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Antenna Selection and Designing for THz Applications: Suitability and Performance Evaluation: A Survey

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ABSTRACT Imperceptible latency, uninterrupted communication, and the availability of inexhaustible bandwidth are conceptualized as essential milestones to revolutionize the modes by which societies generated, circulate, receive, and perceive information. The exponential increase in wireless data traffic has raised concerns to investigate suitable bands in the radio spectrum to satisfy the intensifying user's data rate requirements. Overall the wireless infrastructure needs development and exploitation to synchronize with the massive capacity and connectivity demands. The Terahertz (THz) frequency band (0.1-10 THz) is considered as a pivotal solution to fulfill the needs of applications and devices requiring the high speed transmission, and have received noticeable attention from the research community. Technologies in this spectrum are facing rapid development and hold high potentials in applications like ultra-fast short-range wireless communications, remote sensing, biological detection, and basic material research. The antenna is one of the critical components to support the THz systems and require a considerable attention in terms of precision. Compact high-gain antennas are desirable for low latency and high data rate THz wireless communication systems, specifically for applications having space limitation, for example, in the high speed interlink inside the high density wireless communication base station (BS). Nevertheless, there still exist many challenges, while designing the antenna for THz communications requiring innovative solutions. This paper serves an introductory guideline to address the challenges and opportunities, while designing a THz enabled antenna.

INDEX TERMS THz antennas, material, antenna, large array THz, on chip antennas, mmWave, antenna array, beamformer, THz beamformer, THz communication.

I. INTRODUCTION

Globally, augmented and virtual reality traffic will grow nearly 12-fold from 22 petabytes per month in 2017, to 254 petabytes per month in 2022 [1]. This transition persuades an exponential growth in the demand for high data rates, requiring increased bandwidth, which is approaching its maximum capacity limits. The use of multimedia services is expeditiously gaining popularity in modern wireless communication due to rapid progress in handheld smart terminals [2], [3]. The number of users of wireless networks is dramatically increasing, and currently, 23 billion devices are connected to the internet, and these numbers are expected to increase to 75 billion by 2025 [4], [5]. Moreover, users are consuming more digital information with mobile devices, while comparing to a stationary personal computer connected to a wired network. Nevertheless, the current communication technology is not sufficient to meet the exploding data rate requirements of an ultra-high bandwidth communication network [6]. Such shortcomings have driven the urge to investigate suitable regions in the radio spectrum to satisfy user's expediting demands. The future ultra-fast communication

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systems target terabits per second (Tbps) data rate. However, the communication systems operating at and below 60 gigahertz (GHz) are unable to provide such communication links. To this end, terahertz (THz) frequency band in the range of 0.1-10 THz gained considerable attention in providing a communication link of Tbps speed.

The IEEE 802.15 in 2008 established a THz interest group to standardize the THz communication over the frequency band ranging between 275-3000 GHz [7]. In 2014, the task group 3d (TG3d) was formed to revise 802.15.3 metrics to achieve 100 gigabits per second (Gbps) data rate. The THz spectrum provides much larger bandwidth, i.e., 1 Tbps that can satisfy the beyond 5G (B5G) requirements (providing very high data rate, extremely low latency and ultra-high reliability [8]), as compared to a millimeter-wave (mmWave) system, which offers a 10 Gbps link [9]. The THz signal propagation offers higher directionality and ensures higher security from eavesdroppers [10]. Moreover, the THz frequencies have some advantages over the optical frequencies by supporting the non-line-of-sight (NLoS) communication. The NLoS propagation over the THz band is beneficial even under inappropriate weather conditions [11]. In addition to this, the THz frequencies show a resistive behavior towards the noise originating from optical sources [12].

Practical applications in THz domain include internet-of-nano-things (IoNT), on-chip communication, remote sensing, biological detection, software-defined meta-materials (SDM), in/on-body networks, military defense applications, information shower, THz local area network (T-LAN), THz wireless personal area networks (T-WPAN), THz wireless LAN (T-WLAN), and secure wireless communication. Even with the rapid technological advancements in innovative transceiver architectures, antennas, channel models, materials, medium access control (MAC), and physical layer schemes, there still exist many research challenges that need to be addressed to achieve Tbps data rate. Among these, antenna designing and material selection (for THz-enabled antennas) for THz communication are the least explored areas. High precision in antennas is considered to be a critical component of any communication system, whereas using a suitable material to build up the same plays a key role in achieving such high precision. This paper presents an introductory guideline and state-of-the-art survey on antenna designing and material selection for THz applications.

A. CONTRIBUTIONS OF THIS ARTICLE

This work aims to make the following contributions:

- To provide a detailed summary of the literature on features and characteristics of THz frequency band.
- To survey the various applications of THz band.
- To discuss and compare the types and materials for THz antennas.
- To discuss the design specifications of THz antennas and summarizing the performance metrics.
- To highlight the fabrication and measurement techniques of THz antennas.
- To provide open issues, challenges, and future research directions for the THz antennas.

B. COMPARISON BETWEEN THz AND OTHER WIRELESS TECHNOLOGIES

The traditional cellular communication enabling technologies, i.e. long term evolution (LTE), global system for mobile communication (GSM), etc. provides a maximum data rate of 100 megabits per second (Mbps) while incorporating the high mobility scenarios. However, the IEEE 802.16e (WiMAX) was deployed in some countries in integration with the fourth generation (4G) of cellular communication operating at 2.5-2.7 GHz with a peak data rate of 128 Mbps [13]. The IEEE 802.11 (WiFi) operates on 2.4 GHz band having a peak data rate exceeding 150 Mbps, whereas, the IEEE 802.15 ZigBee operating on, 2.4 GHz, 868 MHz, and 915 MHz bands, respectively, provides a peak data rate of 250 kilobits per second (Kbps). Bluetooth 4.0, which is also known as Bluetooth low energy (BLE), also operates at 2.4 GHz band and delivers a peak data rate of 1 Mbps. The long-range wide area network (LoRaWAN) is operational on 868 MHz, 915 Mhz, and 1 GHz bands, providing a peak data rate of 50 Kbps. Narrowband IoT (NB-IoT) utilizes a frequency band ranging between 700-900 MHz and can be integrated with LTE, supported by the 3^{rd} generation partnership (3GPP) in Release 13. The peak data rate of NB-IoT is 200 Kbps.

The free space attenuation and the molecular absorption increases as you move towards a higher value in the frequency spectrum. The frequencies lying in the THz band are more prone to water vapor absorption, and while considering a NLoS scenario, the THz waves experience a high reflection loss [14]. The scattering effect in the transmitted waves becomes severe as you decrease their wavelength. However, the frequencies above 10 GHz are more affected by atmospheric losses, i.e. fog, rain, pollution, etc. The THz can be used to achieve a drastic improvement in the data rate. The THz band mainly corresponds to 100 GHz-10 THz with the data rate varying from 10-160 Gbps and supporting a transmission range of 10 meters [15]. The new transceiver and physical layer designs for the THz band are required to increase spectral efficiency and the data rate. Moreover, a detailed approximate comparison of different technologies is shown in Table 1.

C. COMPARISON OF THz COMMUNICATION SURVEY ARTICLES

Mukherjee and Gupta [16] delineates the concept of THz frequency generation techniques and highlights the suitable materials for fabricating THz antennas. The paper outlined the features of the THz band and quantum cascade techniques. However, the article is published in 2008, which lacks the significant literature related to the requirements of 5G and B5G applications. The article emphasizes on frequency

TABLE 1. Comparison between THz and other wireless technologies.

