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A Brief Review on Development of Terahertz Antennas

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ABSTRACT:
Terahertz (THz) antennas are crucial components in developing THz systems for sending and receiving THz electromagnetic waves due to their tiny size, wide frequency bandwidth, and high data rate. However, because to their small diameters in high frequency THz wave bands, the majority of THz antennas suffer from relatively high loss and low fabrication precision. As a result, this paper provides a thorough overview of the most recent studies on the enhancement of THz antenna performance. First, a brief history of THz antenna development is given, followed by an introduction to the fundamental principles guiding THz antenna design. Then, THz antennas are divided into metallic, dielectric, and novel material categories. The most recent developments in THz horn antennas, THz microstrip antennas. This document also provides a brief overview of the THz antennas' manufacturing technology.

Keywords: THz antennas, Dielectric antennas, Horn antennas, Microstrip antennas.

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I.INTRODUCTION

With the rise in popularity of wireless technology, data traffic has entered a new phase of rapid development [1], often known as the data traffic explosion. Since wireless devices like mobile phones are portable and easy to use in real time, many applications are currently gradually moving from PCs to them. However, this condition also causes a sharp spike in data traffic and a dearth of bandwidth resources. According to studies, the market's data rate will probably approach Gbps or possibly Tbps within the next ten to fifteen years . THz communication now has a Gbps data rate, although Tbps data rate development is still in its early stages outlined recent developments in the THz band-based Gbps data rate and predicted that polarization multiplexing may be used to achieve Tbps. The development of a new frequency band [2], which is a THz electromagnetic wave at the "blank area" between microwaves and infrared light, is thus a workable solution to boost the data transmission rate. Fixed and land mobile services have been utilized in the ITU World Radio communication Conference 2019 (WRC-19) in the frequency range of 275-450 GHz.. A terahertz electromagnetic wave is typically defined as having a wavelength of 0.03–3mm and operating in the 0.1–10 THz (1 THz = 1012 Hz) frequency range. The IEEE standard defines the THz wave as occurring between 0.3 and 10 THz. The THz wave can be shown in Figure 1 as being halfway between microwaves and infrared light.

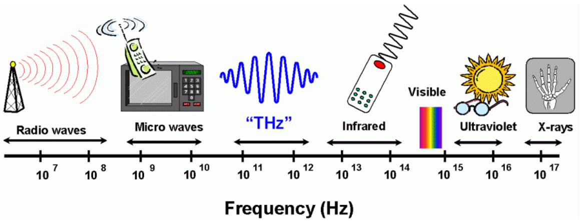


Fig. 1. The position of the THz wave in the Electromagnetic spectrum.

II. THE THZ WAVE CHARACTERISTICS

Low damage: The THz wave's single-photon energy, which is only a few parts per million, is far lower than that of X-rays. As a result, using THz waves in the biomedical industry to scan the body for skin cancer can help treat disease and THz waves are safe for organ systems [3].

Visualization: THz waves' short wavelengths allow them to pass through some non-polar or non-metallic materials. Images with enhanced quality can be presented by scanning opaque visible objects with THz waves. As a result, the THz wave is frequently utilised in sensing applications, such as full-body scanners at airports.

High spectral resolution: The THz band is where the majority of big molecules' spectra are located. The identification of hazardous materials like viruses, explosives, firearms, chemicals, etc. requires a large deal of analysis of the THz radiation spectrum.

Wide bandwidth: In electronics, the THz wave may be the electromagnetic wave at the highest frequency range. Even at Tbps, the rate of information transfer may increase if the THz wave is employed as the signal carrier broadcast by the antennas.

