Review Paper

An Overview of Terahertz Antennas

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Abstract: The terahertz (THz) antennas, which have features of small size, wide frequency bandwidth and high data rate, are important devices for transmitting and receiving THz electromagnetic waves in the emerging THz systems. However, most of THz antennas suffer from relatively high loss and low fabrication precision due to their small sizes in high frequency bands of THz waves. Therefore, this paper presents a detailed overview of the most recent research on the performance improvement of THz antennas. Firstly, the development of THz antennas is briefly reviewed and the basic design ideas of THz antennas are introduced. Then, THz antennas are categorized as metallic antennas, dielectric antennas and new material antennas. After that, the latest research progress in THz photoconductive antennas, THz horn antennas, THz lens antennas, THz microstrip antennas and THz on-chip antennas are discussed. In particular, the practical difficulties for the development of THz antennas are discussed with promising approaches. In addition, this paper also presents a short review of the process technology of THz antennas. Finally, the vital challenges and the future research directions for THz antennas are presented.

Keywords: THz antennas; photoconductive antennas; horn antennas; microstrip antennas; on-chip antennas; technical challenges

Received: Mar. 8, 2020
Revised: May 4, 2020
Editor: Yue Gao

I. Introduction

With the increasing popularity of wireless devices, data traffic has entered a new rapid development period [1], also known as the explosion of data traffic. At present, a large number of applications are gradually migrating from computers to wireless devices such as mobile phones, which are convenient to carry and operate in real time, but this situation also leads to a rapid increase in data traffic and lack of bandwidth resources. According to statistics, the data rate in the market in the next 10 to 15 years is likely to reach Gbps or even Tbps [2], [3]. At present, THz communication has obtained Gbps data rate, while the Tbps data rate is still in an early stage of development [4]. [5] has listed recent progress in Gbps data rate based on THz band and predicted that Tpbs can be obtained by a polarization multiplexing. Therefore, to increase the data transmission rate, a feasible solution is to develop a new frequency band [6], which is a THz electromagnetic wave at the "blank area" between microwaves and infrared light. In the ITU World Radiocommunication Conference 2019 (WRC-19), the frequency range of 275-450 GHz has been used for fixed and land mobile services. Obviously, The THz wireless communication system has attracted the attention of lots of studies.

Teraherz electromagnetic waves are generally defined at the 0.1-10 THz [7] (1 THz = 10^{12} Hz) frequency band with a wavelength of 0.03-3 mm. According to the IEEE standard, the THz wave is defined at 0.3-10 THz. Figure 1 shows that the THz wave is between microwave and infrared light. The THz wave has the following excellent characteristics:

- **Low damage:** The single-photon energy in the THz wave is lower than that of X-rays, only about one part per million. Therefore, the applications of THz waves in biomedical field such as scanning the body for skin cancer can assist in the disease treatment, and THz waves do no harm to the organisms [8].
- **High spectral resolution**: The spectrum of most large molecules is at the THz band. Analyzing the spectrum of THz radiation is of great significance for the detection of dangerous goods such as viruses, explosives, pistols, chemicals, etc. [9].
- **Visualization:** THz waves can penetrate some non-metallic or non-polar materials because of their short wavelengths. The THz waves can be scanned and opaque to visible opaque objects, which can present images with higher definition [10]. Therefore, the THz wave is widely used for sensing applications such as at the airports for the full-body scanner.
- **Wide bandwidth:** The THz wave can be the electromagnetic wave at the highest frequency band in electronics. If the THz wave is used as the signal carrier transmitted by the antennas, the rate of information transfer may reach a new level, even at the rate of Tbps.

In a word, the sensing applications of THz wave have been developed rapidly. However, the applications of THz antennas are currently not mature enough. Due to the serious shortage of current spectrum resources, the antennas are further designed at higher frequency band. Based on the broadband performance of THz spectrum, the antennas operating at the THz band offer much more bandwidth than traditional antennas.

THz waves have the advantages of millimeter waves and light waves. Compared to millimeter waves, the usable frequency band is wider; the beam direction is stronger; the confidentiality and anti-interference performance are better. Compared to light waves, THz waves are more efficient and the penetration is stronger [11]. Obviously, based on the unique characteristics of the THz waves, the best performance of the THz antennas is their wide operating bandwidth.