Technology	Frequency Ranges	Transmission Range	Peak Data Rate
Long-Term Evolution (LTE)	1900–2100 MHz	5 kilometers (Km)	100 Mbps
Global System for Mobile Communications (GSM)	460-1000 MHz, 1700-2000 MHz	1-20 Km	1 Mbps
WiMAX (IEEE 802.16)	2.5-2.7 GHz	50 Km	128 Mbps
Wireless Fidelity (WiFi)	2.4 GHz	30 m	150+ Mbps
ZigBee (IEEE 802.15.4)	2.4 Ghz, 868 MHz, 915 MHz	1Km	250 Kbps
Bluetooth Low Energy (BLE)	2.4 GHz	100 m	1 Mbps
Low Power Wide Area Network (LoRaWAN)	868 MHz, 915 Mhz, Sub 1 GHz	10+ Km	50 Kbps
NarrowBand-Internet of Things (NB-IoT)	700-900 MHz	10+ Km	200 Kbps
Millimeter Wave (mmWave) Communication	~24-100 GHz	100+ meters	10 Gbps
Terahertz (THz) Communication	100 GHz-10 THz	10+ meters	10 Gbps to 160 Gbps

generation instead of antenna designing and material selection. Elayan *et al.* [17] presents an up-to-date analysis and review on THz communication architectures. The survey was published in the fourth quarter of 2019, which makes it the most recent. The article covers the THz generation methods, comparison between THz communication over other wireless communication technologies, channel models, and application of THz band.

Huq *et al.* [18] provides a brief survey on THz wireless systems for 5G and B5G. The article is published in the third quarter of 2019. The main focus of the paper is radio access network designs over the THz spectrum. The article outlined the real-life applications and layer-wise research challenges in shaping B5G over the THz band. The paper also presents an overview of standardizing activities for THz wireless communication. Chen *et al.* [19] highlights the substantial hardware research development and challenges in the context of THz high-speed modulators, practical THz channel models, transceiver designs, and efficient beamforming techniques. Ranjan Jha and Singh [20] presents the research challenges imposed by atmospheric losses. The authors pointed out high power sources, efficient detectors, and high gain antennas as a remedy to the losses incurred by the atmosphere. The research paper was published in 2013, and therefore did not include the literature for the current requirements of wireless communication systems.

Akyildiz *et al.* [6] presented a survey on the THz communication regime. The survey paper delves with the discussion on the application domain of THz communication and research challenges related to channel coding, modulation, synchronization, network, transport, and MAC layers. The survey paper was published in 2014. A review of suitable materials for THz technology is presented in [21]. Huang and Wang [22] described the generalized concept of THz communication while discussing the prospective wave propagation models, transmitters, pulse generators, mixers, and oscillators. In [9], the authors defined a road-map for the commissioning THz for wireless communication. The article highlights potential solutions for prospective THz network designs.

All the research work discussed above does not include the discussion from the perspective of antenna designing and material selection. This article provides the introductory guideline for antenna designing with an emphasis on THz spectrum, performance metrics for THz antennas, techniques for fabrication and measurements, and practical used cases of THz spectrum. Table 2 presents a comparison of this paper with other state-of-the-art.

D. ORGANIZATION OF THIS ARTICLE

The rest of the paper is structured as follows; Section II highlights the features and characteristics of the THz band. Afterward, Section III focuses on THz-enabled applications in the context of the future wireless network paradigm. Moreover, it summarizes the opportunities of THz-enabled antennas for various scenarios. Section IV outlines the different types of THz-enabled antennas from the literature. In addition, this section also discusses some potential aspects of different materials used to build a THz antenna. Section V discusses the design parameters needed to construct a THz antenna. The implementation of THz antennas in MIMO and array domain is demonstrated using some examples. Different approaches to measure the performance of a THz-enabled antenna are discussed. Section VI points out some open issues, which restricts the performance of a THz antenna. In the light of these open issues, some key future research directions are pointed out, which are expected to open up new opportunities for the research community. Finally, in Section VII, we have concluded our discussion. The organization of the paper is illustrated in Fig. 1.

II. FEATURES AND CHARACTERISTICS OF TERAHERTZ BAND

The THz band lies between the microwave and infrared waves on the traditional radio spectrum, as shown in Fig. 2. Laser and microwave-based communications are not replaced by THz. However, the THz has some distinct characteristics which enhance the superiority of THz over laser and microwave. Above 275 GHz, the main part of the THz band exists, also known as sub-millimeter (mm) radiations, and has a frequency range between 0.275-10 THz with a wavelength of 0.03 mm-3 mm. The band above 275 GHz has unique characteristics as compared to other radio frequency bands. The main features and characteristics of THz as listed by International Telecommunication Union (ITU) recommendations [23] are as follows:

TABLE 2. Survey papers discussing the THz communication.

Ref.	Year	THz Applications	Antenna Types	Antenna Designing	Material Type and Suitability	Performance Metrics
[6]	2008	✓	x	x	x	x
[9]	2014	x	x	x	x	x
[17]	2019	✓	x	x	x	x
[18]	2019	x	x	x	x	x
[19]	2019	x	x	x	x	x
[20]	2013	x	✓	x	x	x
[16]	2014	✓	x	x	x	x
[21]	2002	x	x	x	x	x
[22]	2011	x	x	x	x	x
This Work	2020	✓	✓	✓	✓	✓

FIGURE 1. Pictorial view of this article.

1) ***Penetration power*** of radio signal above 275 GHz for dielectric materials and non-polar liquids is impressive. Higher penetration power of THz makes it suitable for scanning opaque objects, making it suitable for quality control or safety inspection based applications. The transmission loss of a THz wave in the smoke or dust is very minute as the wavelength of the THz wave is larger than that of a dust particle. Therefore, it can be used for imaging in a smoky environment such as fire rescue fields or deserts.
2) ***The attenuation loss*** of the radio signals above 275 GHz is severe, which can be used in various medical fields for detection and diagnostics. The water content in the tumor tissue is significantly different from normal tissue cells, and THz can be used to locate or detect cancerous cells by analyzing the data related to the water contents of the tissues.
3) ***The photons energy*** of the THz waves is in milli-electron volts (meV) and is significantly lower than the energy in the chemical bonds. Therefore, the ionization reaction cause due to THz waves is very less, that makes it suitable for the detection of biological samples and human body checkup. The THz is less likely to penetrate the human body that makes it favorable for skin disease detection as the water absorption effect is significantly high for THz.
4) The THz waves contain abundant ***spectral information***, including chemical and physical information of the materials. Organic molecules show strong absorption and dispersion properties in this band. Exploiting these spectral properties, THz can be used for identifying the characteristics, features, and the composition for physical and chemical analysis of the materials.
5) The THz waves show better ***spatial resolution*** as compared to the microwave band. The wavelengths in the sub-mm wave band augment the resolution of the images as compared to microwave imagining.
6) ***The high directivity*** of THz waves is because of a high reflection and absorption loss over such high frequencies, which restrict the communication to a directive line-of-sight (LoS) scenario, as the NLoS condition experiences spreading losses. These features make THz waves promising for high-speed wireless links.

