Optik - International Journal for Light and Electron Optics 231 (2021) 166415

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

Antenna in 6G wireless communication system: Specifications, challenges, and research directions

Zahraa R.M. Hajiyat [a], Alyani Ismail [a,*], Aduwati Sali [a], Mohd. Nizar Hamidon [b]

[a] Wireless and Photonic Network Research Centre (WiPNET), Department of Computer and Communication System Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia

[b] Institute of Advanced Technology (ITMA), Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia

ARTICLE INFO

Keywords:
6G antenna
Challenges
Fabrication
Measurement
Terahertz/THz band
Specifications

ABSTRACT

The Terahertz (THz) frequency band (0.1-10 THz) will be used in the 6G wireless communication system to support the user demand of higher data rates and ultra-high-speed communication for many future applications. In this paper, 6G antenna specifications for these applications are highlighted. An exhaustive review of recent related-works of THz band antenna, fabrication and measurement are presented. Challenges of the THz band antenna design, fabrication and measurement are addressed. Research directions of THz band antenna for 6G technology are included, for THz band in antenna design, manufacturing and testing.

1. Introduction

The increasing demand on higher data rates and ultra-high-speed communication leads towards the development and introduction of new technology such as sixth-generation (6 G) wireless communication system. The 6G wireless communication system is expected to emerge around 2030 [1,2]. 6G wireless communication system is still undefined [3] since it is at an early stage of development. The terahertz (THz) band will play an essential role in the 6G wireless communication system [4–6].

The THz band refers to the frequency range between 0.1 and 10 THz, which is equivalent to the wavelength from 3 mm up to 0.03 mm [4,7]. From 0.1−0.3 THz is defined as a sub-THz region and form 0.3−10 THz is defined as THz region [8]. From 0.1−0.3 THz is defined as a sub-THz region and from 0.3−10 THz is defined as THz region [8]. The THz band, also referred to as the THz gap due to the lack of materials responding to these frequencies [9], is the least studied frequency region among millimetre-wave and infrared regions [5]. The THz band may also be referred to as Tera waves or T-waves [10]. Fig. 1 shows the frequency range in 6G wireless communication system.

Some of the suggested specific applications for THz band wireless communication are health monitoring system, internet of nano-thing (IoNT), ultra-high-speed on-chip communication [5], environmental pollution monitoring, military, entertainment technologies, augmented reality, directional communication links, satellite communications, and heterogeneous networks [6]. To launch these THz band applications, new 6G use cases (scenarios) will be introduced, as THz band applications are categorized under the new 6G scenarios. 6G applications will require a combination of user cases that are already offered in the 5 G standard with new applications which will appear in a close future, such as mobile broadband reliable low latency communication (MBRLLC), massive ultra-reliable low-latency communication (mURLLC), human-centric services (HCS), multi-purpose and energy services (MPS) [11]. Compared to

* Corresponding author.
E-mail address: alyani@upm.edu.my (A. Ismail).

https://doi.org/10.1016/j.ijleo.2021.166415
Received 21 December 2020; Accepted 27 January 2021
Available online 3 February 2021

the 5 G applications, these 6G new use cases is required to support higher data rate or capacity (1 terabit per second), higher convergence, lower latency (1 microsecond), higher reliability (10^{-9}), lower energy and cost (energy/ bit is one pJ/bit), massive connection (1 cm on 3D) [12], global connectivity, battery-free for internet of thing (IoT) devices, connected intelligence with machine learning [4], and a new combination of these requirements for upcoming use cases. The contribution of this paper is to provide overall challenges of THz band wireless communication for 6G technology and more specifically, the challenges of designing THz band antenna. Our study differs from [13] in such a way that we included antenna specifications for short-range ultra-broadband THz wireless communication in 6G technology. This paper also offers a detailed review and analysis of recent studies related to THz band antenna design, manufacture and measurement, with open challenges and future research trends where previous studies do not cover.

This paper is arranged as follows: Section 2 contains THz band wireless communication challenges in overall. Section 3 discusses the antenna specifications for short-range ultra-broadband THz wireless communication in the 6G technology. In Section 4, recent related-works of THz band antenna, fabrication and measurement are addressed. In Section 5, we explain the challenges of the THz band antenna design, fabrication and measurement. Research directions of the THz band antenna in the 6G wireless communication system are presented in Section 6. Finally, Section 7 concludes this paper.

2. THz band wireless communication challenges

There are many challenges to enable the THz wireless communication system in the future due to very high path loss and molecular absorption loss that lies in the nature of the THz frequency band [14]. The THz frequency band suffers from absorption or scattering by molecules and tiny particles in the atmosphere, such as water vapour and oxygen, because their sizes are close to the wavelength of the THz band [15]. The high path loss of THz band presents a significant limitation on the communication distances range (converge area up to 10 m) [5]. Thus, the wireless communication system needs to be developed to meet the short distance communication of the THz band. Challenges in the 6G wireless communication system are machine-type communication (MTC) scenarios [16], THz band devices technologies [5,6], and THz band communication networks [5,6].

6G MTC scenarios challenges are security for MTC, efficient massive connectivity, energy efficiency, multi-access edge computing, artificial intelligence (AI) and machine learning, and vertical-specific wireless connectivity [16]. THz band devices technologies challenges are the THz band transceivers [5,6], THz band antennas [5,6], and THz band amplifiers [6]. THz band transceiver challenge is the design of transceiver that should operate with a wide bandwidth in the THz band [5,6]. High power, low noise figure and high sensitivity are additional features of THz band transceiver [5]. THz band antenna challenge is to develop a design of the antenna that support a very large wideband bandwidth and high directional features [5]. More studies are still needed for graphene antenna types in the THz band [6]. Similarly to the THz band transceiver challenge, THz band amplifier needs to support a wide frequency regime to operate in the THz band [6]. THz band communication networks challenges are channel and noise modelling, physical layer, link layer, network layer, and transport layer [5,6]. Physical layer challenges include modulation schemes, channel coding schemes, multiple-input and multiple-output (MIMO) system, relays, media access controlling (MAC) [17], and synchronisation [5,6].

Fig. 2 shows a summary of general challenges of THz band in 6G wireless communication system.

The THz band antenna for the 6G wireless communication system is the focus of this paper. We will review antenna specifications for short-range ultra-high-speed THz wireless communication in the 6G technology, and recent related-works of THz band antenna, fabrication and measurement with their open challenges, where previous studies did not cover. The research directions of these parts are also included in this paper for further studies.

3. Antenna specifications

Antenna specifications depends on applications. Applications in the 6G technology include short-range ultra-broadband THz wireless communication/ short-range ultra-high-speed THz wireless communication, such as fixed point-to-point (P2P) communication, for example, in the server room or supercomputers. Such antenna could be used to replace the massive wires connection in the server room or supercomputers. Another example is Wi-Fi, and base station that need such antenna to transfer enormous data with ultra-high-speed over short-range in the 6G technology. Such antenna could be also used in medical applications for more accuracy and

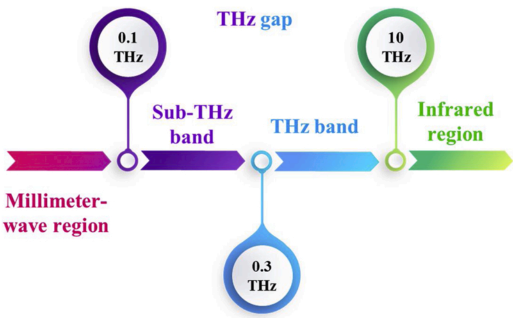


Fig. 1. Frequency range in 6G wireless communication system.

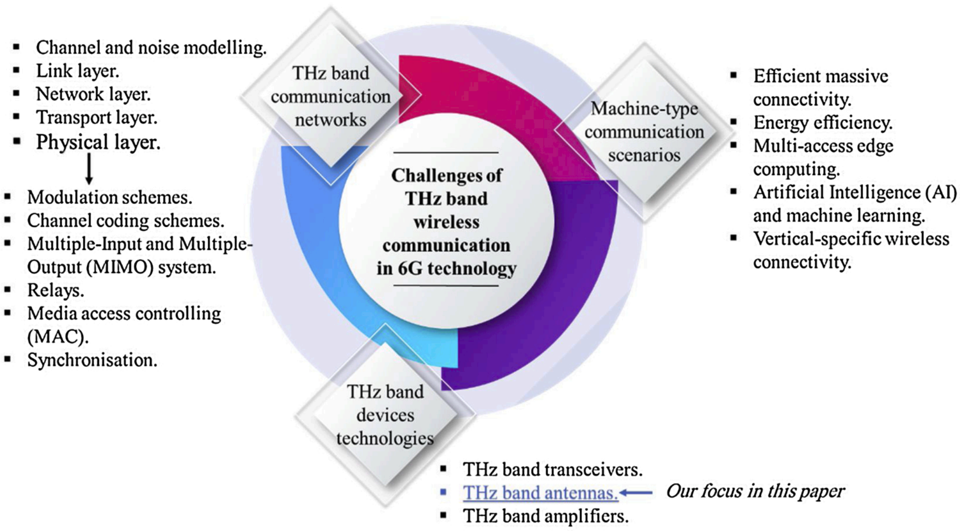


Fig. 2. Summary of general challenges of THz band in 6G wireless communication system.

better detection of cancer, as the study in [18], and [19].

