure, low manufacturing cost, wide bandwidth	Substrate Integrated Waveguide (SIW)	Tb/s short-range links, THz high-speed communication integrated antenna front-end and system applications	Manufacturing tolerance, mutual coupling
[32]	**Graphene-based plasmonicantenna array**	Compact, high gain	Graphene, Metaheuristic optimisation algorithm to tune design parameters	6G THz communications, Short-range high capacity THz wireless links	Material losses, fabrication tolerances, bandwidth constraints, power handling

[33]	**ML-based MIMO antenna**	Very compact	Graphene, RLC equivalent circuit modeling, Machine learning regression models	6G THz wireless communication, especially MIMO systems, indoor or line-of-sight THz links, miniaturized devices	Trade-offs among bandwidth, gain, and isolation, design complexity
[34]	**CMOS-compatible on-chip antennas**	emphasis on compactness and integration rather than peak efficiency	CMOS substrate plus metal layers, dielectric interlayers	On-chip THz detector and source systems, 6G THz links, IoT modules	Fabrication tolerances in CMOS, Integration issues

In sub-THz frequencies that are appropriate for imaging and sensing, a latest stacked planar antenna array showed excellent performance, highlighting high gain and design efficiency [29]. From dipoles and MIMO designs to antipodal Vivaldi structures that provide dynamic control over frequency, polarization, and radiation patterns, graphene makes it possible to create intelligent, reconfigurable THz antennas [35]. THz communication is anticipated to play a significant role in enabling 6G and beyond with these developments, enabling extremely fast, high capacity, and secure wireless networks, appropriate for imaging and sensing, with a focus on high gain and design efficiency [29]. Table 1 provides a comprehensive overview of various THz antenna designs.

Terahertz Antennas Applications

There are numerous applications for terahertz (THz) technology in imaging and sensing. Because metasurface-based THz sensors provide non-destructive imaging of a range of objects, they are suitable for material assessment, security, and medical applications [36]. Several Terabits per second (Tbps) of transmission speeds could be achieved using THz spectrum for applications like autonomous cars, 5G/6G networks, and HD holographic video conferencing. In order to meet the Quality of Experience (QoE) requirements of new cellular systems, including wireless virtual reality, terahertz frequencies are necessary for offering high-rate, high-reliability, low-latency communications. For greater reliability, a large amount of bandwidth and line of sight are needed [37]. Numerous fields, such as biomedicine [19, 38-40], agriculture and food production [41-42], safety surveillance [43], and many more [44-46], show great promise for THz radiation applications. THz antennas are used in industrial settings for material characterization, explosive and weapon detection, and high-speed, short-range indoor wireless communication. Furthermore, THz antennas are useful in biological applications for monitoring blood flow and tissue water levels, which aids in medical imaging, cancer diagnosis, and pharmaceutical research. These antennas are made to satisfy the specific needs of the industrial and biomedical sectors. They have features like high bandwidth, high gain, and circular polarized radiations. The variety of uses for THz antennas demonstrates their adaptability and significance to the advancement of science and medicine.

To detect breast cancer via dielectric contrast, a decagonal patch antenna tuned for THz frequencies is made of graphene [30]. A planar antenna array that performs well in the sub-THz region for imaging and sensing applications is studied in [47]. Because of their high bandwidth and fast transmission rates, terahertz (THz) frequencies are desirable choices for use in wireless communication systems, like 6G technology [48].

Future Directions

Numerous fields of study and advancements in THz antenna usage are being addressed by future directions. Applications such as smart cities and driverless automobiles require the convergence of sensing and communication. AI-driven algorithms for channel estimation, interference management, and real-time resource allocation ought to be encouraged. Quantum effects should be studied to improve signal processing and THz production. THz integrated circuits that are scalable and energy-efficient must be considered for devices that are smaller and less expensive. In non-line-of-sight (NLOS) scenarios, programmable metasurfaces are required to increase coverage and compensate for route loss. Massive MIMO systems with powerful, highly directed beam forming are required, especially for THz frequencies. Innovation in THz components' manufacture is required to make them affordable for mass-market use. It is advised to leverage the highly directed properties of THz beams for secure communication while addressing drawbacks like jamming and eavesdropping. Promoting collaboration amongst the ITU, ETSI, and 3GPP is necessary to establish uniform guidelines for THz spectrum distribution.

Conclusion

Terahertz (THz) communications represent a promising frontier in wireless technology, in keeping with the vision of 6G networks and beyond. They can address the constantly growing demand for ultra-low latency, dense device connections, and faster data speeds. Despite its revolutionary potential, THz communication is still in its infancy and confronts numerous technological and practical challenges. Significant progress has been made in its development and application by the scientific community, industry, and standardisation organisations. THz communication could advance from a laboratory-scale invention to a crucial technology for the creation of ultra-high-speed, pervasive wireless networks in the future with collaboration between researchers, industry, and policymakers.

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