III. OPPORTUNITIES AND CHALLENGES FOR THz BAND COMMUNICATION

The high usage of mobile devices like smartphones, digital cameras, and high definition (HD) video cameras have expedited the recent trends and pushed the data traffic expansion around the globe. The steady progress in increasing the data capacity, cannot fulfill the future demands to support these trends for both industry and end-users. Moreover, the new industrial applications such as augmented/virtual reality, tactile Internet, vehicular communication/network, and the Internet of Everything (IoE) will cause a major shift in

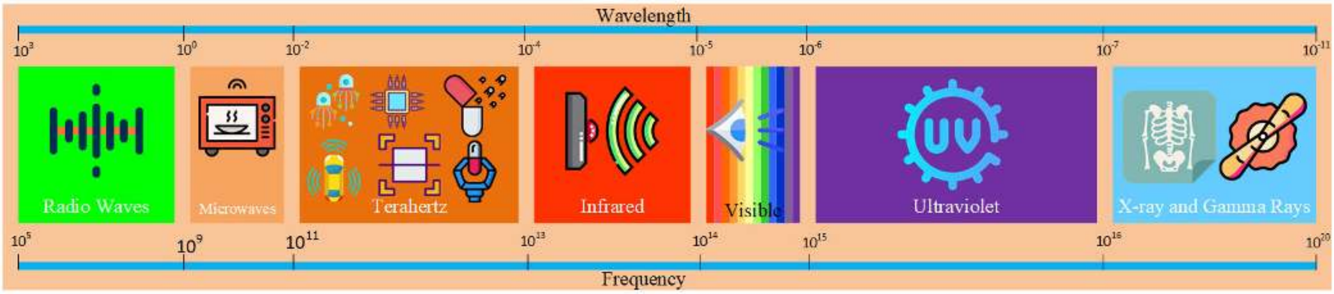

FIGURE 2. Simplistic representation of Terahertz band and its applications in the radio spectrum.

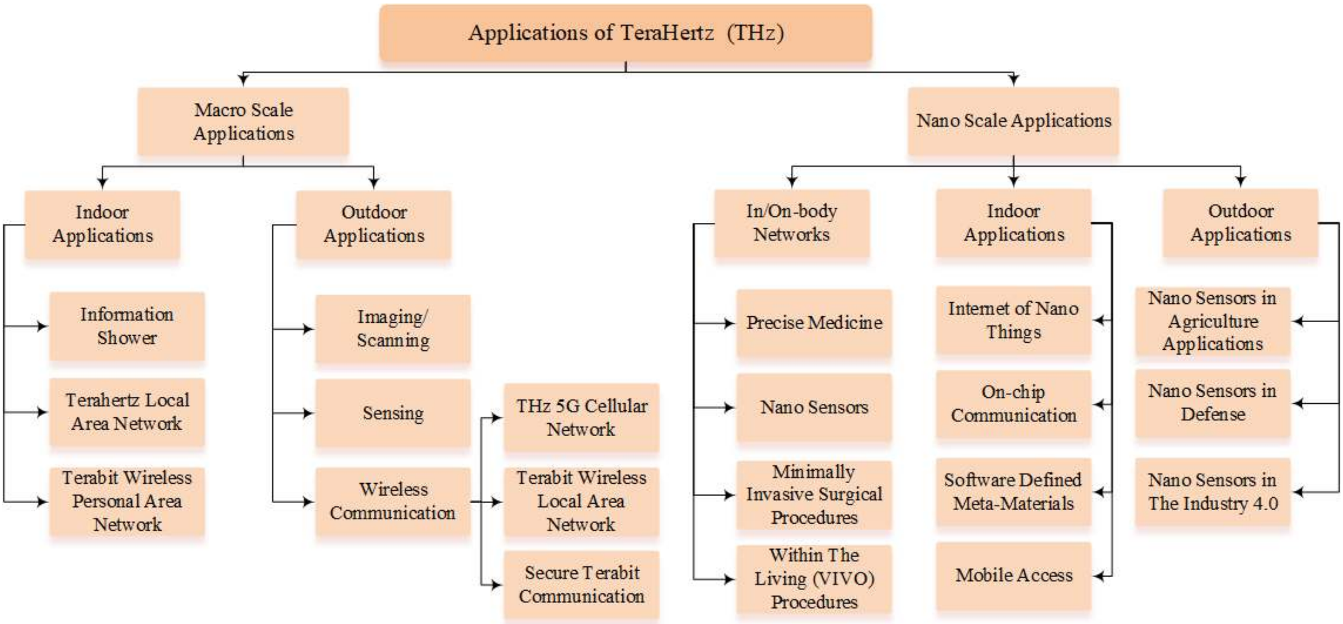

FIGURE 3. Taxonomy of the THz applications.

key industrial applications. The requirements of these applications mainly include a high throughput, ultra-low latency, ultra-reliability, and a massive level of connectivity. The THz bands, specifically the bands above 275 GHz, are alluring a huge concern because of wider spectral bandwidth. Typically, the spectrum between 0.1-10 THz is considered as a scientific breakthrough to support the requirement for 5G and B5G network [24]. Hence it is essential to explore the possible multimedia applications and extend the existing wireless applications over the THz band. The THz-enabled applications are categorized into nano and macro-scale networks that are sub-divided into indoor and outdoor applications due to the difference in the coverage level and the environment. In this section some of the applications are discussed to show the sustainability of the THz band to meet the requirements of existing and emerging applications. Fig. 3 depicts the taxonomy of THz band applications. Moreover, the affects on the designing parameters of an antenna for such nano and macro scale applications is also discussed.

A. NANO SCALE APPLICATIONS

Nanotechnology comprises nano components that are designed to perform simpler and specific tasks, such as computation, storage, actuation, and sensing. The nano components are integrated into a tiny device of a few cubic meters, which leads to the development of more advance nano-devices. The nano-devices are deployed in a centralized or distributed manner to achieve complex tasks. These nano-devices enable unique and interesting applications in plant monitoring, bio-medical, health monitoring, chemical, and biological attack prevention, military, nanosensor network, and system-on-chip wireless networks. The communication range in nano-sensor network is in centimeters (cm) or below 1 meter. The main challenges in nanotechnology is to design transceiver, channel models, and physical layer communication protocols. The THz spectrum is the prospective enabling technology for communication in the nano network. In molecular communication, the absence and the presence of molecules are digitally encoded in messages to communicate. The applications of molecular communication include health monitoring, disease detection, and drug delivery. These applications are categorized into indoor, outdoor, and in-body networks [25].

The detection of diseases and monitoring of glucose, cholesterol, and blood pressure levels can be performed using nano-scale sensors. The nano-sensors can be used to detect infected tissues even before the infection is started by using the THz communication. The gathered information can be transmitted over the Internet for analysis. One of the main challenges in nano-scale in/on-body networks is the antenna designing on THz frequency. Efficient THz frequency usage, medium access control (MAC) designing, channel propagation model, the interaction between nano-devices, efficient communication protocol, and safety constrained are additional challenges. The indoor applications of THz include IoNT, On-chip communication, and SDM.

The IoNT is a new mechanism that refers to the nano-devices connected using the traditional Internet by means of a communication stack. The IoNT devices are connected using nano-antennas and nano-transceiver. The applications of IoNT mostly lies in the field of healthcare and bio-medicines [26]. The major challenge in THz based IoNT is the nano transceiver designing [27] . As the number of processing cores in the on-chip network increases, the wired network faces a series of issues in performing routing with the increased complexity. To address these issues, the use of the on-chip network in wireless communication is under consideration. On-chip wireless communication can only be enabled with nano-scale transceivers, thus necessitate the THz band to be used. Graphene-based THz electronics are the primary enabler for massive multi-core wireless network-on-chip (NoC) [28]. The SDM are artificial materials with special structures and consist of nano-networks. Their properties can be changed by programming via a computer interface and can be controlled by a network of nano-machines, integrated into the structures of meta-materials. The applications of SDM are radiation absorption, efficient antennas for sensors, and implantable communication devices [29].