For these applications, the antenna specifications in the 6G wireless communication systems are:

- The frequency range is the THz frequency band (0.1–10 THz) [4–6].
- Ultra-wideband and multi-band antenna [5]. Antennas with a fractional bandwidth (FBW) more than 50 % are referred to as ultra-wideband antenna [20].
- Omnidirectional antennas will be needed in some applications, while very directional antennas will be required in some other applications [5]. Depends on applications, high directional antenna of 25 dBi [21]\ over 25 dBi or antenna (omnidirectional \directional) with the high gain between 18–34 dB [22]\ between 25–40 dBi is needed [23]\ even up to 60 dB gain [24].
- Compact size [5] and low-cost.
- Circular polarization is preferred [25].

Multi-band antennas can be used to improve the bandwidth, capacity and data rate of THz wireless communication system [26]. In addition, an antenna with multi-band can be used for more than one uses cases (multi-function/ multi-purpose antenna). Ultra-wideband and multiband with circular polarization antenna is to enable the ultra-high-speed THz wireless communication system in the 6G technology. Antenna with low-cost characteristics can reduce the cost in the antenna fabrication process and increase the spread in the market. Highly directional antenna or omnidirectional with high gain antenna is needed to overcome the very high propagation loss [27] of the THz band and to offer a reliable communication for short-range ultra-broadband THz wireless communication in the 6G technology. Besides, due to the limited output power of THz band transceivers, high gain directional antennas are demanded to communicate over distances beyond a few meters [28].

More details on directional antenna of ultra-broadband THz wireless communication system in 6G indoor and outdoor applications, and 6G antenna polarization type are presented next.

3.1. Directional antenna in 6G indoor and outdoor applications

The high frequency of the THz band suffers from high path loss and molecular absorption loss [14]. Therefore, the need for high gain antenna is very important in order to overcome high atmospheric absorption and high path loss at the THz frequencies band [29].

For ultra-broadband THz wireless communications system in 6G outdoors applications, highly directional antenna or/and highly directional antenna arrays are needed [6]. The number of antenna elements in the array will be less (4×1 array) compared to 5 G technology (8×8 array of antenna gain = 18 dBi) [17,30,31] as 6G antenna array is more directional than 5 G antenna array for the same desired gain of the antenna. In the 6G technology, THz band in ultra-massive MIMO technology [32] introduced as a way to increase the communication distance and the achievable capacity of THz band communication networks [28]. Still, THz band in ultra-massive MIMO technology has difficulties in a fabrication antenna array, channel modelling, physical layer design, link layer and above [28]. More studies are needed in optimization problems of antenna array design and resource allocation [32]. On the other hand, a small number of antenna elements are still preferred to decrease the complexity and cost of the system in 6G outdoor applications as its very high directional features of antenna array could meet the required communication distance. An application example that use an antenna array of outdoor ultra-high-speed THz wireless communications system is base stations in the 6G technology.

For ultra-high-speed THz wireless communications system in 6G indoor applications, a highly directional antenna is also required. Nonetheless, an antenna array may not be necessary for indoor applications compared to outdoor applications as the desired distance is usually smaller. Besides, the THz band in ultra-massive MIMO technology is extremely complex and might exceed the distance requirement of indoor ultra-broadband THz wireless communication scenarios [14] in 6G technology. Hence, a single element of high-directional antennas is more suitable for indoor applications rather than outdoor applications, due to the need of more directional antenna. Fig. 3 shows an example of an indoor ultra-high-speed THz wireless communications system in 6G technology between wireless fixed device such as TV and router in the same room, and the antennas are facing each other.

3.2. Antenna polarization type in 6G

The polarization of an electromagnetic field is the direction in which the electric field oscillates while travelling through the medium [25]. In wireless communications, the choice of polarization of the antenna depends upon the application as well as the medium [25]. Linear polarization is useful in many applications but, it cannot be very effective when the communication systems have to operate in indoor environments where multipath and scattering processes can reduce the quality of the radio link [33,34]. In linear polarization, a horizontally polarized antenna will not communicate with a vertically polarized antenna [35]. This is due to the reciprocity theorem, antennas transmitting and receive in precisely the same manner [35]. Thus, linear polarization suffers from power loss due to polarization mismatch. Circular polarization antennas in transmit and receive do also suffer a signal loss due to polarization mismatch but not as much loss as linear polarization, as some portion of the transmitted power are always transferred to linearly polarized receiver antenna for any spatial direction [36]. Circular polarization antenna receives the signal in both the horizontal and vertical planes compared to linear polarization antenna, which is either horizontal or vertical polarized.

For THz wireless communication, including satellite communication, circularly polarized waves are preferred because of their lower sensitivity towards multipath fading as compared to linearly polarized waves [25], which can improve the quality of signal transmission [37]. Also, very high accuracy alignment and location system of the THz band antenna are required [38] due to the very short wavelength of THz band antenna. Nevertheless, its alignment between transmitter and receiver is a difficult task due to its smaller size. Hence, circular polarization on the wideband antennas has received significant recent attention among the researchers due to its capabilities in fulfilling the requirement of the high gain, high data rate transmission [39–41], and lower losses in case of misalignment [42]. These features are desired in the 6G wireless communication system. Thus, a circular polarization antenna is preferred in the 6G indoor and outdoor applications of ultra-high-speed THz wireless communication system, such as router, and base stations, where rotation of antenna in some cases is unfeasible for fixed applications.

4. Literature review of related-works

The review section includes the performance of the most recent related-works of the THz band antenna for matching the antenna specifications in the 6G wireless communication system and the analysis of the latest related-works of THz band antenna fabrication and measurement.

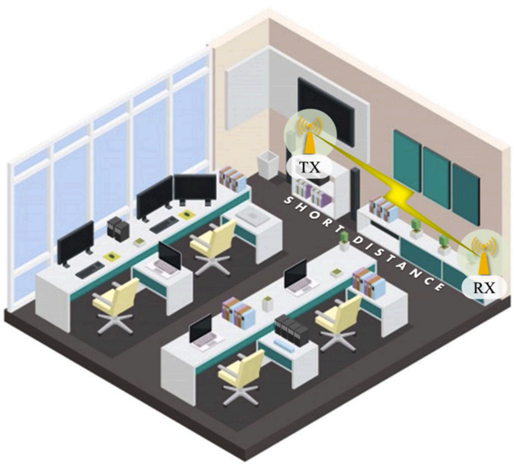
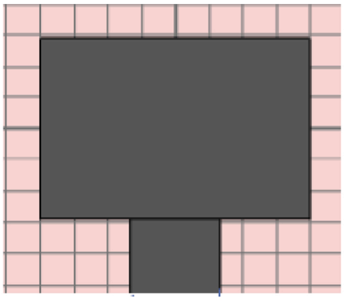
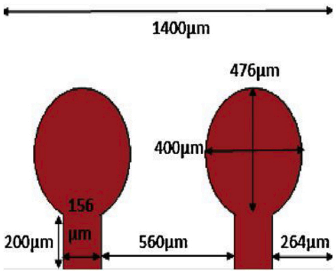


Fig. 3. Example of short distance point-to-point communication in 6G wireless communication system between wireless fixed device such as TV and router.
The 3D office image has taken from Naulicreative, "Modern isometric 3D office interior design Free Vector," in image: Freepik.com, ed: Freepik, 2017 and we modified it to show our example, which agrees with Freepik license (free for personal and commercial purpose with attribution).

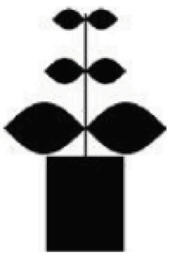


(a) Plasmonic rectangular microstrip antenna (2020, [89]), 0.1-20 THz (ultra-wideband), gain= 12 -25 dB, linear polarization, and material used is graphene on silicon dioxide substrate.