THz antennas are indispensable devices for THz wireless communication systems to radiate and detect THz waves. The performance of THz antennas directly affects the quality of the entire system, especially the operating bandwidth and gain of the antennas. Besides, the property of THz antennas is closely related to data transmission rate, system imaging resolution and the working range of the detection system. Thanks to the advantages of THz waves, THz antennas have superiority of wide frequency band, high resolution, strong directivity and miniaturization. In addition, it should be emphasized that the THz antennas have many new challenges compared with the microwave antennas. Since the THz antenna operates at the high frequency band, the device size is greatly reduced. The packaging of THz antennas is limited by materials and process techniques. How to make THz antennas radiate effectively is another challenge in terehertz antennas [12]. Therefore, THz antennas have more stringent requirements in terms of antenna model, manufacturing materials, and process technology.

To provide readers a reference for the future research and application of THz antennas, this paper gives a comprehensive overview of

This paper carried out in-depth analysis of terahertz antennas, including research background, basic concepts, typical terahertz antennas and process techniques.

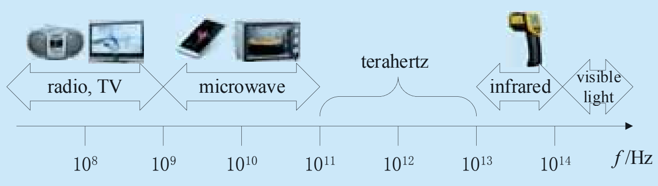


Fig. 1. *The position of the THz wave in the electromagnetic spectrum.*

THz antennas. In Section II, the development of the THz antennas with regard to different references is presented, which is helpful for readers to understand the design concepts of THz antennas. In Section III, the basic types of THz antennas are outlined: metallic antennas, dielectric antennas and new material antennas. In Section IV, five different kinds of THz antennas including THz photoconductive antennas, THz horn antennas, THz lens antennas, THz microstrip antennas and THz on-chip antennas are detailed. In Section V, considering the manufacturing process of the THz antennas, the performance index of the process technology is analyzed. Section VI summarizes the challenges during the current development of THz antennas. Section VII presents the future research directions. Finally, a brief conclusion is given in Section VIII.

II. DEVELOPMENT OF TERAHERTZ ANTENNAS

In order to facilitate readers' understanding, we briefly describe the development of THz antennas in this section. Then, the design ideas of the THz antennas are discussed. Although the study of THz began in the 19th century, it was not studied as an independent field at that time. Most of the studies related to THz belong to far-infrared region. It was not until the middle and late 20th century that researchers began to advance millimeter-wave research into the THz band and established specialized research on THz technology. The emergence of THz radiation source made it possible for THz waves to be applied in practical systems during the 1980s [13]. The development of THz technology is shown in Figure 2.

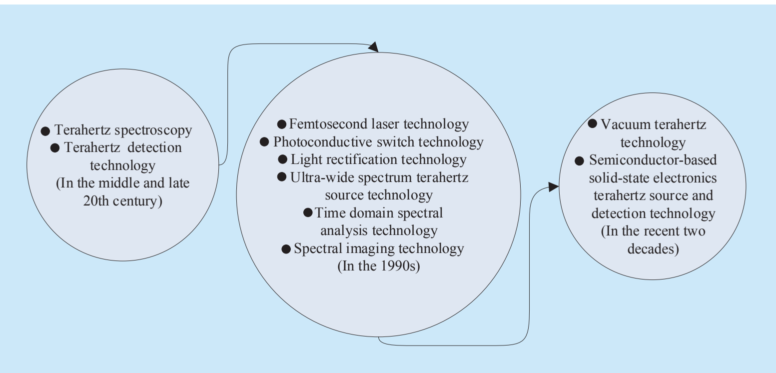


Fig. 2. *The development of THz technology.*

Since the beginning of the 21st century, wireless communication technology has developed rapidly, and the demand for information and the increase of communication equipment have put more stringent requirements on the transmission rate of communication data. Therefore, one of the challenges of future communication technologies is to operate at a high data rate of gigabits per second in one location [14]. Under the current economic development, band resources have become increasingly scarce. However, human demand for communication capacity and speed is endless. For the spectrum congestion problem, many businesses use multiple-input multiple-output (MIMO) technology to increase spectral efficiency and system capacity by spatial multiplexing [15], [16]. With the advancement of 5G networks [17], the data connection speed of each user will exceed Gps, and the data traffic of base stations will also increase greatly. For traditional millimeter-wave communication systems, microwave links will not be able to handle these huge data flows [18]. Besides, under the influence of line-of-sight, the transmission distance of infrared communication is short, and the position of its communication equipment is fixed. Therefore, the THz wave between microwave and infrared can be used in the construction of high-speed communication system [19]-[21], and the data transmission rate is improved by using the THz links [22].