The major application in the areas of nano-sensors utilizing THz in outdoor locations are agricultural monitoring, defense monitoring, and the biological attack prevention. The plants have the ability to communicate with each other using their biological system, which includes roots and pollination. Nano-sensors at THz band can be used to better understand and monitor the communication to identify their requirements and detect diseases. The characteristic of moisture sensitivity of the THz frequency makes it favorable for monitoring and data communication [30]. Nano-sensors operating at THz band have the ability to work at the molecular level, which makes them highly capable of detecting destructive biological chemicals. In addition, due to the miniature-sized nano-sensors, they can be deployed in a distributed manner to detect these threats at a rapid pace from the molecular level [31]. However, challenges exist while using THz band for nano-sensors in defense and industrial applications, which includes data acquisition, big data analysis at molecular level, highly directive high gain nano-antennas, transmission range, and channel propagation model.

B. MACRO SCALE APPLICATIONS

The applications of the THz band are categorized according to their respective transmission range. The applications which support transmission range higher than 1 meter are known as macro scale applications. The transmission distance depends upon the free space and absorption losses. These losses open up new challenges for antenna characterization, which includes transmission power and the size of the antenna. The macro applications are further categories into indoor applications in which transmission ranges vary from 10-20 meter and outdoor applications that support transmission range between few meters up to Km.

The indoor applications can have a peak data rate of 100 Gbps and needs to uphold a sustainable molecular and path loss. Outdoor applications suffer from reflection and scattering phenomena due to path obstacles and absorption losses. The indoor applications include information shower and T-LAN. The small THz cell communication deployment (few meters in radius) can be used for high data up to Tbps. The access points (APs) associated with these small cell can be deployed in an efficient manner to provide coverage in an area with high human mobility, i.e. subway stations, shopping malls, building entrances, etc. Such a concept of deploying APs is known as an information shower or data shower. Information shower can provide the bulk of data to every passing user. However, this requires redesigning of several layer protocols to transfer the data in a minimum amount of contact time [32]. The THz band can provide consistent communication between fiber optics terminal point and wireless routers to extend the wireless links for Ad-hoc devices, i.e. laptops, cell phones, and wireless devices [33]. The users of these devices can access high-speed Internet in Gbps or Tbps using T-LAN [24].

The major applications in the area of macro-scale utilizing THz in outdoor locations are in radars, sensing, wireless communication, etc. The impact of weather and light is very minute on THz frequencies. These characteristics make radars operating at THz frequencies very effective as compared to light detection and ranging (LIDAR). The practical applications of THz radar are driving assistance, flying in foul, as well as in national and military security applications. Radar operating at several hundreds of GHz can provide high definition imaging quality as compared to radar operating at lower frequencies, which provide longer range but low imaging quality [34]. The small wavelength and wide bandwidth of THz, enable high spatial resolution imaging. The THz scattering exhibits specular and diffusing scattering from most path obstacles surface. The strong specular from the surface like an electrical mirror enables imaging around the obstacles, while maintaining a high spatial resolution [35].

The THz frequencies can exploit the selective frequencies from the environment to gain knowledge about the environment based on their signal propagation. Beam scanning enables to create images of physical spaces through systematic monitoring of received propagated signal from different angles. Electrical beam steering in real-time and small radio propagation distance enables to measure the properties of office, room, building, and complex structures in less than a second. This ability is known as wireless reality sensing, which opens up a new paradigm for wireless communication to create 3D maps on the fly and immediately upload them on the cloud servers [36]. Few of the used cases of THz communication comprises of antenna miniaturization, high directivity [6], ultra-wide frequency bandwidth, manufacturing power amplifiers, oscillators, and beam steering antennas, etc. THz directional links can be used to provide ultra high-speed wireless backhaul communication to the small cells in 5G [6]. The high directive antennas using THz band with large arrays results in very narrow, almost razor-shape beams, which drastically limit successful eavesdropping.

C. IMPLICATIONS ON ANTENNA DESIGNING

There is a wide range of opportunities available in THz-enabled communication, in nano as well macro scale applications. From an antenna designing perspective for such applications, it imposes certain implications and challenges to achieve such performance. The most important challenge is first to grasp a complete understanding of the physics of such structures and the issues related to the fabrications and achieving high throughput, needs to be tackled in an effective manner. To the best of our knowledge, there are two important aspects, which make the design requirements of metallic nano-antennas distinctive from the well-known RF/microwave antennas, and are as follows:

- Firstly, the perfect electrical conductors (PEC) based assumption in designing a RF-enabled antenna, losses its validity at THz frequencies, as the Ohmic losses substantially increases with an increase in the frequency range [37].
- Secondly, at the nanoscale region the dielectric and metallic interfaces can sustain surface plasmon polaritons (SPP) waves [37], which practically void the RF/microwave antennas based assumptions on the manufacturing of THz antennas.

Hence, the designing of nano-antennas is drastically different in comparison to RF/microwave regime. Moreover, for such nanoscale antennas, the antenna theory requires new theoretical, analytical and modelling tools, which accounts the deviation from RF/microwave range to nano-antennas. Furthermore, some efforts have been reported in the literature to study such deviations of RF antennas to their nano counterparts [38].

IV. CATEGORIZING THz ANTENNAS AND MATERIAL SUITABILITY

This section discusses different types of THz antennas and provides a comprehensive study of materials suitable for developing such type of antennas.

A. THz ANTENNA TYPES

The very first link over 120 GHz was established by a planar dipole and a slot-ring antenna integrated with a photo-diode and Schottky-barrier diode for the transmitter [40], [41] and a receiver [42], respectively. A short coverage range up to 1 meter is supported by providing a peak data rate of 10 Gbps. Hirata *et al.* [43] proposed a Gaussian-optic lens antenna to enhance the coverage range. The antenna has a diameter of 375 mm, where a detector-diode and photo-diode are assembled into hollow waveguides to exploit a horn antenna as a feeder. Hirata *et al.* [44] extended the coverage range up to 200 meters by using a 450 mm diameter Cassegrain antenna for outdoor trials. The peak data rate achieved in real-time video broadcast transmission is 10 Gbps. A pair of the dielectric lens of 50 mm diameter and a horn antenna operating at 300 GHz is used to demonstrate a transmission over the range of 2 meters [45]. Nagatsuma and Carpintero [46] achieved a gain of 48 dBi with a lens having a diameter of 100 mm and is able to cover an area of 20 meters. Waveguides with slot array antenna, operating at 120 and 300 GHz resonance frequency is explored to achieve a high gain while reducing the overall antenna size [47]. Tekkouk *et al.* [48] proposed a slotted array antenna having a resonance frequency of 300 GHz with a hollow waveguide fabrication, and such array antennas with slotted aperture are quiet beneficial for near-field communication.

A taper slot structure of polymeric substrate for ultra-broadband antennas with a low dielectric constant is demonstrated over 120 and 300 GHz frequencies, respectively [49]. An increase in 3 dB gain is achieved in this study by exploiting 8 elements array antenna. A reflector antenna over 300 GHz band for real-time transmission with a coverage area of 100 meters and 50 Gbps data rate is demonstrated in [50]. The gain of a planar antenna is effectively increased by using a bow-tie antenna integrated with resonant tunneling diodes (RTDs) on Indium Phosphide (InP) substrate and Silicone (Si) lens [51]. The non-metallic antenna over 300 GHz band with photonic crystal slabs on Si substrate is investigated in [52]. A peak data rate of 10 Gbps is achieved by using a rod (operating at 100 GHz) as a unit cell, while 40 elements antenna array is shown to have an overall antenna gain of 20 dBi [53]. Fuscaldo *et al.* in [54] proposed a leaky-wave based Fabry-Perot cavity antenna, operating at 1 THz, and showed that the antenna is able to achieve a gain of 30 dB.