(b) Inverted K-shaped patch antenna (2020, [90]), 0.46-8.84 THz (very wide bandwidth), gain= 22.1 dB at 8.8 THz, radiation efficiency= 72 -93 %, and material used is perfect electrically conducting (PEC) on polyamide substrate.



(c) 2-elements of elliptical-shaped microstrip antenna/ MIMO antenna (2020, [91]), 0.33-10 THz (super-wideband, 187%), peak realized gain= 19 dBi, radiation efficiency is greater than 70%, and it is designed on RT5880 substrate.



(d) Plant-shaped with 6 leaves patch antenna (2020, [92]), 1.12-10.02 THz (wide bandwidth, 159.78%), gain =18.66 dBi at 7.5 THz, and it is designed on polyamide substrate.

(caption on next page)

Fig. 4. THz band antenna design [89–92].
(a) Plasmonic rectangular microstrip antenna (2020, [89]), 0.1−20 THz (ultra-wideband), gain = 12–25 dB, linear polarization, and material used is graphene on silicon dioxide substrate.
(b) Inverted K-shaped patch antenna (2020, [90]), 0.46–8.84 THz (very wide bandwidth), gain=22.1 dB at 8.8 THz, radiation efficiency = 72–93 %, and material used is perfect electrically conducting (PEC) on polyamide substrate.
(c) 2-elements of elliptical-shaped microstrip antenna/ MIMO antenna (2020, [91]), 0.33−10 THz (super- wideband, 187 %), peak realized gain = 19 dBi, radiation efficiency is greater than 70 %, and it is designed on RT5880 substrate.
(d) Plant-shaped with 6 leaves patch antenna (2020, [92]), 1.12–10.02 THz (wide bandwidth, 159.78 %), gain = 18.66 dBi at 7.5 THz, and it is designed on polyamide substrate.

4.1. Recent THz band antennas

The most recent studies of the THz band antennas in [19,29,37,43–60] have achieved wideband bandwidth and few of them are ultra-wideband bandwidth. Still, their directivity (or omnidirectional) or/and gain is low compared to the required directivity (or omnidirectional) with the minimum high gain antenna of 18 dBi in the 6G wireless communication system. Besides, the radiation efficiency of these ultra-wideband antennas is either very low or unknown.

Some recent related-works of the THz band antennas in [18,61–68] have achieved the minimum high gain antenna of 18 dBi or above for the 6G wireless communication system. Nevertheless, the radiation efficiency and fractional bandwidth of these studies are either low or unknown, FBW of ultra-wideband antenna is above 50 %. Also, most of these investigations have not included an ultra-wideband and multi-band antenna within their studies. They could have not intended their work for 6G wireless communication system at that time.

Few studies on dual-band, triband, and multi-band antennas have also been stated on the THz band as in [26,69–80]. Still, their dual-band, triband, or multi-band antennas are multi-narrow bands instead of multi-ultra-wideband or/and they have not mentioned their antenna performance in terms of radiation and total efficiencies, polarization, and FBW. Their directivity/ gain is also below 18 dBi. Perhaps, they did not intend their work for 6G wireless communication system at the time. Some few studies on wideband and dual-band antenna have been reported on the THz band as in [81–84]. Nevertheless, their directivity/ gain is also unmentioned or below 18 dBi. On the other hand, THz band antenna studies in [85] and [86] have achieved the high gain antenna of above 18 dBi on one-band only of their multi-bands, and their other dual-band and triband are not ultra-wideband bandwidth, respectively.

Some few studies of large antenna array on the THz band in [87] and [88] have reached very high gain or high directional antenna of above 18 dBi, which is required in the 6G wireless communication system. Nevertheless, their bandwidth is not ultra-wideband, and

Table 1
summarizes the most recent related-works of fabricated THz band antenna.

Table 1. Recent related-works of fabricated THz band antenna

No.	Antenna type	Frequency range	Material	Fabrication technology
1.	Conical horn antenna (2020, [29])	0.270 - 0.330 THz	Metal	Wire-cutting EDM[1]
2.	16-element planar array of cavity-backed patch antenna (2020, [93])	0.135−0.155 THz	Megtron 7 N substrate	Multilayer high-frequency PCB[2] technology
3.	Elliptical lens antenna (2020, [61])	0.14−0.22 THz	Topas	HDPE[3] manufacturing process
4.	Cassegrain antenna (2020, [62])	0.22−0.3 THz	Brass with gold plating	CNC[4] machining
5.	Lens antenna (2019, [63])	0.24−0.32 THz	High-temperature resin is chosen as the printing material [63]	3D printer technology
6.	Vivaldi patch antenna (2019, [94])	0.56−0.74 THz	Metallic on Rogers RT5880 substrate	Antenna scale modelling. Fabricated antenna at 0.0615 and 0.0625 THz by traditional PCB etching procedure
7.	Horn antenna (2019, [37])	0.22−0.32 THz	Metal	CNC technology
8.	Horn antenna (2018, [54])	0.09−0.140 THz	Copper	Plunge-wire EDM
9.	Rectangular horn antenna (2017, [64]) Cassegrain antenna (2017, [64]) Parabolic antenna (2017, [64])	0.3 THz	–	–
10.	Planar bow-tie antenna (2017, [95])	1 THz	FR-4 substance	Antenna scale modelling. Fabricated antenna at 0.001 THz
	Horn antenna (2016, [68])	0.325−0.5 THz	–	Low cost milling process
11.	Lens antenna (2016, [66])	0.320−0.380 THz	Teflon	No mention the fabrication technology but the porotype has made of fine copper
12.	Lens antenna (2016, [67])	0.11−0.17 THz	Metallic	Conventional milling process

[1] EDM: Electrical Discharge Machining.
[2] PCB: Printed Circuit Board.
[3] HDPE: High Density Polyethylene.
[4] CNC: Computer Numerical Control.

multiband is not included in their studies.

Form these analyses of the performance of the latest related-works of the THz band antenna, further enhancement in antenna directivity or/ and bandwidth in any of mentioned THz band antenna investigations is still required for the upcoming 6G wireless communication system. Therefore, there is still a need to develop a novel multi-ultra-broadband with a very high directional (or omnidirectional with very high gain) antenna in the THz band for the 6G wireless communication system.

On the other hand, THz band antenna studies in [89–92] have achieved the ultra-wideband bandwidth and the minimum high gain antenna for 6G technology, FBW is more than 50 % and gain is over 18 dBi. But, their THz band antenna fabrication and measurement need to be explored, measured and considered as further studies, with its multi-ultra-broadband antenna specification. Also, their antenna types were on microstrip/ patch antenna only (single/ array) and maximum gain was 25 and 22.1 dB for a single patch antenna. Other antenna types on THz band could be needed to consider in future studies as the higher-gain directional antenna (18–40 dBi) is required for 6G technology to overcome the high path loss of THz band and this antenna type may not achieve it with other 6G antenna specifications. Thus, there is still needs to develop a novel higher-gain directional (or omnidirectional) of a single element or maybe very few elements of the antenna, for example, 2–3 elements, of THz band antenna, which meets all 6G antenna specifications,

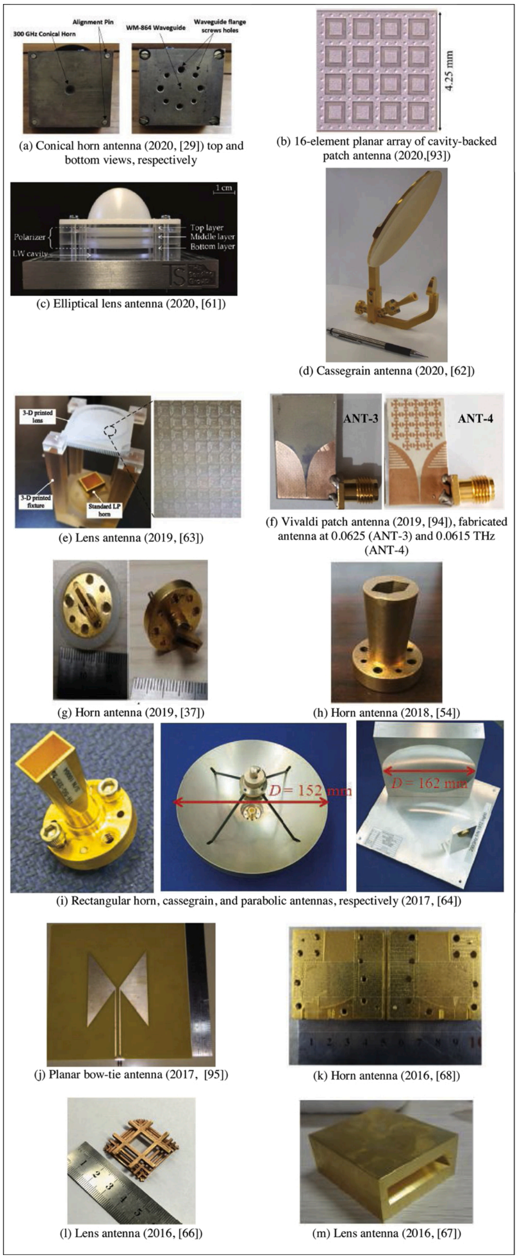


Fig. 5. Recent related-works of fabricated THz band antennas.

as it reduces the cost and complexities in manufacturing and is suitable for indoor applications. Fig. 4 shows the THz band antenna design and performance of [89–92] works.