In a word, THz wave sensing applications have advanced quickly. THz antenna applications, however, are not yet developed enough. The antennas are further constructed at higher frequency band due to the severe limitation of present spectrum resources. Based on the THz spectrum's ability to operate in a wide bandwidth, THz band antennas provide significantly higher bandwidth than conventional antennas. THz waves have advantages over light and millimeter waves. The usable frequency band is bigger, the beam direction is stronger, the secrecy and anti-interference performance are better than with millimeter waves. THz waves are more effective and have greater penetration than light waves. The large operational bandwidth of THz antennas gives them the best performance, as would be expected given the special properties of THz waves.

THz antennas are essential components for transmitting and receiving THz waves in THz wireless communication systems. Particularly the working bandwidth and gain of the antennas, the performance of THz antennas directly impacts the quality of the overall system. Additionally, the data transmission rate, system imaging resolution, and the detection system's operational range are all intimately tied to the property of THz antennas. THz antennas excel in a wide frequency band, excellent resolution, strong directivity, and miniaturization thanks to the benefits of THz waves. It should be emphasised as well that there are numerous new difficulties facing THz antennas in comparison to microwave antennas. The gadget size is significantly decreased because the THz antenna operates in the high frequency range. Materials and manufacturing techniques have a limit on how THz antennas may be packaged. Another issue with terahertz antennas is how to make them radiate efficiently [4]. THz antennas must therefore adhere to stricter specifications for antenna type, manufacturing materials, and process technology.

This study presents a thorough review of THz antennas to serve as a reference for readers' future research and use of THz antennas. To help readers comprehend the design principles of THz antennas, Section II presents the THz wave characteristics, in Section III. Basic Terahertz Antennas, Section IV describes the development of THz antennas in relation to other references. Section V describes the Typical THz antennas and Section VI About process technology of THZ antennas. Section VII is provided conclusion.

III. BASIC TERAHERTZ ANTENNAS

There are numerous forms of THz antennas that are currently in use, including the pyramidal cavity with dipole, angle reflector array, bow-tie dipole, dielectric lens planar antennas, photoconductive antennas for producing THz source radiation sources, THz horn antennas, and THz antennas made of graphene materials, among others[5]. THz antennas can be broadly categorized into metallic antennas (mostly horn antennas), dielectric antennas (based on lens antennas), and novel material antennas based on the manufacturing material. One of the common types of metallic antennas is the horn, which is made to function as an antenna in the THz band. The traditional millimeter-wave receiver's antenna is a conical horn. A rotationally symmetric radiation pattern, a high gain of 20 to 30 dBi, and a low cross-polarization level of -30 dB with 97%–98% [6]coupling efficiency are just a few benefits of the corrugated and dual-mode antennas.

The dielectric antennas are made up of an antenna radiator and a dielectric substrate. The advantages of the dielectric antennas include a straightforward method, simple integration, and inexpensive cost when impedance matching with the detector is achieved by suitable design. In recent years, researchers developed a number of narrowband and wideband edge-emitting antennas, such as butterfly antennas, dual U-shaped antennas, logarithmic periodic antennas, and log periodic sinusoidal antennas that can be matched to low-impedance detectors for THz dielectric antennas. There is another form of THz antenna composed of novel materials in addition to the first two types of antennas mentioned. For instance, a carbon nanotube dipole antenna was suggested by Jin Hao et al. in 2006. Instead of a metal component, the dipole is constructed of carbon nanotubes. Carbon nanotube dipole antennas' optical and infrared characteristics are thoroughly investigated in [7]. Finite length carbon nanotube dipoles' common antenna properties, including input impedance, current distribution, gain, efficiency, and radiation mode, are reviewed.

IV. DEVELOPMENT OF TERAHERTZ ANTENNAS

In this part, we provide a quick overview of THz antenna creation to aid readers in understanding. THz research was started in the 19th century, however at that time it was not treated as a separate discipline. The majority of THz research focuses on the long to far-infrared area. Researchers did not start expanding millimeter-wave study into the THz band and establishing specialized research on THz technologies until the middle and late 20th century. In the 1980s, THz waves could be used in real systems thanks to the development of THz radiation sources. Figure 2 depicts how THz technology has advanced.