An ultra-wide circular microstrip patch antenna on Si wafer is presented in [55]. The authors presented the results of the Graphene microstrip antenna over the frequencies of 504 GHz, 2 THz, and 3.5 THz, with an antenna efficiency of -3.4 dB at 2 THz is observed. Luo *et al.* in [56] investigated a reconfigurable multi-beam Yagi-Uda antenna over THz frequency. Grzyb *et al.* in [57] presented a dual polarization-based on-chip antenna. The authors tested the on-chip antenna design up to 1 THz, and directivity of 27 dB over 1 THz is verified. Wu *et al.* in [58] proposed a circular polarized (CP) lens antenna. A linear polarized pyramidal

TABLE 3. THz antenna designs [39].

Antenna Type	Operating Frequency	Gain (dBi)	Link Performance	Ref.	Year
Planar dipole/slot ring	120 GHz	25	10 Gbps, 0.5-1 m	[40]–[42]	2000-2002
Dielectric lens	120 GHz	53	10 Gbps, 100 m	[43]	2004
Cassegrain antenna	120 GHz	49	10 Gbps, 5.8 km	[44]	2006
Horn and dielectric lens	300 GHz	40/48	2/50 Gbps, 20 m	[45], [46]	2009-2015
Waveguides	120/300 GHz	30/32	10/20 Gbps	[47], [48]	2011-2016
Taper slot	100-300 GHz	10-13	10 Gbps	[49]	2014
Reflector antenna	300 GHz	54	50 Gbps, 100 m	[50]	2016
Planar dipole	300 GHz	25	9 Gbps, <0.1 m	[51]	2016
Dielectric resonator	300 GHz	11	-	[52]	2017
Rod antenna	300 GHz	22	10 Gbps, <0.1 m	[53]	2018
leaky wave	1 THz	15-30	-	[54]	2018
Microstrip antenna	504 GHz, 2 and 3.5 THz	-3.4,-0.2 dB efficiency	-	[55]	2018
Yagi-Uda antenna	1.1 1.25 THz	5.7-6.5	-	[56]	2019
On-chip antenna	1 THz	27 dB directivity	-	[57]	2019
Lens antenna	300 GHz	31	-	[58]	2019
Scaled up microstrip	4.9-5.9 THz	-	-	[59]	2019

TABLE 4. A comparison of material suitability for THz-enabled antennas.

Parameter	Copper	Graphene	CNT
Electronic mobility	$32\ cm^2V^{-1}S^{-1}$	$2\times10^5\ cm^2V^{-1}S^{-1}$	$8\times10^4\ cm^2V^{-1}S^{-1}$
Current density	$10^6 Acm^{-1}$	$10^9 Acm^{-1}$	$10^9 Acm^{-1}$
Tensile strength	587 MPa	1.5 TPa	5-500 GPa
Thermal conductivity	$400\ Wm^{-1}K^{-1}$	$5000\ Wm^{-1}K^{-1}$	$3000\ Wm^{-1}K^{-1}$

horn is used to feed the CP lens antenna. The proposed antenna operates over 300 GHz. A gain of 31 dBi at 300 GHz is measured. A linear scaling methodology to scale-up the microstrip patch and slot GHz antenna to THz antenna is devised in [59]. The novel scaling methodology is justified analytically for a rectangular patch antenna as well as for a wide-band slot antenna. The proposed technique scaled up a 5 GHz antenna to a 4.9-5.9 THz antenna. Table 3 summarizes some of the existing works in THz-enabled antennas and their design methodologies.

B. MATERIAL SUITABILITY

The selection of a suitable material having minimum propagation losses is yet another challenging task in designing an efficient antenna. The properties of Copper makes it a favorable choice for antenna fabrication. At THz frequency range, the skin depth and conductivity of the Copper metal decreases and hence reduce the radiation efficiency of the antenna elements [60]. At lower THz frequency range, e.g. at 6.45 THz resonance frequency, the ohmic-resistance plays a dominant role in contributing to the surface impedance of Copper, and hence making it a difficult task to design such antennas using Copper material. Although the Copper is considered as an appropriate material in designing antennas operating at lower RF bands, yet it imposes considerable disadvantages in developing THz-enabled antennas. To overcome such constraints, the research community has explored other elements. Literature shows that the use of Carbon, i.e. Graphene and Carbon nanotubes (CNT) are the best alternative of the Copper for the fabrication of THz antennas [60].

The Graphene was first discovered by Novoselov *et al.* in 2004 by using a micro-mechanical technology [61]. The atoms in the Graphene structure are arranged in the shape of honeycomb hexagonal lattice, having an interplanar spacing of 0.335 nm [61]. The electrical conductivity of Graphene is very high. These rare properties of Graphene make it highly suitable for the development of THz-enabled antennas. One of the key phenomena of Graphene is the generation of plasmon polariton wave at the THz frequency [62]. Using an infinite thin conductive sheet, the Graphene can be modeled to operate at THz frequency bands having complex surface conductivity, and this complex surface conductivity can be found using Kubo formula [63]. Moreover, with the help of chemical doping or electrostatic biasing, the surface conductivity of Graphene can be controlled, and hence one can easily tune the properties of THz-enabled antennas.

Similar to Graphene, the CNT also shows favorable circumstances for the THz frequency band. They are formed using the rolling of Graphene sheets and have different properties and structure, which varies from single to multi-walled CNT structures. At THz frequency band, the inverse relation between the quantum resistance and the radius of wire (conductive part) vanishes and is much smaller, while comparing to a Copper wire of the same size [64]. The CNT uses the π-bond of Carbon atoms to perform conduction, which significantly reduces the skin-effect at THz frequencies to such an extent that the skin-effect can be ignored as well [65]. This phenomenon leads to an increase in antenna efficiency by minimizing power dissipation. In comparison to Copper, the CNT supports low wave propagation modes, which helps in miniaturization of the antennas [66]. A brief comparison between the material suitable for THz-enabled antennas, i.e. Copper, Graphene, and CNT is provided in Table 4.

V. THz ANTENNAS: DESIGNING, MEASURING AND PERFORMANCE EVALUATION

This section of the paper mainly focuses on the design parameters and performance evaluation of THz-enabled antennas and encompasses the comparison of various techniques available in literature used to improve the performance of the radiating elements. Some measurement techniques are discussed to verify the performance and suitability of such devices. Moreover, the key differences between MIMO and array antenna is explained using detailed examples. In the last of this section, some key design challenges and existing technologies of phased array for THz multi-antenna systems is discussed.

A. BASIC THz ANTENNA DESIGN

The electromagnetic radiations produced by any antenna follows the regulations set by James Clerk Maxwell [67], [68]. According to his famous equations, the changing electric field caused by the acceleration of charged particles will give rise to changing magnetic fields, and this combined effect would generate electromagnetic field radiations. These four sets of vector-differential equations are as follows

$$\nabla \cdot \mathcal{E} = \frac{\rho}{\varepsilon_0}, \tag{1}$$

$$\nabla \cdot \mathcal{B} = 0, \tag{2}$$

$$\nabla \times \mathcal{E} = -\frac{\partial \mathcal{B}}{\partial t}, \tag{3}$$

$$\nabla \times \mathcal{H} = \mu_0\left(J + \varepsilon_0 \frac{\partial \mathcal{E}}{\partial t}\right). \tag{4}$$