THz waves can provide much wider communication bandwidth compared to microwaves, since the frequency range of THz frequencies is about 1000 times that of mobile communication. Thus, the use of THz to build an ultra-high-speed wireless communication system is a promising solution to solve the challenge of high data rate [23]-[25], which has attracted the interest of many research teams and industries. In September 2017, the first THz wireless communication standard

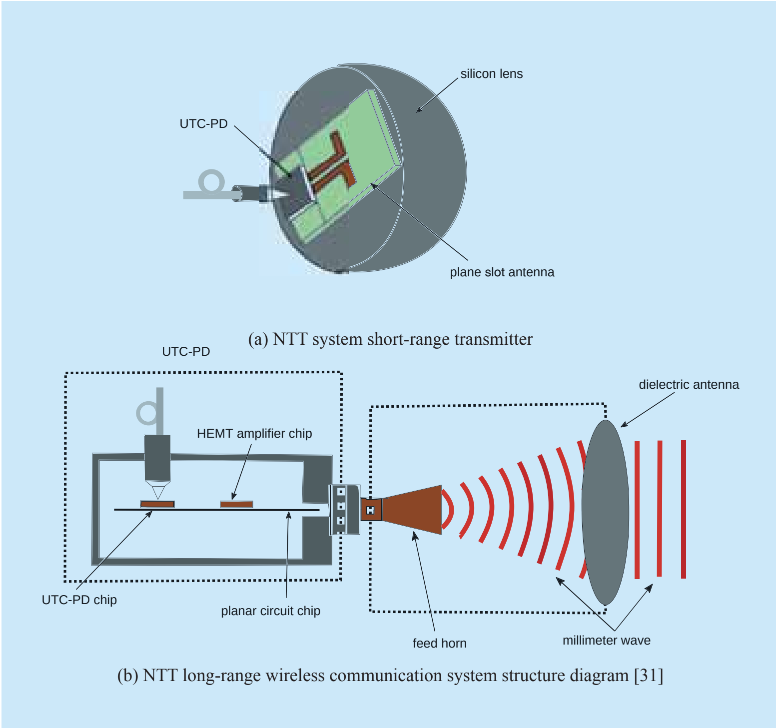
IEEE 802.15.3d-2017 was released [26], which defines exchange point-to-point at the lower THz frequency range of 252-325 GHz. The alternative physical layer (PHY) of the link achieves data rates of up to 100 Gbps with different bandwidths.

The THz communication system has large capacity and high data transmission rate that cannot be achieved by millimeter waves. It is mainly used in space communication and terrestrial short-distance communication. Even if THz waves are absorbed in the atmosphere, its good confidentiality and high transmission rate can well meet the current needs. Therefore, the establishment of the THz communication system has received the attention of all countries in the world, and a series of studies have been carried out. As an important part of the THz communication system, the THz antennas have also been rapidly developed.

In 2004, the THz communication system operating at 0.12 THz was successfully established for the first time, and the THz communication system of 0.3 THz was realized by 2013. Table 1 lists the research progress of Japan's THz communication system from 2004 to 2013. For the antenna geometry of the communication system developed in 2004, Nippon Telegraph and Telephone (NTT) Corporation of Japan published a detailed introduction in 2005 [31]. [31] introduced the antenna configuration in two cases, as shown in Figure 3. The system integrates the photoelectric conversion and the antennas, and it works in two ways:

1) In the indoor environment at a short distance, the planar antenna transmitter used indoors consists of an uni-traveling carrier photodiode (UTC-PD) chip, a planar slot antenna chip, and a silicon lens, as shown in Figure 3(a).