4.2. Fabrication of THz band antenna

From Table 1, few studies fabricated their THz band antenna as compared to the amount of related-works in subsection 4.1. It is to note that recent related-works used a low-cost material to manufacture their THz band antenna and showed an agreement with their simulation results. This is to reduce the cost in the fabrication technology of the THz band antenna. Moreover, it is observed that no fabrication was done for THz band antenna having frequency of 0.5 THz and higher. Alternatively, the geometry antenna modelling technique is used. Besides, the fabricated THz band antennas that are shown in Table 1 are limited to a simple structure of antennas like horn, lens, planar, cassegrain, parabolic, and patch antennas only. This is due to the smaller size of the THz band, which causes difficulties in the fabrication process of the THz band antenna. Also, THz band antenna requires very high precision fabrication technology [13] as the cost associated with the fabrication of THz band antennas are high. Fig. 5 shows recent related-works of fabricated THz band antenna that is shown in Table 1.

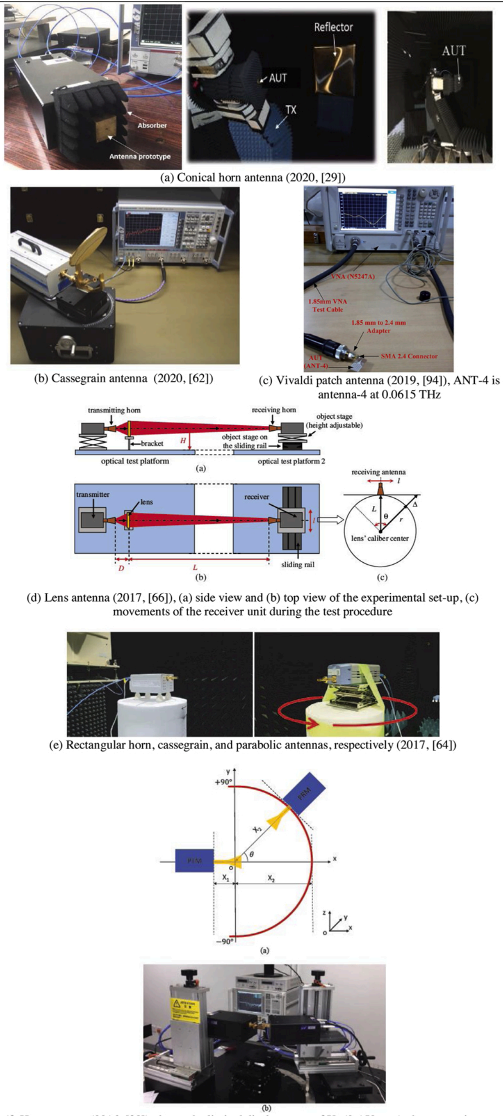
4.3. Measurement of THz band antenna

From Table 2, it is observed that few studies tested their THz band antenna compared to the many related-works in subsection 4.1. This is due to the very short wavelength of THz band antenna that requires very high accuracy alignment and location system. It is also observed that THz band antenna measurement limited up to 1.1 THz as antenna measurement equipment's for frequency higher than 1 THz is not available yet. Besides, the high cost with high accuracy difficulties in alignment and location system for frequency higher than 1 THz is due to the very small size of the THz band antenna. Moreover, some of these few studies in the low-THz band/ sub-THz band (0.1−0.4 THz) used the standard microwave/ millimetre-wave antenna measurement to verify the agreement with their simulation results. This is to reduce the cost of THz band antenna measurement associated with the availability of microwave/ millimetre-wave antenna measurement equipment. Thus, outdoor measurement facility is considered for future study as no THz band anechoic chamber is available for far-field measurements in the range of 0.3 THz and above. Fig. 6 shows antenna measurement setup of some recent related-works of THz band antenna that is shown in Table 2.

Table 2
summarizes the most recent related-works of THz band antenna measurement.

Table 2. Recent related-works of THz band antenna measurement

No.	Antenna type	Frequency range	Material	Measurement
1.	Conical horn antenna (2020, [29])	0.270−0.330 THz	Metal	Millimeter-wave anechoic chamber with absorber mounted on a standard UG-387 waveguide flange. Also, antenna radiation pattern far-field measurement setup
2.	Cassegrain antenna (2020, [62])	0.22−0.3 THz	Brass with gold plating	Rohde & Schwarz ZVA67 vector network analyzer with frequency extender module and standard WR-03 waveguide input. Outdoor measurement facility is considered for further work as no anechoic chamber available for such far-field measurements at 0.3 THz range [62]
3.	Vivaldi patch antenna (2019, [94])	0.56−0.74 THz	Metallic on Rogers RT5880 substrate	Agilent Technologies 65 GHz vector network analyzer (N5247A). Antenna measurement at 0.0615 THz
4.	Horn antenna (2019, [37])	0.22−0.32 THz	Metal	Compact antenna test range system [96] [37]
5.	Horn antenna (2018, [54])	0.09−0.140 THz	Copper	Linear polarization rotation method [97] and in-house developed phaseless gain measurement [98] [54]
6.	Lens antenna (2017, [66])	0.320−0.380 THz	Teflon but, copper for the porotype	Place the lens antenna in the nearby transmitter side of antenna measurement setup
7.	Rectangular horn antenna (2017, [64]) Cassegrain antenna (2017, [64]) Parabolic antenna (2017, [64])	0.3 THz	–	Anechoic chamber
8.	Planar bow-tie antenna (2017, [95])	1 THz	FR-4 substance	Common microwave antenna measurement. Antenna scale modelling at 0.001 THz
9.	Lens antenna (2016, [67])	0.11−0.17 THz	Metallic	THz chamber
10.	Horn antenna (2016, [68])	0.325−0.5 THz	–	THz chamber. The Agilent vector network analyzer is used with two OML terahertz extenders
11.	Horn antenna (2016, [38])	0.22−1.1 THz	–	In-house far-field THz antenna measurement system



(a) Conical horn antenna (2020, [29])

(b) Cassegrain antenna (2020, [62])

(c) Vivaldi patch antenna (2019, [94]), ANT-4 is antenna-4 at 0.0615 THz

(d) Lens antenna (2017, [66]), (a) side view and (b) top view of the experimental set-up, (c) movements of the receiver unit during the test procedure

(e) Rectangular horn, cassegrain, and parabolic antennas, respectively (2017, [64])

(f) Horn antenna (2016, [38]), due to the limited displacement of X_2 (0-159 mm), the system is more suitable for measuring the antennas in the range of 0.5-1.1 THz [38]

Fig. 6. Antenna measurement setup of recent related-works of THz band antenna.

5. THz band antenna challenges

Difficulties in the THz band antenna include design, manufacture and measurement which are discussed in the next sections.

5.1. THz band antenna design

In a traditional network, although directional antennas are used for point-to-point connectivity, they cover long transmission distance [17]. In the future 6G wireless communication system, highly directional antennas are needed to cover short transmission distance due to the high propagation loss at THz frequencies. But, highly directional antennas at the THz band introduces challenge of antenna design trade-offs for 6G technology. Because it is not only highly directional antenna required as in traditional network but, it also should have ultra-wideband and multi-band, small size, and low-cost features.

Ultra-broadband and compact low-profile antennas generally conflict in requirements that lead to a trade-off between the bandwidth and the antenna size [34]. A compact low-profile antenna is usually a narrowband bandwidth. This is why most of the existing antennas in traditional networks have a design to have either one of these requirements, and an optimal antenna design to have all the requirements, but at the cost of big antenna size that leads to a high cost in implementation.

Moreover, it is usually easy to meet one of the required specifications but challenging to meet both requirements, which is particularly true for a broadband antenna [99]. Usually, an ultra-broadband antenna has low directivity/ gain while a narrowband antenna has high gain/ directivity. This is because of the effect of antenna size on the gain and bandwidth. Bandwidth and directivity cannot both increases if the antenna size kept small [100]. A high-gain antenna means that the aperture size of the antenna has to be very large, which may be a problem in practice [99].