The Eq.1 defines the Gauss law. In Eq.1, $\nabla \cdot \mathcal{E}$ is the divergence of the electric field, ρ represents the total charge density, and ε_0 is the electric constant. Eq.2, explains the Gauss law of magnetism, where $\nabla \cdot \mathcal{B}$ is the divergence of magnetic field. Eq.3 represents Faraday's law of induction, where $\nabla \times \mathcal{E}$ shows the curl of electric field. The Eq.4 shows the mathematical formulation of Ampére's circuital law. In Eq.4, μ_0 is the magnetic constant and J is the magnetic current density. In any antenna simulation and manufacturing, the most critical designing parameter is the resonance length. A simple antenna being fed using a frequency source having a resonance length L, which can be calculated using the following expression

$$L = \frac{\lambda}{2} = \frac{c}{f \times \sqrt{e_{ff}}}, \tag{5}$$

where λ is the wavelength of electromagnetic waves, c is the speed of light, f is the operating frequency of the dipole antenna, and $\sqrt{e_{ff}}$ is the dielectric constant, and for free space, it is 1. A plethora of work is available in the literature, which discusses the basic designing parameters of THz antennas [16], [69], [70]. The antennas in the starting generations of THz systems were designed inside the semiconductor devices by using InP or Gallium Arsenide (GaAs) [71]. The controlling of input impedance and the radiation pattern in these semiconductors are considered to be a tedious task, as they possess a high dielectric constant having $\epsilon_r \approx 12$. To overcome the issues of high dielectric constant, the lens antenna was proposed [72]. For instance, in [73], a metallic lens-based antenna operating at 412.5 GHz is proposed. The design is feed using a horn, and ten symmetrical waveguides are further employed to adjust the phase in radiation plane [73]. The horn antenna is considered as a suitable choice for feeding such structure. Similarly, in [74], a folded reflector array antenna (FRA) have been proposed for THz-based wireless applications. Although the lens antenna provides an alternative way to overcome the problems related to the controlling of input impedance, it reduces the efficiency of the device and results in a subsequent increase in the size [72].

To overcome antenna efficiency problems, new approaches have been proposed, which include the stacking of different substrate layers having different dielectric properties. The stacking approach enhances the upward radiation. A THz-enabled antenna is proposed in [75], and shows that an efficient power coupling between the antenna and source, results in a considerable improvement in the performance of the antenna. Moreover, the layering concept is used in [76] to build up a simple printed Yagi-Uda antenna, which uses two different substrates, i.e. InP (high ϵ_r) and benzocyclobutene (BCB) (low ϵ_r) to place the conducting part.

B. FABRICATION AND MEASUREMENT TECHNIQUES

The antenna operating at THz frequencies imposes a versatile set of challenges. Although the THz-enabled antennas provide very high improvements in the performance of a system, yet the fabrication and measurement restrict the antenna engineering. These challenges have been actively addressed in the literature using a series of experimental trials [77]–[79]. Mostly the design techniques employed for lower frequencies are applicable for THz as well, but the process of fabrication completely changes the scenarios, and new novel ideas are needed to achieve such goals. In [80], two different approaches have been discussed to overcome the fabrication difficulties and to develop a low cross-polarization and high gain horn antenna. Moreover, the accuracy and the precision of the fabrication process can be effectively increased by using Si-based micromachining process. In [81], the similar Si-based micromachining process is used to develop a 2 × 2 array, operational at 1.9 THz. A similar way of micromachining has been utilized in the development of microlens antenna [82]. Again, in [80], the fabrication process for the leaky-waveguide has been discussed, which contains air-cavity, waveguide, and membrane. Graphical illustration of this antenna can be seen in Fig. 4.

Testing the performance of the fabricated antenna at THz frequency is yet another challenging task, but with the advancement in technology, sufficient amount of research work is available. The antenna functioning at THz band can easily be tested in reception instead of transmission, such

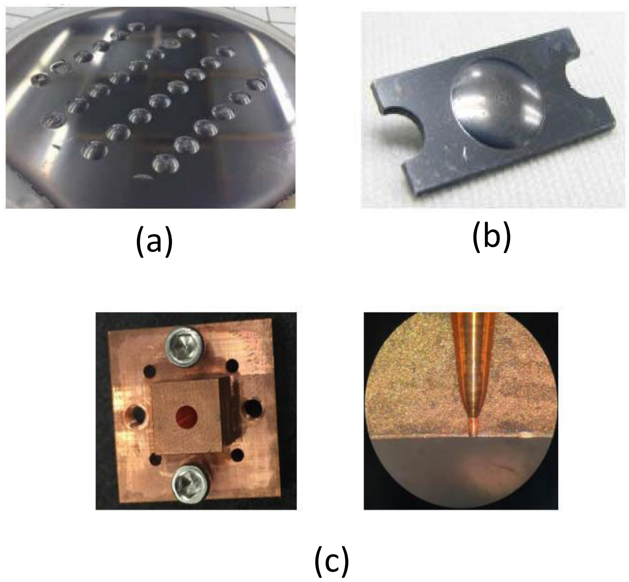

FIGURE 4. Photographs of the antennas presented in (a) [81] (a 2 × 2 array, operational at 1.9 THz),(b) [82] (micro-lens antenna) and (c) [80] (a leaky-waveguide THz antenna).

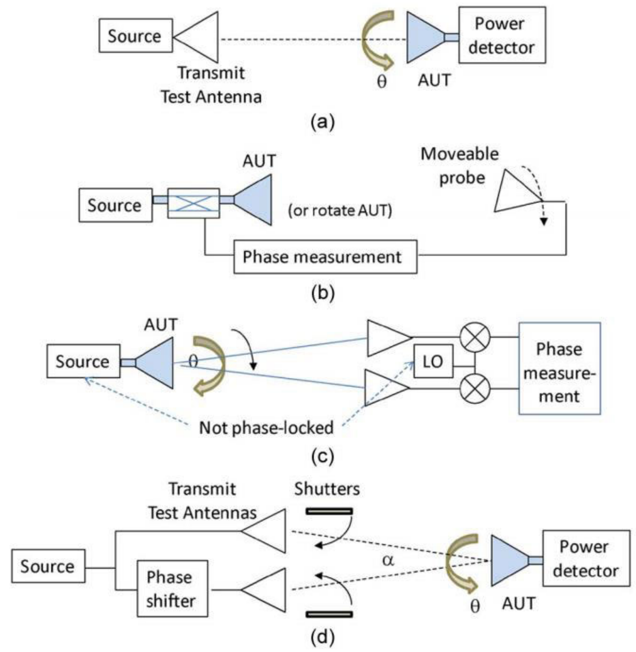

FIGURE 5. A graphical representation of the THz antenna measurement setup [83].

that the coupling between the few coherent sources and the feed-points stays at the bear minimum. A simplistic graphical representation of THz-enabled antenna measurement setup is presented in [83], and can be seen in Fig. 5. In order to perform the performance evaluation of micromachined based waveguided circuits, tuned at 500-750 GHz operating frequency, a novel measurement setup has been constructed in [84]. The setup in [84], uses a novel micromechanical compression pin to adjust the wafer alignment. In [85], two hologram-based antenna test ranges centered at 322 GHz and 650 GHz are constructed and used to test a THz antenna. Graphical illustration of a typical measurement setup can be seen in Fig. 6 [83].

C. MIMO CONFIGURATIONS AND THz ANTENNA ARRAYS

The MIMO is considered an effective solution to overcome the capacity constrain in a wireless communication system. The merger THz with the MIMO technology can simplify the things further by providing practical ways to address the ever-increasing capacity demands [86]. On the other hand, an array of antennas (mostly described as a phased array), is a group of 2 or more than 2 antenna elements feeds using a single frequency source. The key idea behind them is to combine the signals from each antenna to enhance the overall performance of the system.