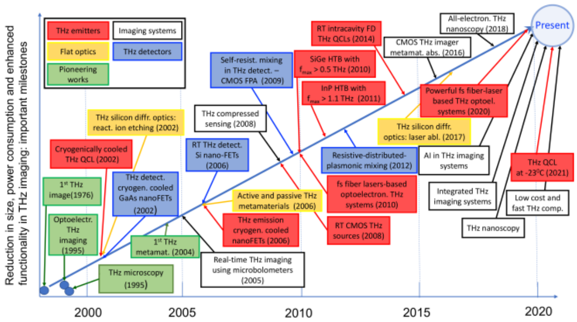


Fig. 2. *The development of THz technology*

Since the dawn of the 21st century, wireless communication technology has advanced quickly, and the need for information as well as the expansion of communication tools has increased the demands on the data transmission rate. Therefore, operating at a high data rate of gigabits per second in one area is one of the issues facing future communication technologies. Resources for the band have become more and scarcer due to the current economic development. Humans, however, have an infinite need for communication's capacity and speed. Many companies use multiple-input multiple-output (MIMO) technology to boost spectral efficiency and system capacity via spatial multiplexing in order to address the issue of spectrum congestion , [8].Each user's data connection speed will surpass GPS thanks to the development of 5G networks , and base station data traffic will rise significantly as well. Microwave links won't be able to support these massive data rates for conventional millimeter-wave communication systems. Additionally, infrared communication's transmission distance is low and its communication equipment's position is fixed when line-of-sight is present. As a result, high-speed communication systems can be built employing the THz wave between microwave and infrared, using THz lines; the data transfer rate is increased.

In comparison to microwaves, THz waves can offer a substantially wider communication bandwidth because their frequency range is roughly 1000 times larger. As a result, using THz to create an ultra-high-speed wireless communication system is a viable solution to the high data rate difficulty, which has piqued the interest of numerous research teams and industries. The first THz wireless communication standard IEEE 802.15.3d-2017 [9], which specifies exchange point-to-point at the lower THz frequency range of 252-325 GHz, was released in September 2017. With various bandwidths, the link's alternative physical layer (PHY) can reach data rates of up to 100 Gbps.

Unlike millimeter waves, the THz communication system has a big capacity and a high data transfer rate. It is mostly used for short-distance communication on Earth and in space. Although THz waves are absorbed by the atmosphere, their high transmission rate and good confidentiality can still match the needs of the time. As a result, the development of the THz communication system has attracted the interest of all nations, and several researches have been conducted. The THz antennas have advanced quickly as a crucial component of the THz communication system.

The first successful establishment of a THz communication system running at 0.12 THz took place in 2004. By 2013, the THz communication system functioning at 0.3 THz has been realized. The development of Japan's THz communication system's research from 2004 to 2013 is shown in Table 1. Nippon Telegraph and Telephone (NTT) Corporation of Japan gave a thorough introduction for the antenna geometry of the communication system created in 2004 in 2005. Figure 3(a) and (b) illustrates how used the antenna configuration in two instances. The system combines antennas with photoelectric conversion, and it functions in two different ways:

1) As illustrated in Figure 3(a), the planar slot antenna chip, uni-traveling carrier photodiode (UTC-PD), and silicon lens make up the planar antenna transmitter utilised in doors for short-range indoor communications.

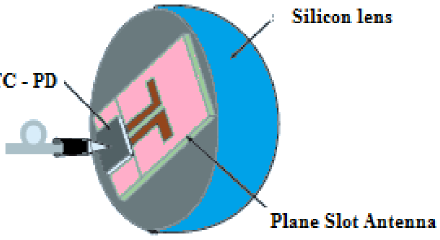


Fig.3(a): NTT system short-range transmitter

2) The antennas of transmitters must have high gain in an outdoor setting at a distance in order to counteract the effects of high transmission loss and poor detector sensitivity. The currently available THz antennas use a Gaussian optical lens and offer gains more than 50 dBi. As seen in Figure 3(b), the feed horn and the dielectric lens are integrated.