Nevertheless, the smaller size of the THz band antennas, due to their shorter wavelength, allow for widening their aperture to increase the gain performance. However, this advantage will narrow the bandwidth of the antenna due to the effect on the antenna size (trade-off). Thus, if the higher gain is desired, the antenna must necessarily be a narrowband device [101]. This feature leads toward correlative design trade-off between the high directivity and ultra-wideband with compact low-profile antenna, which requires new antenna design on the THz band for the 6G wireless communication system.

Low-cost antenna is needed as many antennas will be manufactured for several THz applications in the future. The material and shape of the antenna affect the manufacturing cost. Thus, a cost consideration of antenna manufacture should be kept to a minimum [99]. Conventional antennas are unable to serve the new frequency band due to the limitations in fabrication and installation, mainly for smaller sizes [102]. New low-cost materials and their fabrication technology are needed for the THz band antenna to satisfy the new user requirements of the 6G wireless communication system. As many antennas will be used in the future 6G wireless communication system, the material and manufacture technology should be widely available to enable the usage of these antennas.

Therefore, even though graphene material is a promising material for THz band, it may find some limitation and/or challenging to implement in applications as cost and technology to fabricate the antenna shape, such as 3D antenna, may limit its use. Graphene is still within the research phase and little or no measurement data, especially at the THz band, are available [103]. More studies on using graphene in different antenna types are needed [6]. New broadband antenna design needs to be explored, which ultimately depend on the latest techniques to manufacture and tailor graphene [6]. For these antennas, the high material costs are the main causes that limit their broad spread in the market [34]. Thus, novel low-cost material and investigation of existing materials for each type of antennas will be needed. This is an open research direction on the THz band that needed to be discovered.

On the other hand, metallic antennas are suitable when a low-cost antenna is needed [104]. Metal antenna reduce the cost and fabrication complexity [105]. The properties of copper material make it a favourable choice for antenna fabrication [13]. At THz frequency range, the skin depth and conductivity of the copper metal decreases and thus reduce the radiation efficiency of the antenna elements [13]. At lower THz frequency range, for example, at the resonance frequency of 6.45 THz, the ohmic resistance plays a dominant role in contributing to the surface impedance of copper and thus makes it difficult to design antennas with copper material [13]. Along with the antenna design trade-offs to meet the user specifications in the 6G technology. In [46], patch metal (copper) antenna showed a greater bandwidth and a deeper return loss compared with patch thin graphene antenna (in [46]). That also makes copper antenna on the THz band a favourable choice when a wideband bandwidth feature is needed as in the 6G technology. Nevertheless, due to metal surface loss, it a challenging task to design such THz band antennas using copper material. This is an open research direction on the THz band antenna design using metal material that needed to be solved or discovered for different types of antenna.

Moreover, tunability in frequency response is not required in case of the ultra-wideband (UWB) devices response [81]. The use of graphene material in the implementation of UWB devices, such as antenna, appears to be less effective because the main advantage of using graphene material is its ability to be electrically adjustable by applying an external electrostatic voltage [81]. Graphite material does not need for frequency tuneable in UWB [81]. Thus, the use of graphite material in the implementation of the UWB device for THz application is justifiable [81]. The use of graphite material can provide the robustness and prevent the complexity in manufacture because the requirement of maintaining the uniformity of its layered architecture can be mitigated [81]. Still, ultra-broadband antenna design using graphite material needs to be explored for different types of antenna, such as 3D antenna, to meet the other 6G antenna specifications.

Similarly, the challenge of omnidirectional with high gain antenna design comes at having ultra-wideband and multiband in one antenna while maintaining low-cost feature in 6G technology. Existing ultra-wideband and omnidirectional antennas have difficulty in

Table 3
Current fabrication technology for the THz band antenna.

Fabrication technology	Used	Limitations	Frequency range
Printed circuit broad (PCB) technology	Suitable for simple and 2D structures	Only for simple and 2D structures	0.22–0.325 THz (R-band) [108]
3D printer or additive manufacturing (AM) technology	Suitable for structural parts of large size and complex shape [109]. The precision of the 3D printing equipment can be reach 0.01 mm [109]. Low cost [63]	Unacceptable surface roughness, and limited precision/ resolution for higher THz frequencies [106]	Microwave and millimeter-wave frequencies [63], and some of low-THz band such as 0.22-–0.325 THz (R-band) [108]
Micromachining or micro-electromechanical system (MEMS) technology	Suitable for 3D micro- and nano-structures [106] as it allows a highly accurate manufacturing of devices [42]	Very costly and complicated [63] process. At higher frequency, smaller dimensions of devices and the requested very high accuracy is challenging [42] due to its limited accuracy or tolerance. Micromachining technology machine can have a fine tolerance of 1um [108]	Beyond R-band and up to 1 THz [108]
Nanofabrication technology	Allows to manufacture very precise elements for optical frequencies [42]	Some THz designs can be proven to be too large for this technology [42]	Optical frequency [42]

meeting cheap feature as material and manufacturing technology at the THz band are still open problems. Nevertheless, 6G directional antennas have more priority compared to 6G omnidirectional antennas, due to very high path loss that lies in the nature of the THz band, which shows a significant need of directional antennas in the 6G technology to overcome the high propagation loss of THz band and to provide reliable communication.

5.2. THz band antenna fabrication technology and measurement

Low cost, high precision and reliability manufacturing processes played a major role in the development of THz band antennas [105]. Fabrication and measurements of THz band antenna are also challenging due to its smaller size. Conventional manufacturing technologies for most microwave and millimetre wave antennas will not be applicable at THz frequencies [106] because the fabrication of the THz band antenna needs very high precision, tolerance and very smooth surface finishing [107]. As large surface roughness leads to increased insertion loss, which affects the antenna performance [107]. Table 3 summarizes the limitations of the current fabrication technology for the THz band antenna.

From Table 3, it is observed that current fabrication technologies for THz band antenna limited up to 1 THz only. Fabrication technology for THz frequency more than 1 THz of the antenna is not yet available in the open literature. Because of the reduced antenna size at the THz band, the suitable fabrication processes are limited [105]. Thus, unique and complicated manufacturing techniques are required to permit the high precision for THz band antenna design [105]. This is an open research problem that needs to be solved in the future as it is related to the cost of the antenna, and it is implementation. The THz band antenna measurement also limited to 1.1 THz (shown in Table 2) as antenna measurement equipment, such as vector network analyser, for frequency higher than 1 THz is not available yet [108]. Due to high cost and accuracy difficulties in alignment and location system of THZ band antenna. This is also an open research problem that needs to be solved in the future as it related to the cost of the antenna and its measurement processes.

6. Resaech directions

The possible research directions are as follow:

- Design THz band antenna that meets specifications for the 6G wireless communication system.
- Design THz band antenna using metal material that meets specifications for the 6G technology.
- Develop or enhance any of THz band antenna studies in subsection 4.1 to meet specifications for the 6G technology, with its fabrication and measurement.
- Explore 3D/ 2D THz band antenna using graphene and graphite materials for the 6G technology, with its fabrication and measurement.
- Investigate existing low-cost materials (if any) for different type of antennas on the THz band that meets 6G antenna specifications.
- Explore fabrication of 3D antenna or other antenna types that is shown in Table 1 on the THz band.
- Develop any of fabrication technology that is shown in Table 3, for THz band antennas.
- Develop antenna measurement equipment/ setup for THz band antenna higher than 1 THz. THz band anechoic chamber is not available for antenna far-field measurements/ outdoor measurements facilities in the range of 0.3 THz and above.
- Develop a novel low-cost material on the THz band.

Fig. 7 shows a brief of possible research directions of THz band antenna in the 6G wireless communication system: design, fabrication, and measurement. It summarizes the open problems or needed studies, which is discussed in the previous section (section 5). Design difficulties in meeting all 6G antenna specifications for THz band antenna, unique and complicated manufacturing techniques are required to permit the high precision for THz band antenna design, and accuracy difficulties in alignment and location system of THz band antenna, with its fabrication and measurement availability. It also shows the connection between them for further studies. THz band studies in others field such as material science, manufacture technology, and measurement equipment will help to implement the THz band antenna in the 6G wireless communication system.

7. Conclusion

THz bands (0.1−10 THz) provide extreme-wide bandwidth allowing an ultra-high-speed communication for many future 6G applications. Many challenges on the THz band needs to be overcome for the next 6G wireless communication system. In this paper, a detailed review of the most significant THz band antenna challenge is presented. We have highlighted the antenna specifications in 6G technology for ultra-high-speed THz wireless communication applications. The antenna design challenges to meet the 6G antenna specifications are clarified. Some difficulties in THz band antenna fabrication and measurement are discussed. In the end, we have indicated some open research directions, which opens the way for the development of THz band antenna for future 6G wireless communication system.