Exploring the literature for MIMO THz antenna configuration, a sufficient amount of work is available to understand and validate the concept. In [87], the properties of Graphene-based nano patch antennas are manipulated to develop a novel reconfigurable MIMO antenna suitable for THz based wireless communication. Moreover, the authors in [87], show the improvement in capacity by employing the MIMO configuration, while selecting the best channel state. In [88], the THz band is explored in the context of high bandwidth coverage and providing higher data rates. The issues of low power and short communication in the THz domain are addressed and have been rectified by employing massive MIMO antennas [88]. A 2×2 MIMO antenna being separated using pattern diversity, ensuring a coupling level suitable for MIMO applications, tuned at THz band, is proposed in [89]. The proposed configuration uses the Graphene patch, which provides flexibility in tuning the antenna parameters.

In the context of array THz antennas, adequate work have been proposed in the literature by the research community. In [90], microstrip patch-based antenna array, optimized at THz frequency band is used to study the performance of a THz based source and detector system. This is done by employing quantum well-infrared photodetector and a quantum cascade laser. To overcome the challenge endured while achieving wide-bandwidth at THz frequency band, a 2×2 slot antenna array, backed by a cavity, is proposed in [91]. The authors use the approach of the unidirectional antenna and achieved cardiac radiation pattern by the integration of parallel-resonant magnetic dipole with a series-resonant electric dipole. Moreover, in [92], the liquid crystalline polymer substrates are used to design simple microstrip patch antenna array, operational at THz band. The proposed configuration is suitable for medical and implant applications, which includes cancer detection using THz spectroscopy and sign detection using doppler radars, etc. Some of the reported designs can be seen from Fig. 7.

D. DESIGN CHALLENGES FOR PHASED ARRAY THz-ANTENNAS

The phased arrays antenna technology, in the RF band is well explored and is mature enough to perform beam steering

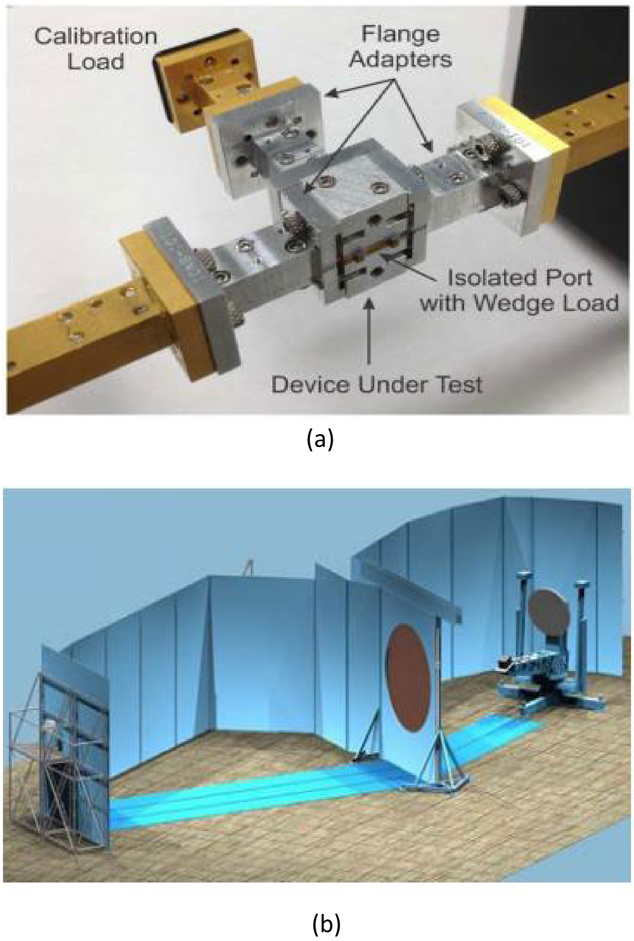

FIGURE 6. An illustration of the measurement setups for THz antennas proposed in (a) [84] and (b) [85].

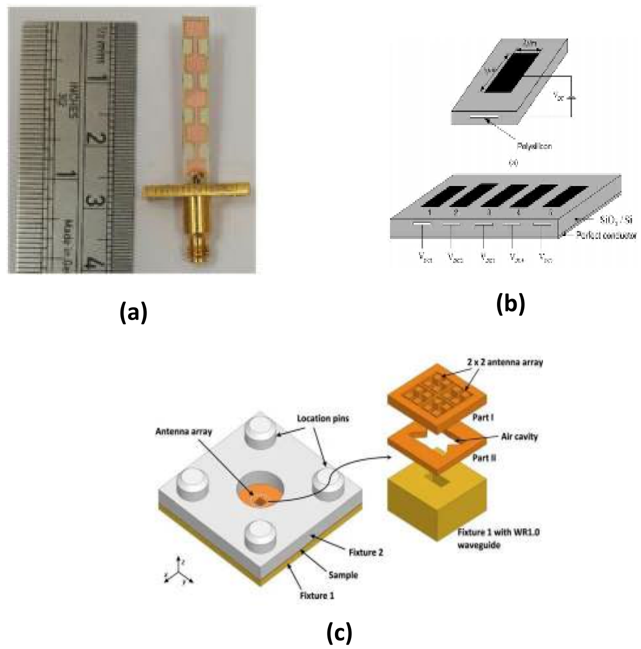

FIGURE 7. MIMO configurations and array antennas presented in (a) [92] (microstrip patch antenna array, operational at THz band),(b) [87] (reconfigurable MIMO antenna suitable for THz) and (c) [91] (2 × 2 slot antenna array).

in the desired applications. However, in THz based applications, requiring the functionality of phased array, endure high losses, due to the presence of semiconductor based switches [93]. To overcome such losses the researchers have proposed mechanism of shifting the phase before the frequency being converted to THz. This technique requires the development of spatial phase modulators, constructed using liquid crystals and graphene [94]. Moreover, some of the techniques being used in microwave and mm-Wave based phased array technologies are still applicable in THz range as well, which includes lens antennas, multibeam switching mechanism, mechanical scanning, pattern reconfigurable antennas, etc. The use of reconfigurable metasurface technology is yet another promising solution to overcome the losses endured due to beam steering functionality of phase array [95].

VI. FUTURE RESEARCH DIRECTIONS

It is envisioned that THz will revolutionize the wireless communication industry, however, considerable attention is needed on each component of THz based wireless communication system. For instance, the antennas operating on the THz band need exploration. Although sufficient research work is available, yet it contains, following gaps that pave the way for new research challenges. To best of the our knowledge, some of the future research tracks and open issues have been listed below (see Fig. 8).

A. THz SIGNAL GENERATION

One of the main research challenges in THz communication is the signal generation for THz-enabled antennas. This issue is generally referred to as 'THz gap'. In general, the regular oscillators available in the market are not efficient enough to work at such high frequencies. Despite these hurdles, there is some work available in the literature to deal with such issues [96]. At the moment, these solutions are quite expensive and require a lot of research efforts in terms of cost and complexity reduction.

B. THz TRANSCEIVER DESIGN

To overcome high path loss, experience by THz waves, additional features such as high power, low noise, and high sensitivity are required, while designing THz transceivers. The THz band offers high diversity and directivity gain due to the ability to host a large number of antenna elements in a relatively smaller aperture area. Novel and efficient transceivers and RF front end architectures are required to handle such an antenna gain [97].