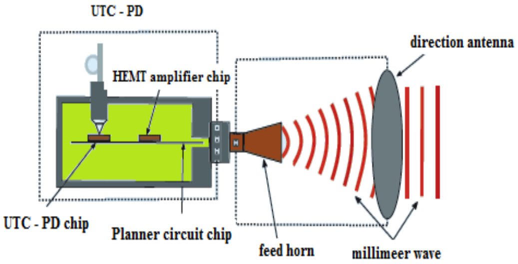


Fig. 3(b): NTT long-range wireless communication system structure diagram.

In addition to creating a 0.12 THz communication system in 2012 [14], NTT also created a 0.3 THz communication system. The transmission rate may reach 100 Gbps through ongoing optimization. Table 1 show that it makes a significant contribution to the advancement of THz communication.

Table I. Research results related to THz communication in Japan.

Year	f(THz)	Description
2004	0.12	10 Gbps Data transfer rate [10]
2006	0.12	Receive power is less than -30dBm using combined photon technology [11]
2009 2011	0.12	Band binary phase shift keying modulator and demodulator fabricated directly on microwave monolithic integrated circuit[12][13] .
2012	0.3	On both sides of the emitter and detector, the UTC-PD transmit power is less than 200 microwatts, and the effective antenna gain is 40 dBi and 35 dBi, respectively [14].
2013	0.3	The data transmission rate can be 50 Gbit/s and 100 Gbit/s By improving the baseband circuit bandwidth of the detector [15]
2018	0.1 – 10	A causal channel model with the impact of molecular absorption[16]
2019	0.33	High-definition 4K video transmission can be reached without compressed by combining wireless and fiber links, 8 Gbps error free transmission [17]
2019	0.72	12.5-Gbps wireless link based on photonics [18]
2019	0.35	THz all-dielectric rod antenna arrays with 28% relative bandwidth and more than 20 dBi gain[19]
2020	0.356	The defect-row structure of the photonic crystal waveguide track is adapted to suppress the Bragg-mirror effects with six-fold enhanced bandwidth[20]

Low operating frequency, large size, expensive cost, and other drawbacks of current research studies are present. There isn't much innovation in THz antennas, which are often modified millimeter wave antennas. Therefore, optimizing the THz antennas is crucial for enhancing the system performance of THz communication.

A study on the THz indoor wireless communication system has also been started by the CSIRO ICT Centre [21]. As seen in Figure 5, this centre investigated the connection between the calendar year and communication frequency. Figure 5 shows that by 2020, research on wireless communication is likely to focus on the THz band. Every twenty years, the maximum frequency of radio communication grows by around ten times. The centre has recommended conventional antennas for THz communication systems, such as horns, transmitters, and lenses, as well as standards for THz antennas. According to Figure **4,** both types of horn antennas have basic structures and operate at frequencies of 0.84 THz and 1.7 THz, respectively, where each antenna holds simple structure, and has good Gaussian beam performance.

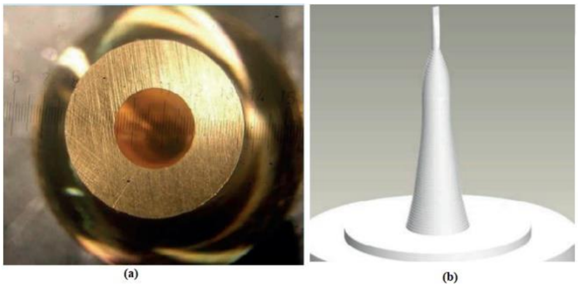


Fig. 4: Two types of THz horn antennas produced by the CSIRO ICT Center: (a) 0.84 THz horn and (b) 1.7 THz horn

The generation and detection of THz waves have been the subject of substantial research in the US. Famous THz research facilities include the National Fund (NSF), National Laboratory (LLNL), National Aeronautics and Space Administration (NASA), Stanford Linear Accelerator Centre (SLAC), and Jet Propulsion Laboratory (JPL). For terahertz applications, new THz antennas such bow-tie antennas and frequency beam-steering antennas have been developed [22]. We may derive three fundamental design concepts for modern THz antennas from the evolution of terahertz antennas, as depicted in Figure 5.