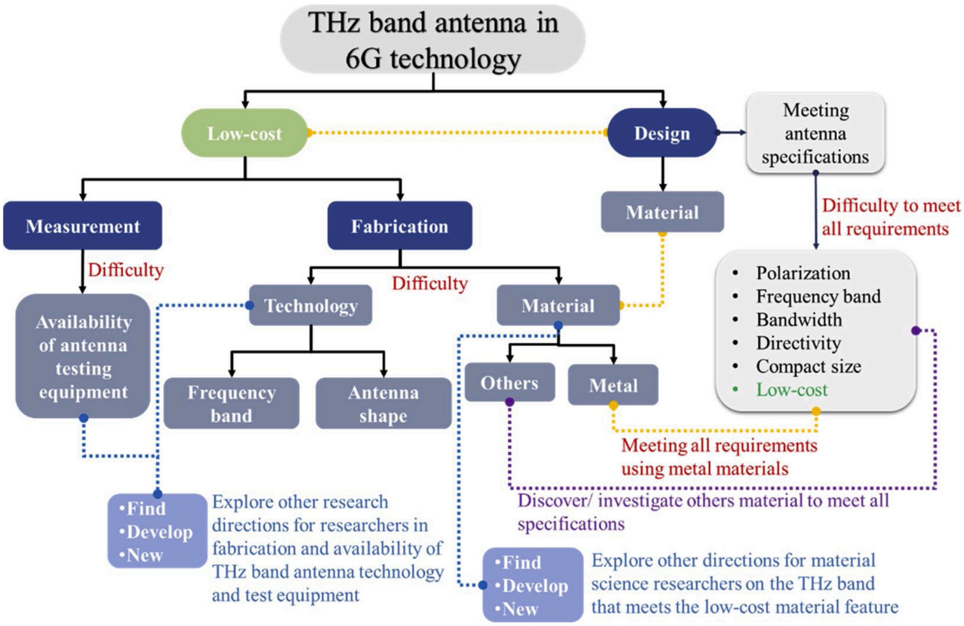


Fig. 7. Brief research directions of THz band antenna in 6G wireless communication system.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, M. Zorzi, Towards 6G networks: use cases and technologies, arXiv preprint arXiv 1903 (2019) 12216.
[2] M. Latva-aho, K. Leppänen, F. Clazzer, A. Munari, Key Drivers and Research Challenges for 6G Ubiquitous Wireless Intelligence, 2020.
[3] J.F. O'Hara, S. Ekin, W. Choi, I. Song, A Perspective on Terahertz Next-Generation Wireless Communications, Technologies 7 (2) (2019), p. 43.
[4] M.Z. Chowdhury, M. Shahjalal, S. Ahmed, Y.M. Jang, 6G wireless communication systems: applications, requirements, technologies, challenges, and research directions, arXiv preprint arXiv 1909 (2019), 11315.
[5] I.F. Akyildiz, J.M. Jornet, C. Han, Terahertz band: next frontier for wireless communications, Phys. Commun. 12 (2014) 16–32.
[6] K. Tekbıyık, A.R. Ekti, G.K. Kurt, A. Görçin, Terahertz band communication systems: challenges, novelties and standardization efforts, Phys. Commun. 35 (2019) 100–700.
[7] ITU-R SM 2352-0, Technology Trends of Active Services in the Frequency Range 275-3 000 GHz, Jun, 2015.
[8] J. Federici, L. Moeller, Review of terahertz and subterahertz wireless communications, J. Appl. Phys. 107 (11) (2010), p. 6.
[9] A.K. Varshney, N.P. Pathak, D. Sircar, Design of Graphene-Based THz Antennas, Singapore, Springer, Singapore, 2019, pp. 29–35.
[10] N. Naeem, S. Parveen, A. Ismail, Terahertz communications for 5G and beyond. Antenna Fundamentals for Legacy Mobile Applications and Beyond, Springer, 2018, pp. 305–322.
[11] W. Saad, M. Bennis, M. Chen, A vision of 6G wireless systems: applications, trends, technologies, and open research problems, IEEE Netw. (2019).
[12] E.C. Strinati, S. Barbarossa, J.L. Gonzalez-Jimenez, D. Kténas, N. Cassiau, C. Dehos, 6G: the next frontier, arXiv preprint arXiv 1901 (2019), 03239v2.
[13] M.A. Jamshed, A. Nauman, M.A.B. Abbasi, S.W. Kim, Antenna selection and designing for THz applications: suitability and performance evaluation: a survey, IEEE Access 8 (2020), pp. 113246-113261.
[14] X. Ma, Z. Chen, W. Chen, Y. Chi, Z. Li, C. Han, et al., Intelligent reflecting surface enhanced indoor terahertz communication systems, Nano Commun. Netw. 24 (2020), p. 100284.
[15] J.-h. Zhang, P. Tang, L. Yu, T. Jiang, L. Tian, Channel measurements and models for 6G: current status and future outlook, Front. Inf. Technol. Electron. Eng. 21 (1) (2020), pp. 39-61.
[16] N.H. Mahmood, H. Alves, O.A. López, M. Shehab, D.P.M. Osorio, M. Latva-aho, Six key enablers for machine type communication in 6G, arXiv preprint arXiv 1903 (2019), 05406.
[17] S. Ghafoor, N. Boujnah, M.H. Rehmani, A. Davy, MAC protocols for terahertz communication: a comprehensive survey, arXiv preprint arXiv 1904 (2019), 11441.
[18] G. Geetharamani, T. Aathmanesan, Metamaterial inspired THz antenna for breast cancer detection, SN Applied Sciences 1 (6) (2019), p. 595.
[19] S. Poorgholam-Khanjari, F.B. Zarrabi, Reconfigurable Vivaldi THz antenna based on graphene load as hyperbolic metamaterial for skin cancer spectroscopy, Opt. Commun. (2020). , p. 126482.
[20] P.J. Bevelacqua, Fractional Bandwidth (FBW), Available:, 2008 http://www.antenna-theory.com/definitions/fractionalBW.php.
[21] Y. Yuan, Y. Zhao, B. Zong, S. Parolari, Potential key technologies for 6G mobile communications, arXiv preprint arXiv (2019), 1910.00730.
[22] R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch, J. Schoebei, et al., Short-range ultra-broadband terahertz communications: concepts and perspectives, IEEE Antennas Propag. Mag. 49 (6) (2007) 24–39.