C. THz ANTENNA EQUILIBRIUM TEMPERATURE

The overheating is another critical issue faced by THz antennas. The miniature size of THz antennas raises ambiguity regarding the levels of energy radiated from them, without facing overheating. One of the solutions available in

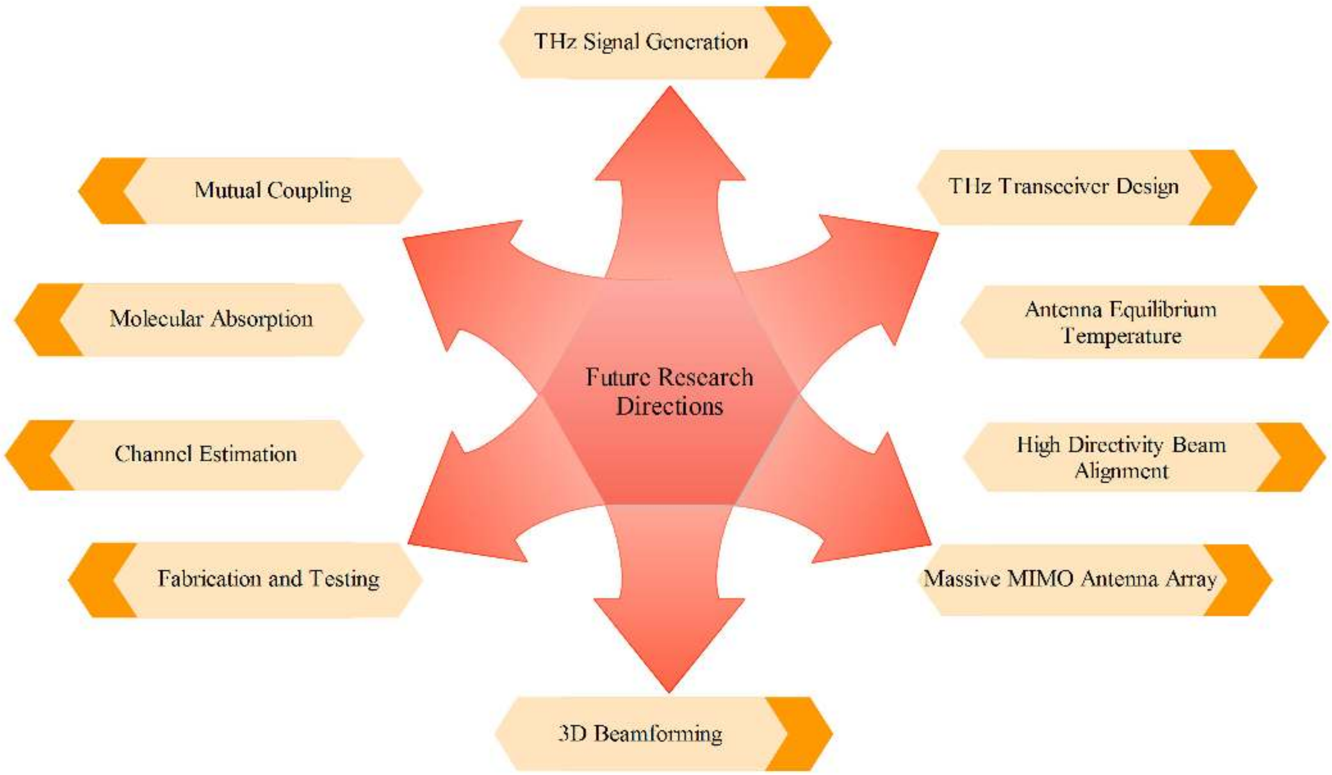

FIGURE 8. An overview of future research directions.

the literature [98], is to utilize metallic antennas supporting power levels for the lower THz band. The higher THz frequencies require new research paradigms to solve the new challenges both from academia as well industry.

D. HIGH DIRECTIVITY BEAM ALIGNMENT

The received power at the receiver is directly proportional to the transmission power of the transmitter and inversely proportional to the path loss [99]. The power at the receiver increases with the transmission power and decreases with an increase in path loss, and vice versa. The path loss increases as the frequency become higher and decrease the transmit power, which results in decreased received power. The antenna gain is inversely proportional to the antenna beam width. Thus, the THz antennas need to have a narrow beam width [100]. However, the drawback of the directional antenna is that the position of the receiver should be known, which is possible in a static communication scenario. This gives rise to the issue of beam alignment. Moreover, this alignment time can increase exponentially in a densely populated area, which eventually reduces the overall throughput of the system [101]. Therefore, mobility management is essential to avoid outages in THz communication.

E. 3-D BEAMFORMING

The abrupt increase in population in urban areas are projected to grow exponentially by 2050 [102]. With increasing population density, the number of connected devices in the cellular network is also bound to increase [103]. However, advancement is still challenging for urban areas due to heterogeneous users and traffic. This scenario becomes more challenging for THz band due to sensitivity for blockage and 3-D beam patterns [104]. New mathematical models and tools are needed to analyze and realize the benefits of 3-D beamforming in such a heterogeneous environment. The use of reconfigurable metasurface technology is one of the promising solution to overcome such beam pattern issues [95].

F. CHANNEL ESTIMATION FOR THz COMMUNICATION

The primary source of error in channel state information (CSI) is the channel coherence interval, which limits the number of orthogonal training sequences that can be used and can lead to severe pilot contamination. One of the interesting aspects of THz frequencies is the LoS propagation that would mitigate the pilot contamination effect [105]. A direction-of-arrival (DOA) based estimation for the LoS scenario in THz propagation with narrow beam widths could allow a fast channel estimation. However, the DOA-based estimation needs to calibrate a large array and adds to the complexity of DOA estimation.

G. FABRICATION AND TESTING

Fabrication and testing of THz antennas is yet another challenge and needs exploration. The cost associated with the fabrication of THz antennas is immense, as it requires very high precision. The work in [106], proposes a batch processing mechanism, which reduces the cost and time of THz antenna fabrication. Although, based on our discussion in the previous section, the research community is putting their efforts to resolve this issue, but still, a lot is to been done.

H. MASSIVE MIMO ANTENNA ARRAYS

The THz band allows miniature antennas, which offers the integration of a large number of antenna arrays for coverage enhancement. However, such massive MIMO structures require efficient antennas with low RF cross talk and mutual coupling, having a capability of sharing transceiver resources and choosing the carrier frequency of their choice [107].

I. MUTUAL COUPLING

A high antenna gain is required to overcome the path loss experienced at THz frequency range [108]. To enable antennas with such high gain, large antenna arrays are required [109]. Although a large antenna array structure can be manufactured using printed antennas, yet it arises some significant issues, such as mutual coupling [110]. A significant amount of research work is available in the literature regarding the reduction of mutual coupling [111], [112], but in the THz domain, it requires considerable attention.

J. MOLECULAR ABSORPTION

The molecular absorption (coexistence of natural resonance frequency of many atmospheric molecules in THz band) at THz frequency range is a significant issue, which reduces the achievable data rates by impairing the communication, despite the presence of huge bandwidth [113]–[115]. Some of the work in literature put emphasis on this issue [116], while considering a wireless communication scenario, still, it needs a plethora of research. For instance in [117], [118], the researchers proposed a solution based on exploiting the perceived knowledge of atmospheric window, which can largely mitigate the atmospheric losses. In our opinion the reinforcement learning based algorithms can also play an important role in exploiting the knowledge of atmospheric window in an effective manner.

VII. CONCLUSION

In this paper, we have surveyed characteristics, features, and applications of the THz antennas. A brief overview of the THz communication has been covered up. The necessity of enabling the THz band and its applications in the future wireless communication have been discussed. A detailed comparison of different types of THz antennas available in literature is provided, along with that some discussion on the selection of material for the THz antennas is presented. The basic designing parameters of a THz antenna are explained using some examples, and their manufacturing and fabrication process is discussed in detail. Moreover, the difference between array and MIMO THz antennas is well explained. In the end, we have pointed out some open research issues, which open up new horizons for the researches.

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