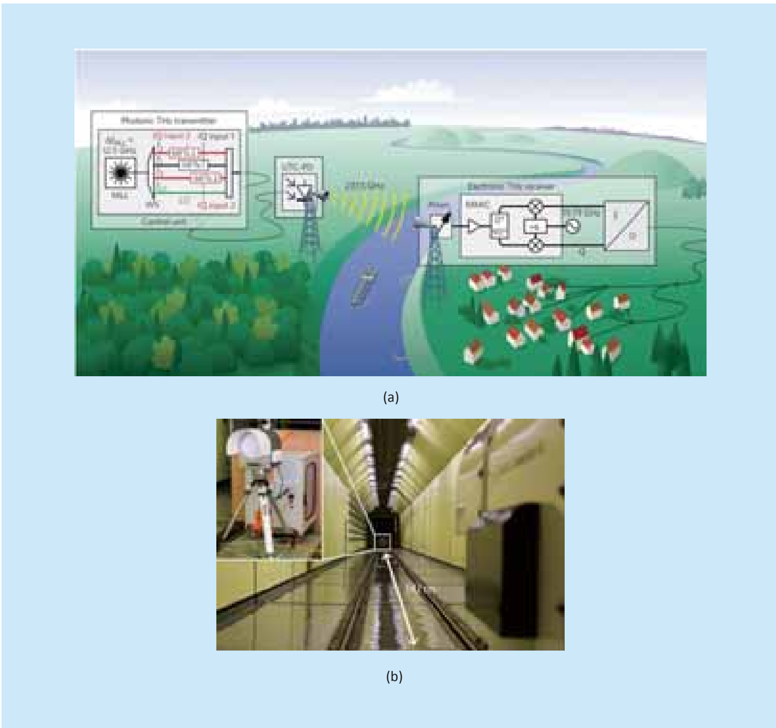
2) In the outdoor environment at a long distance, in order to eliminate the influence of large transmission loss and low sensitivity of the detector, the antennas of transmitters must have high gain. The existing THz antennas adopt a Gaussian optical lens and have a gain of exceeding 50 dBi. The feed horn and the dielectric lens are combined as shown in Figure 3(b).



(a) NTT system short-range transmitter

(b) NTT long-range wireless communication system structure diagram [31]

Fig. 3. *Japan NTT 120 GHz wireless communication system diagram.*


(a)

(b)

Fig. 4. *An example of a German study of THz communication: (a) KIT 220 GHz wireless communication system [42] and (b) wind tunnel test chart [43].*

In addition to the development of the 0.12 THz communication system, NTT also developed a 0.3 THz communication system in 2012 [32]. By continuous optimization, the transmission rate can be as high as 100 Gbps. It can be seen from Table 1 that it provides a great contribution to the development of THz communication. However, some shortcomings of current research works are low operating frequency, large size, high cost, and so on.

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

Ref.	Year	*f* (THz)	Other
[27]	2004	0.12	Data transfer rate up to 10 Gbps
[28]	2006	0.12	Combined photon technology and receive power less than -30 dBm
[29], [30]	2009, 2011	0.12	Band binary phase shift keying modulator and demodulator fabricated directly on microwave monolithic integrated circuit
[32]	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
[33]	2013	0.3	By improving the baseband circuit bandwidth of the detector, the data transmission rate can be 50 Gbit/s and 100 Gbit/s
[34]	2018	0.1-10	A causal channel model with the impact of molecular absorption
[35]	2019	0.33	By combining wireless and fiber links, 8 Gbps error free transmission and uncompressed high-definition 4K video transmission can be reached
[36]	2019	0.72	12.5-Gbps wireless link based on photonics
[37]	2019	0.35	THz all-dielectric rod antenna arrays with 28% relative bandwidth and more than 20 dBi gain
[38]	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

Table II. *Research results related to THz communication in Germany.*

Ref.	Year	*f* (THz)	Other
[39]	2007	0.3	4×4 microstrip antenna array
[40]	2011	0.22	Data transfer rate up to 25 Gbit/s for the first time
[41]	2011	0.24	Transmission rate can reach 30 Gbit/s
[42]	2011	0.22	Combining photonics and electronics
[43]	2015	0.22	Wind tunnel test
[44]	2016	0.24	A circularly polarized radar in 0.13-μm SiGe HBT technology
[45]	2019	0.504	The broadband detection capability of the proposed AlGaN/GaN detectors at the range from 0.2 to 1.2 THz
[46]	2019	0.3	A transmitter system-in-package with a multilayered stacked patch antenna and GaAs-based MMICs

Most of the used THz antennas are modified by millimeter wave antennas, and there is little innovation on the THz antennas. So, in order to improve the system performance of THz communication, an important job is to optimize the THz antennas.