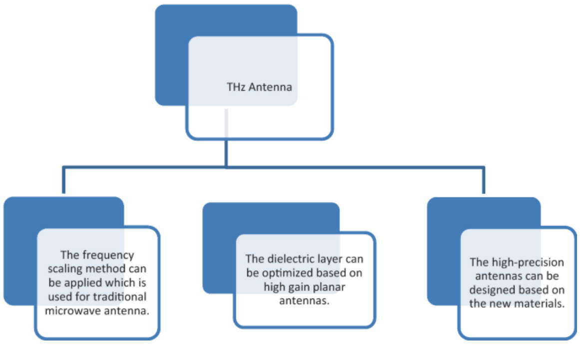


Fig. 5: THz antenna design ideas.

The research above demonstrates that while THz antennas have received significant interest from several nations, they are still in the early stages of exploration and development. Due to significant propagation loss and molecule absorption, THz antennas frequently have a limited range of coverage and transmission. Additionally, some research concentrated on the THz band's lower working frequency. The current THz antenna research largely focuses on raising the gain utilizing dielectric lens antennas and other similar devices, and improving communication efficiency using suitable algorithms [23]. It is also vital to figure out how to increase the effectiveness of THz antenna packing.

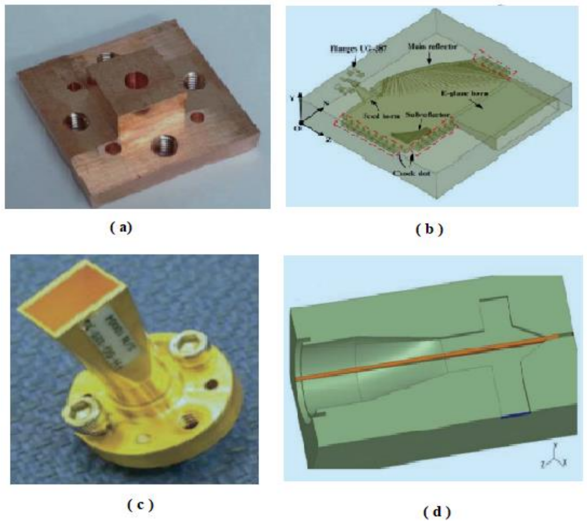
V.TYPICAL TERAHERTZ ANTENNAS

This section studies and analyzes the THz antennas. Two THz antennas are described in detail and analyzed, including THz photoconductive antennas, THz horn antennas, THz lens antennas, THz microstrip antennas, and THz on-chip antennas.

5.1 Terahertz horn antennas

The horn antenna can be used as a standalone antenna, a feed source for a lens antenna, or a transmitting antenna in a high-speed THz communication system. Horn antennas have been commonly employed in high gain THz antennas because of its straightforward construction, good performance, minimal cross-polarization, and broad frequency range. The THz wave's path loss in free space is far worse than that of the millimeter wave because of its extremely high frequency. The development of high-gain THz horn antennas has made significant strides in recent years. Using an oxygen-free copper metal block as an example, Nacer Chahat et al. proposed a multi-angle horn antenna [24]. The antenna, which works at 1.9 THz as illustrated in Figure 6(a), has an optimized directivity of up to 31.7 dB and a cross polarisation level of less than -22 dB.