[23] T. Kürner, THz communications: challenges and applications beyond 100 Gbit/s, in: 2018 International Topical Meeting on Microwave Photonics (MWP), IEEE, 2018, pp. 1–4.
[24] Z. Chen, X. Ma, B. Zhang, Y. Zhang, Z. Niu, N. Kuang, et al., A survey on terahertz communications, China Commun. 16 (2) (2019) 1–35.
[25] A.K. Fahad, C. Ruan, K. Chen, A wideband terahertz transmissive polarization manipulator based on metasurfaces, Electronics 8 (10) (2019), p. 1068.
[26] M. Shalini, Performance predictions of slotted graphene patch antenna for multi-band operation in terahertz regime, Optik (2020), p. 164223.
[27] Q. Xia, J.M. Jornet, Expedited neighbor discovery in directional terahertz communication networks enhanced by antenna side-lobe information, Ieee Trans. Veh. Technol. 68 (8) (2019), pp. 7804-7814.
[28] I.F. Akyildiz, J.M. Jornet, Realizing ultra-massive MIMO (1024× 1024) communication in the (0.06–10) terahertz band, Nano Commun. Netw. 8 (2016) 46–54.
[29] B. Aqlan, M. Himdi, L. Le Coq, H. Vettikalladi, Sub-THz circularly polarized horn antenna using wire electrical discharge machining for 6G wireless communications, IEEE Access 8 (2020), pp. 117245-117252.
[30] H. Jalili, O. Momeni, Scalable wideband and Wide-angle beam steering mm-Wave/THz radiator and phased arrays in silicon, in: 2018 Asia-Pacific Microwave Conference (APMC), IEEE, 2018, pp. 1157–1159.
[31] W. Roh, J. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, F. Aryanfar, Millimeter-wave beamforming as an enabling technology for 5g cellular communications: theoretical feasibility and prototype results, IEEE Communications Magazine 52 (2) (2014) 106–113.
[32] H. Sarieddeen, M.-S. Alouini, T.Y. Al-Naffouri, Terahertz-band ultra-massive spatial modulation MIMO, Ieee J. Sel. Areas Commun. 37 (9) (2019) 2040–2052.
[33] P. Bernardi, R. Cicchetti, O. Testa, An accurate UTD model for the analysis of complex indoor radio environments in microwave WLAN systems, IEEE Trans. Antennas Propag. 52 (6) (2004) 1509–1520.
[34] R. Cicchetti, E. Miozzi, O. Testa, Wideband and UWB antennas for wireless applications: a comprehensive review, Int. J. Antennas Propag. 2017 (2017).
[35] P.J. Bevelacqua, Polarization of Plane Waves, Available:, 2008 http://www.antenna-theory.com/basics/polarization.php#polarization.
[36] M. Secmen, J. Maicas, Multiband and wideband antennas for mobile communication systems, in *Recent Developments in Mobile Communications—a Multidisciplinary Approach*, InTech (2011) 143–163.
[37] H.-y. Yu, J. Yu, Y. Yao, X. Liu, X. Chen, Wideband circularly polarised horn antenna with large aspect ratio for terahertz applications, Electron. Lett. 56 (1) (2019) 11–13.
[38] H.-T. Zhu, Q. Xue, W.-Q. Che, An in-house far-field THz antenna measurement system, in: 2016 IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), IEEE, 2016, pp. 1–2.
[39] M. Zeain, M. Abu, Z. Zakaria, H. Sariera, H. Lago, Design of helical antenna for wideband frequency, Int. J. Eng. Res. Technol. Ahmedabad (Ahmedabad) 11 (4) (2018) 595–603.
[40] Y. Liang, J. Zhang, Q. Liu, X. Li, High-power dual-branch helical antenna, IEEE Antennas Wirel. Propag. Lett. 17 (3) (2018) 472–475.
[41] X.-Q. Yang, Z.-H. Yan, T.-L. Zhang, B. Fan, A novel printed helical antenna for a circularly polarized tilted beam, Prog. Electromagn. Res. 53 (2015) 51–55.
[42] D. Warmowska, K.A. Abdalmalak, L.E.G. Muñoz, Z. Raida, High-gain, circularly-polarized THz antenna with proper modeling of structures with thin metallic walls, IEEE Access 8 (2020), pp. 125223-125233.
[43] S. Singhal, Compact superwideband terahertz antenna, in: 2020 URSI Regional Conference on Radio Science (URSI-RCRS), IEEE, 2020, pp. 1–4.
[44] H. Vettikalladi, W.T. Sethi, A.F.B. Abas, W. Ko, M.A. Alkanhal, M. Himdi, Sub-THz antenna for high-speed wireless communication systems, Int. J. Antennas Propag. 2019 (2019).
[45] S. Singhal, Hexagonal fractal antenna for super wideband terahertz applications, Optik (2019), p. 163615.
[46] A. Hocini, M. Temmar, D. Khedrouche, M. Zamani, Novel approach for the design and analysis of a terahertz microstrip patch antenna based on photonic crystals, Photonics and Nanostructures-Fundamentals and Applications 36 (2019), p. 100723.
[47] H. Davoudabadifarahani, B. Ghalamkari, High efficiency miniaturized microstrip patch antenna for wideband terahertz communications applications, Optik (2019) 194, p. 163118.
[48] S. Singhal, Elliptical ring terahertz fractal antenna, Optik 194 (2019), pp. 163-129.
[49] S. Singhal, Ultrawideband elliptical microstrip antenna for terahertz applications, Microw. Opt. Technol. Lett. 61 (10) (2019) 2366–2373.
[50] A. Dhiflaoui, L. Ladhar, M. Aseeri, T. Aguili, N. Eltresy, H. Rmili, Design of a wideband and High directive Log spiral THz antenna for photoconductive sources, in: 2018 International Conference on Internet of Things, Embedded Systems and Communications (IINTEC), IEEE, 2018, pp. 64–67.
[51] R.T. Hussein, H.A. Abdulnabi, Zigzag edges toothed Log periodic terahertz antenna design based on graphene hilbert curve AMC, in: 2018 Third Scientific Conference of Electrical Engineering (SCEE), IEEE, 2018, pp. 140–143.
[52] T. Saeidi, I. Ismail, W.P. Wen, A.R. Alhawari, UWB transparent THz antenna for medical imaging and satellite communication applications, in: 2018 IEEE International RF and Microwave Conference (RFM), IEEE, 2018, pp. 341–344.
[53] X. Zhang, C. Ruan, J. Dai, T. ul Haq, Frequency and radiation pattern reconfigurable graphene square spiral antenna at terahertz band, in: 2018 IEEE Asia-Pacific Conference on Antennas and Propagation (APCAP), IEEE, 2018, pp. 1–2.
[54] S. Bhardwaj, J.L. Volakis, Hexagonal waveguide based circularly polarized horn antennas for sub-mm-wave/terahertz band, IEEE Trans. Antennas Propag. 66 (7) (2018), pp. 3366-3374.
[55] A. Dhiflaoui, H. Rmili, O. Boularess, A. Yahyaoui, T. Aguili, R. Mittra, Design of an ultra-wideband and highly-directive photoconductive THz vivaldi antenna, in: 2017 10th Global Symposium on Millimeter-Waves, IEEE, 2017, pp. 103–105.
[56] T. Wahyudi, C. Apriono, F.Y. Zulkifli, E.T. Rahardjo, Broadband planar bow-tie antenna on high resistivity silicon substrate for terahertz application, in: 2017 15th International Conference on Quality in Research (QiR): International Symposium on Electrical and Computer Engineering, IEEE, 2017, pp. 372–376.
[57] L. Guo, H. Meng, L. Zhang, J. Ge, Design of MEMS on-chip helical antenna for THz application, in: 2016 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), IEEE, 2016, pp. 1–4.
[58] R.A. Sadeghzadeh, F.B. Zarrabi, Metamaterial Fabry–Perot cavity implementation for gain and bandwidth enhancement of THz dipole antenna, Optik 127 (13) (2016), pp. 5181-5185.
[59] Y. Li, S.-b. Wang, L.-a. Yang, S.-r. Xu, Y. Hao, Design of wideband and high efficiency THz yagi antenna by using air bridge technology, in: 2016 13th IEEE International Conference on Solid-State and Integrated Circuit Technology (ICSICT), IEEE, 2016, pp. 1573–1575.
[60] M. Biabanifard, S. Biabanifard, S.J. Hosseini, A. Jahanshiri, Design and comparison of terahertz graphene antenna: ordinary dipole, fractal dipole, spiral, bow-tie and log-periodic, Eng Technol Open Acc. 2 (2) (2018), pp. 555-584.
[61] M.A. Campo, G. Carluccio, D. Blanco, O. Litschke, S. Bruni, N. Llombart, Wideband circularly polarized antenna with in-lens polarizer for high-speed communications, IEEE Trans. Antennas Propag. (2020).
[62] A. Kosogor, Y. Tikhov, A 220-300 GHz offset dual-reflector antenna for Point-to-Point radio, in: 2020 14th European Conference on Antennas and Propagation (EuCAP), IEEE, 2020, pp. 1–3.
[63] G.B. Wu, Y.-S. Zeng, K.F. Chan, S.-W. Qu, C.H. Chan, High-gain circularly polarized lens antenna for terahertz applications, IEEE Antennas Wirel. Propag. Lett. 18 (5) (2019), pp. 921-925.
[64] H. Sawada, A. Kanno, N. Yamamoto, K. Fujii, A. Kasamatsu, K. Ishizu, et al., High gain antenna characteristics for 300 GHz band fixed wireless communication systems, in: 2017 Progress in Electromagnetics Research Symposium-Fall (PIERS-FALL), IEEE, 2017, pp. 1409–1412.
[65] Z. Li, Y. Liu, B. Li, X. Lv, Design of a terahertz circularly polarized quasi-diagonal horn antenna based on MEMS technology, in: 2017 International Applied Computational Electromagnetics Society Symposium (ACES), IEEE, 2017, pp. 1–2.
[66] W. Pan, W. Zeng, X. Yu, J. Zhang, A novel high-gain directional Lens antenna for terahertz band, Prog. Electromagn. Res. 68 (2016) 107–117.
[67] Z.-C. Hao, J. Wang, A D-band high-gain antenna for terahertz applications, in: 2016 International Symposium on Antennas and Propagation (ISAP), IEEE, 2016, pp. 546–547.
[68] K. Fan, Z.-C. Hao, W. Hong, A 325–500 GHz high gain antenna for terahertz applications, in: 2016 International Symposium on Antennas and Propagation (ISAP), IEEE, 2016, pp. 780–781.