Table 2 lists the research progress of the German THz communication, and Figure 4(a) shows a representative THz wireless communication system that combines photonics and electronics [42]. Figure 4(b) shows the wind tunnel test scenario [43]. From the current research situation in Germany, its research and development also have some disadvantages, such as low operating frequency, high cost and low efficiency.

The CSIRO ICT Center has also launched a study on the THz indoor wireless communication system [47]. This center studied the relationship between the year and the frequency of communication, as shown in Figure 5. It can be seen from Figure 5 that the study of wireless communication tends to be at the THz band by 2020. The maximum frequency of communication using the radio spectrum increases about ten times every two decades. The center has made recommendations for the requirements of THz antennas, and proposed conventional antennas for THz communication systems such as horns, transmitters, and lenses. As shown in Figure 6, the two types of horn antennas operate at 0.84 THz and 1.7 THz respectively, where each antenna holds simple structure, and has good Gaussian beam performance.

The United States has conducted extensive research on the emission and detection of THz waves. Famous THz research laboratories include Jet Propulsion Laboratory (JPL), Stanford Linear Accelerator Center (SLAC), National Laboratory (LLNL), National Aeronautics and Space Administration (NASA), National Fund (NSF) and so on. New THz antennas such as bow-tie antennas and frequency beam-steering antennas for terehertz application have been designed [48], [49]. Based on the development of terehertz antennas, we can get three basic design ideas for current THz antennas, as shown in Figure [7].

The above analysis shows that although many countries have given great attention to the THz antennas, it is still in the stage of primary exploration and development. THz antennas are often limited by their transmission distance and coverage due to high propagation loss and molecular absorption [50], [51]. Moreover, some sutdies focused on lower operating frequency of the THz band [52]. The existing research of THz antennas mainly concentrates on improving the gain by using dielectric lens antennas etc., and increasing the communication efficiency by using appropriate algorithms [53], [54]. In addition, how to improve the efficiency of THz antenna packaging is also very urgent.

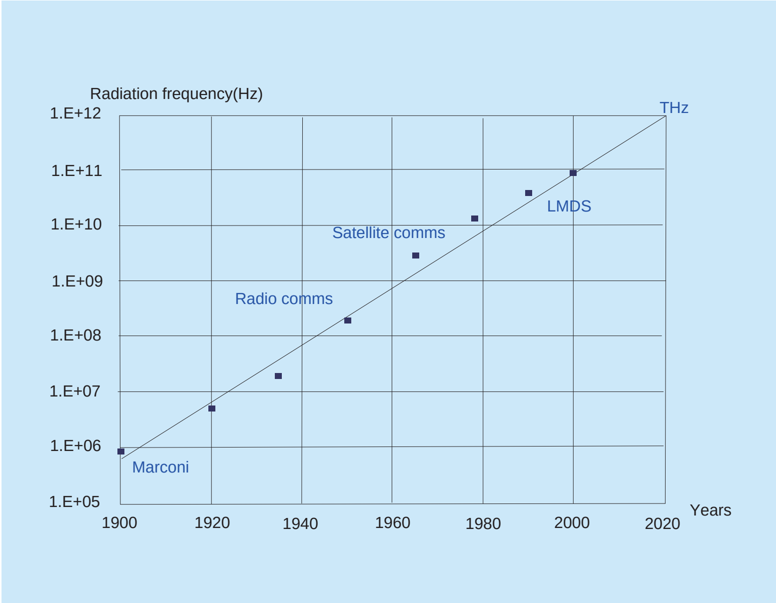


Fig. 5. *Relationship between year and radiation frequency [47].*

III. BASIC TERAHERTZ ANTENNAS

THz antennas have many available types: pyramidal cavity with dipole, angle reflector array, bow-tie dipole, dielectric lens planar antennas [55], photoconductive antennas for generating THz source radiation sources, THz horn antennas, THz antennas based on graphene materials, etc. Based on the manufacturing material of THz antennas, they can be roughly classified into metallic antennas (mainly horn antennas), dielectric antennas (based on lens antennas) and new material antennas. This section first makes a preliminary analysis of these antennas, followed by a detailed introduction and in-depth analysis of five typical THz antennas in the next section.