The fact that this horn antenna is made up of numerous elements necessitates a costly, time-consuming, and difficult production process. Accordingly, a new highly integrated radiating structure with a horn antenna coupled with an E-plane horn and a double H-plane reflector for high radiation gain, driven by standard WR2.2 waveguides, was proposed by Kuikui Fan et al. in 2016 [25]. The suggested antennas use the THz horn antenna as their primary feeder, and Figure 6(b) depicts the structure. A prototype was also created at the same time utilizing affordable commercial milling technology. With an antenna gain of more than 26.5 dBi, particularly at 500 GHz with a maximum gain of 32.0 dBi, and a high radiation efficiency of more than 43.75%, this horn antenna operates in the 325-500 GHz band. It is obvious that a reference prototyping model for low cost and great performance can be the horn antenna. Three high-gain antennas rectangular horn, Cassegrain, and offset paraboloid type have been developed by certain researchers to operate at 300 GHz; the prototype of the rectangular horn antenna is depicted in Figure 6(c) [26]. The three horn antennas mentioned above are single-band devices; however communication systems frequently use multi-band horn antennas with rich spectrum information. The THz horn antenna, however, is incredibly tiny and challenging to produce. Xiannan (Placeholder1) Wang et al. created a dual-band horn antenna that operates at 94 GHz and 340 GHz in response to this occurrence [27]. The geometry is made up of a tapering media strip and a corrugated conical horn, as seen in Figure 6(d). The media strip is installed to enable simultaneous operation of the conical horn at 340 GHz and 94 GHz. Low cross polarisation, excellent port isolation, and a high frequency ratio are benefits of the design. Additionally, each band's gain can be altered separately. The design is straightforward to put together and simple to produce. A 750–1000 GHz H–plane dielectric horn antenna has been suggested in [28]. Although it has a larger size and a lower gain, it exhibits good performance and is compatible with Si manufacturing and planar circuit integration.



(a) (b) (c) (d)

Fig. 6. Four THz horn antennas:
(a) multi-angle horn, (b) E-plane horn,
(c) rectangular horn (d) dual-band horn

The performance comparison of various THz horn antennas is shown via Table 2. According to Table 2, the majority of horn antennas operate in the THz wave's low frequency region.

Table 2. Performance comparison of several THz horn antennas

Antenna type	**f (THz)**	**Gain (dBi)**	**Return loss**	**Other**
Multi-angle horn	1.9	N/A	N/A	Cross polarization level below -22 dB
Integrated E-plane horn and H-plane reflector	0.4125	>26.5	>20 dB	Radiation efficiency 43.75%
Dual frequency loading media horn	0.34	22.8	N/A	Sidelobe level below -25.4 dB cross polarization below -41.2 dB

5.2Terahertz microstrip antennas

A metal patch is attached to a thin dielectric substrate to create a microstrip antenna. The microstrip antenna is suited for mass production since it is compact, lightweight, easily made, and wearable. Microstrip antennas have been produced in numerous varieties recently, including T-type, slotted, stacked, single-band, and dual-band. The current study on THz microstrip antennas is focused on the low frequency range of THz (0.1–1 THz) since the substrate of the microstrip antennas is very thin and sensitive to frequency. The microstrip antennas are divided into two frequency bands in this section for study. The design of low-band THz microstrip antennas varies. The most recent research findings are listed below. As seen in Figure 7(a), Ge Zhang et al.'s [29] 2017 proposal for an improved THz microstrip antenna uses a dual-surface, multi-channel open-loop resonator. The identical multiple-way open-loop resonator connected to the feed line is located on both surfaces of the antenna substrate.

Dual-band microstrip antennas typically use a T-shaped form. A unique dual-frequency THz microstrip antenna with the structure depicted in Figure 7(b) was studied by Wang Haijun et al. in 2017 [30]. The concept of double T-shaped slits serves as the foundation for the antenna design. In order to achieve the effect of dual-frequency resonance, the radiation gap of the double T-shaped is loaded onto the radiating metal patch.