[69] G. Bansal, A. Marwaha, A. Singh, A graphene-based multiband antipodal Vivaldi nanoantenna for UWB applications, J. Comput. Electron. (2020), pp. 1-10.
[70] N.S. Badr, G. Moradi, Graphene-Based microstrip-fed hexagonal shape dual band antenna, Optik 202 (2020), p. 163608.
[71] H.-F. Zhang, G.-B. Liu, T. Huang, L. Zeng, Design of a frequency reconfigurable broadband THz antenna based on the vanadium dioxide, Plasmonics (2020), pp. 1-7.
[72] S.P.J. Christydass, J. Suganthi, S. Kavitha, R. Yuvaraj, Ring monopole antenna for Tera-Hertz application, Mater. Today Proc. (2020).
[73] M.A.K. Khan, T.A. Shaem, M.A. Alim, Graphene patch antennas with different substrate shapes and materials, Optik 202 (2020) 163–700.
[74] M.R. Tripathy, V. Choudhary, A. Gupta, P. Ranjan, D. Ronnow, A Diamond-shaped fractal bow-tie antenna for THz applications. Advances in Communication, Cloud, and Big Data, Springer, 2019, pp. 97–104.
[75] S. Ullah, C. Ruan, T.U. Haq, Z-shaped dual band circular polarized microstrip antenna for THz communication, in: 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), IEEE, 2019, pp. 1–2.
[76] S. Ullah, C. Ruan, M.S. Sadiq, T.U. Haq, A.K. Fahad, Design of a simple inter-connected U-shaped circular polarized monopole antenna for THz communication applications, in: 2019 PhotonIcs & Electromagnetics Research Symposium-Spring (PIERS-Spring), IEEE, 2019, pp. 3652–3655.
[77] M.A.K. Khan, T.A. Shaem, M.A. Alim, Analysis of graphene based miniaturized terahertz patch antennas for single band and dual band operation, Optik 194 (2019), p. 163012.
[78] G. Samanta, D. Mitra, Wideband THz antenna using graphene based tunable circular reactive impedance substrate, Optik 158 (2018) 1080–1087.
[79] D. Kumar, M. Tripathy, D. Ronnow, P. Geethu, L. Saurabh, Performance analysis of meta-material based bow-tie shaped fractal antenna for THz application, in: 2017 7th International Conference on Cloud Computing, Data Science & Engineering-Confluence, IEEE, 2017, pp. 764–769.
[80] M. Khulbe, M. Tripathy, H. Parthasarthy, J. Dhondhiyal, Dual band THz antenna using T structures and effect of substrate volume on antenna parameters, in: 2016 8th International Conference on Computational Intelligence and Communication Networks (CICN), IEEE, 2016, pp. 191–195.
[81] G. Varshney, Ultra-wideband Antenna Using Graphite Disk Resonator for THz Applications, Superlattices and Microstructures, , p. 106480, 2020.
[82] V.S. Yadav, A.K. Nayak, S. Kulshrestha, B.K. Kaushik, A. Patnaik, Prospective design of dual band graphene-based patch antenna for mid-THz band, in: 2020 URSI Regional Conference on Radio Science (URSI-RCRS), IEEE, 2020, pp. 1–4.
[83] A. Hlali, Z. Houaneb, H. Zairi, Dual-band reconfigurable graphene-based patch antenna in terahertz band: design, analysis and modeling using WCIP method, Prog. Electromagn. Res. 87 (2018), pp. 213-226.
[84] J.N. George, M.G. Madhan, Analysis of single band and dual band graphene based patch antenna for terahertz region, Physica E Low. Syst. Nanostruct. 94 (2017), pp. 126-131.
[85] M. Faridani, R. Sadeghzadeh, M. Khatir, Terahertz dual-band dipole antenna with novel small flat quartz-copper reflector, Optik 136 (2017) 336–340.
[86] G. Bansal, A. Singh, R. Bala, A triband slotted bow-tie wideband THz antenna design using graphene for wireless applications, Optik 185 (2019) 1163–1171.
[87] U.N. Nissan, G. Singh, P. Kumar, N. Kumar, High gain terahertz microstrip array antenna for future generation cellular communication, in: 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), IEEE, 2020, pp. 1–6.
[88] Y. Huang, X. Li, Z. Qi, H. Zhu, J. Xiao, J. Chu, A 140-GHz high-gain broadband tapered box-horn array antenna, in: 2017 IEEE Asia Pacific Microwave Conference (APMC), IEEE, 2017, pp. 765–767.
[89] H.A. Abdulnabi, M.A. Shuriji, S. Ahmed, UWB THz plasmonic microstrip antenna based on graphene, Telkomnika 18 (1) (2020).
[90] U. Keshwala, S. Rawat, K. Ray, Inverted K-shaped antenna with partial ground for THz applications, Optik (2020), p. 165092.
[91] G. Saxena, Y. Awasthi, P. Jain, High isolation and high gain super-wideband (0.33-10 THz) MIMO antenna for THz applications, Optik 223 (2020) 165335.
[92] U. Keshwala, S. Rawat, K. Ray, Plant shaped antenna with trigonometric half sine tapered leaves for THz Applications, Optik (2020), p. 165648.
[93] A. Lamminen, J. Säily, J. Ala-Laurinaho, J. de Cos, V. Ermolov, Patch antenna and antenna array on multilayer high-frequency PCB for D-Band, IEEE Open Journal of Antennas and Propagation 1 (2020) 396–403.
[94] R.K. Kushwaha, P. Karuppanan, Design and analysis of Vivaldi antenna with enhanced radiation characteristics for mm-wave and THz applications, Opt. Quantum Electron. 51 (9) (2019), p. 309.
[95] A.P. Aji, C. Apriono, F.Y. Zulkifli, E.T. Rahardjo, Radiation pattern validation of a THz planar bow-tie antenna at microwave domain by scaling up technique, in: 2017 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET), IEEE, 2017, pp. 108–111.
[96] X. Chen, X. Liu, J. Yu, Y. Yao, C. Yang, H. Wang, et al., A tri-reflector compact antenna test range operating in the THz range, in: 2015 9th European Conference on Antennas and Propagation (EuCAP), IEEE, 2015, pp. 1–3.
[97] IEEE Standard Test Procedures for Antennas, IEEE StandardANSI/IEEE, 1979, pp. 149–1979.
[98] S. Bhardwaj, N.K. Nahar, J.L. Volakis, Novel phaseless gain characterization for circularly polarized antennas at mm-wave and THz frequencies, IEEE Trans. Antennas Propag. 63 (10) (2015) 4263–4270.
[99] Y. Huang, K. Boyle, Antennas: From Theory to Practice, John Wiley & Sons, 2008.
[100] C.A. Balanis, Modern Antenna Handbook, John Wiley & Sons, 2011.
[101] R.F. Harrington, Effect of antenna size on gain, bandwidth, and efficiency, J. Res. Nat. Bur. Stand 64 (1) (1960) 1–12.
[102] S.N.H. Sa'don, M.H. Jamaluddin, M.R. Kamarudin, F. Ahmad, Y. Yamada, K. Kamardin, et al., Analysis of graphene antenna properties for 5G applications, Sensors 19 (22) (2019) 4835.
[103] M. Bharadwaj, J. Prajapati, R. Bhattacharjee, Novel graphene based antennas for the terahertz region, Semicond. Sci. Technol. 34 (1) (2018) 014003.
[104] Y. He, Y. Chen, L. Zhang, S.-W. Wong, Z.N. Chen, An overview of terahertz antennas, China Commun. 17 (7) (2020) 124–165.
[105] C. Gu, S. Gao, B. Sanz-Izquierdo, Low-cost wideband low-THz antennas for wireless communications and sensing, in: 2017 10th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies (UCMMT), IEEE, 2017, pp. 1–4.
[106] S.-Y. Zhu, Y.-L. Li, K.-M. Luk, S.W. Pang, Compact high-gain Si-Imprinted THz antenna for ultrahigh speed wireless communications, IEEE Trans. Antennas Propag. 68 (8) (2020) 5945–5954.
[107] B. Zhang, W. Chen, Y. Wu, K. Ding, R. Li, Review of 3D printed millimeter-wave and terahertz passive devices, Int. J. Antennas Propag. 2017 (2017).
[108] C.H. Chan, THz Antennas–Design, fabrication and testing, in: 2019 13th European Conference on Antennas and Propagation (EuCAP), IEEE, 2019, pp. 1–4.
[109] R. Xu, S. Gao, B.S. Izquierdo, C. Gu, P. Reynaert, A. Standaert, et al., A review of broadband low-cost and high-gain low-terahertz antennas for wireless communications applications, IEEE Access 8 (2020) 57615–57629.