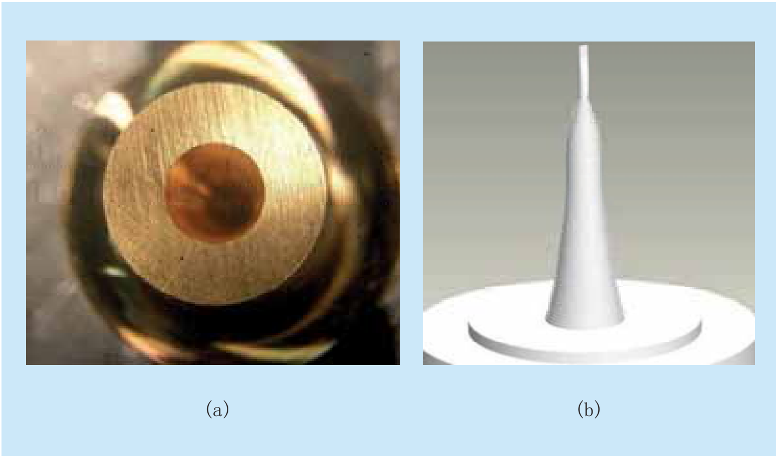


Fig. 6. *Two types of THz horn antennas produced by the CSIRO ICT Center: (a) 0.84 THz horn and (b) 1.7 THz horn [47].*

3.1 Metallic antennas

Horn antennas are one of the typical metallic antennas, and the horn is designed as an antenna operating at the THz band. The antenna of the classic millimeter-wave receiver is a conical horn. The corrugated and dual-mode antennas have many advantages, including 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% coupling efficiency. The available bandwidth of the two horn antennas are about 30%-40% and

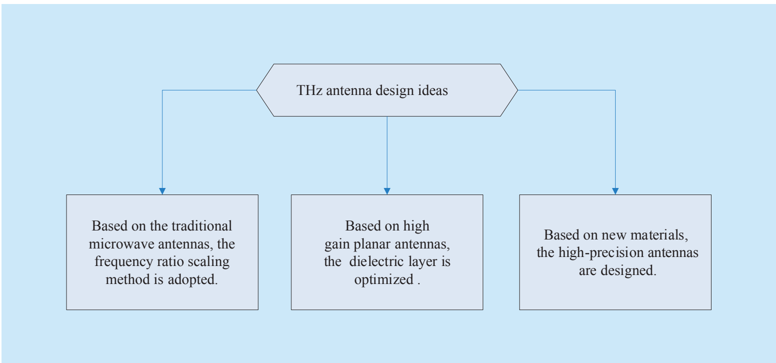


Fig. 7. *THz antenna design ideas.*

6%-8%, respectively [56].

Since the frequency of the THz wave is very high, the size of the horn antenna is very small, which makes the processing of the tip end of the horn difficult, especially in the design of antenna arrays [57], and the complexity of the process technique leads to high cost and limited production. Due to the difficulty in manufacturing the bottom of the complex horn design, a simple horn antenna in the form of a tapered or conical horn is usually used, which can reduce the cost and process complexity, and the radiation performance of the antenna can be kept good.

Another metallic antenna is a traveling-wave corner cube antenna [58], [59] consisting of a traveling-wave antenna integrated on a 1.2 micron dielectric film and suspended in a longitudinal cavity etched on the silicon wafer, as shown in Figure 8. This antenna is an open structure that is compatible with Schottky diodes. Due to its relatively simple structure and low manufacturing requirements, it can generally be used in frequency bands of above 0.6 THz. However, the antenna's sidelobe level and cross-polarization level are higher, probably because of its open structure. Thus its coupling efficiency is relatively low (about 50%) [58].

3.2 Dielectric antennas

The dielectric antennas are the combination of dielectric substrate and antenna radiator. By proper design, the dielectric antennas can achieve impedance matching with the detector, and have the advantages of simple process, easy integration, and low cost. In recent years, researchers designed several narrowband and