T-type dual-frequency microstrip antennas were also created by M. Khulbe et al. [31], but they enhanced the gain by maximizing the substrate volume. As illustrated in Figure 7(c)and (d), developed a dual-band coaxial feed slot microstrip patch antenna based on a T-shaped patch on an epoxy resin (FR-4) substrate, in contrast to the substrate material. The slot is created by symmetrically cutting copper, and the use of this structure improves radiation efficiency and direction. Applications for this THz microstrip antenna include quick and secure data transfer, biomedical use, radar and THz imaging, nano-antenna applications, and more.

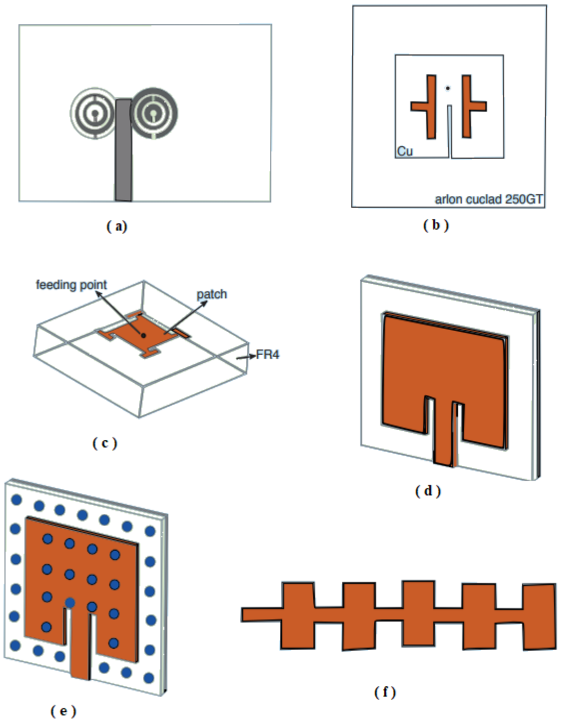


Fig:7. Schematic of the low-band microstrip antennas: (a) MSRRs microstrip antenna , (b) dual T-slot patch antenna , (c) FR-4 based T-type microstrip antenna, (d) RMPA, (e) slotted RMPA and (f) microstrip antenna array.

The epoxy resin substrate employed in [31] has very low absorption loss, little suppression, and strong directivity to the human body at the THz band, making it an excellent choice for producing a wearable microstrip antenna. It is also reasonably inexpensive. Additionally, Liton Chandra Paul et al. [32] created a compact and wide-bandwidth (26.4 GHz) microstrip antenna in 2017 using a photonic band gap (PBG) substrate and a defective ground structure (DGS).

A THz stacked microstrip antenna using a FR-4 substrate was created by Gurnoor Singh Brar et al. in 2016 [33].Shown in Figure 8(a).The semiconductor's features are by using the suppression effect theory to detect. .Liquid crystal polymers were employed as substrates in 2017 by Muhammad Saqib Rabbani et al. [34] functioning at frequencies of 0.835, 0.635, and 0.1 THz. Figure 7(e) and (f) depicts the geometry. For a number of medical applications, such as cancer detection by THz spectroscopy and vital signs detection by Doppler radar or vitro technology, the design can be produced on a straightforward printed circuit board (PCB).

A rectangular THz microstrip patch antenna with a slotted ground was proposed by Prince et al. in 2017 [35], as depicted in Figure 8(b)**.** A rectangular groove is formed on the ground, and the suggested antenna is made of copper. The antenna has a very low return loss and a gain of 4.254 dBi at the resonance frequency, making it suitable for biomedical applications like the detection of vitamins.

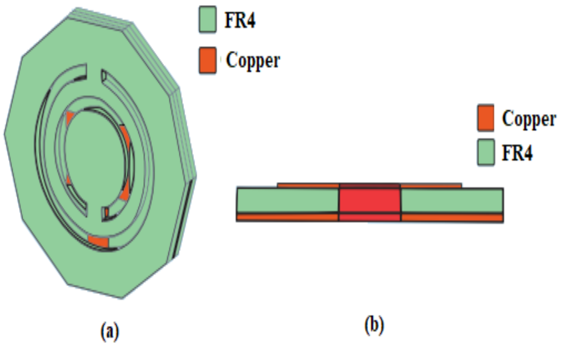


Fig.8: High-band THz microstrip antennas: (a) stacked microstrip antennas and (b) slotted rectangular microstrip patch antennas.

The THz band microstrip antennas obviously have low gain performance as well, and the optimization can begin with the structural and material factors. Table 6 compares the performance of various THz microstrip antennas based on the examination of THz microstrip antennas that was done earlier.

Table 6. Comparison of several THz microstrip antennas

Antenna type	**f (THz)**	**Gain (dBi)**	**Return loss**	**Substrate Material**
Double T-type slot microstrip antenna	0.3 and 0.76	7.13 and 3.71	-29 and -40	Arlon Cu-clad 250GT
T-type dual-frequency microstrip antenna	0.632 and 0.8702	Peak gain 8.2	N/A	FR-4
Slotted patch RMPA	0.703	5.235	-50.948	PBG and DGS
Microstrip antenna array	0.1	15.7	-26.04	Liquid crystal

				polymer
Stacked microstrip antenna	8.2	6.48	-38.85	FR-4
Slotted rectangular microstrip antenna	4.952	4.254	-55.31	FR-4

VI. PROCESS TECHNOLOGY OF THz ANTENNAS

The millimeter wave wavelength is much larger than the THz wavelength. Therefore, it is incorrect to assume that antenna surfaces are smooth at THz frequencies. The performance of the THz antennas is decreased because metal surfaces should be regarded as rough surfaces at THz frequencies [36]. The relationship between antenna surface roughness and machining accuracy is widely recognized. The research on process technology is crucial since many designs are constrained by it.

6.1 Micromachined THz process Technology

Lithography, laser milling, and mould replication are examples of silicon technology that provides the foundation for micromachining. For instance, researchers have created and commercialized a low-cost milling technology for high-gain antennas operating at 0.325-0.5 THz with an antenna gain of more than 26.5 dBi [37]. A silicon microlens antenna that operates at 1.9 THz and a THz antenna [38] with beam scanning at 0.55 THz can both be designed thanks to advances in silicon micromachining technology. The durability and integration capability are increased, which helps with antenna miniaturization and has significant application potential for the design of planar THz array antennas.

6.2 New terahertz process technology

The primary components of the new THz process technology are electroforming, discharge, milling, thick photoresist, and other processes [39]. A complex inner surface of a component, such a corrugated horn, is frequently made using electro forming, which involves depositing a target material (metal or a composite material) on a conductive original model and separating it from the original mould to achieve the desired product. Electrical energy is used in discharge to transform a pliable metal into one with a crisp structure. The original mould is fixed during the milling process, which involves rapid rotation. The appropriate product shape is cut out using a knife that has been machined onto the mold. The cost of this procedure is quite low. It is a kind of cold metal technique and a widely used technology in the present day THz antenna process. An innovative method for THz antenna lithography is thick photoresist SU-8, a chemically amplified negative photoresist. High precision and low cost are required for future THz antenna processing approaches. The techniques for the process can hopefully be standardized.

VII. CONCLUSION

Future spectrum resources are shifting to the THz band due to the development trend in wireless communications, and the building of a THz wireless communication system can offer a greater data transfer rate. For transmitting and receiving THz waves in communication systems, THz antennas are crucial components. The effectiveness of THz antennas, nevertheless, has a significant impact on the quality of a communication system. This work conducted a thorough examination of THz antennas, covering the research context, fundamental ideas, typical THz antennas, and methodological approaches. Analysis reveals that THz antennas now face difficulties such as high cost, limited gain, and others. The majority of THz antennas are still in the theoretical development stage, and few actual products are produced. Clearly, the THz antennas' research mission in the future is highly challenging.

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