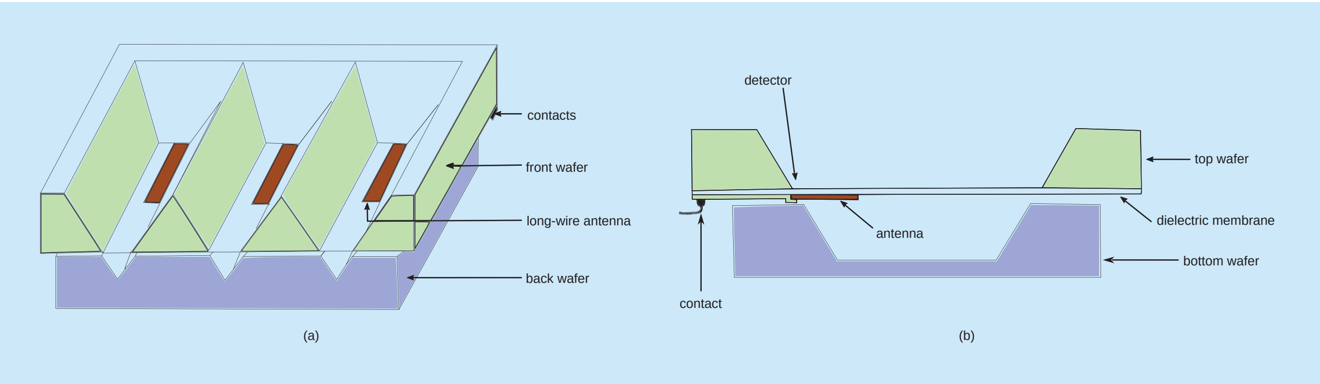


Fig. 8. *Traveling wave corner cube antenna: (a) geometry and (b) side view [58].*

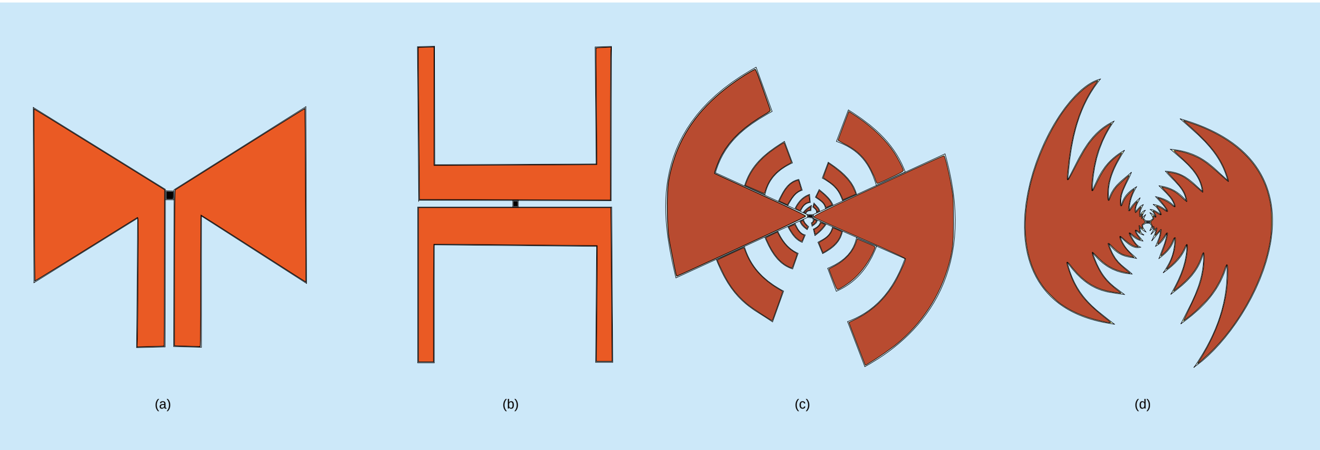


Fig. 9. *Four planar antennas: (a) butterfly antenna, (b) dual U-shaped antenna, (c) log periodic antenna and (d) log periodic sinusoidal antenna.*

wideband edge-emitting antennas that can be matched to low-impedance detectors for THz dielectric antennas: butterfly antennas, dual U-shaped antennas, logarithmic periodic antennas, and log periodic sinusoidal antennas, as shown in Figure 9. In addition, more complex bent-wire antenna geometries can be designed by means of a genetic algorithm [60].

However, since the dielectric antennas are combined with the dielectric substrate, surface wave effect (also called thick medium mode) is generated when the frequency tends to the THz band. This fatal disadvantage causes a large amount of energy loss during operation and results in a significant decrease in antenna radiation efficiency. As shown in Figure 10, when the antenna radiation angle is greater than the cut-off angle, its energy is trapped in the dielectric substrate and coupled with the substrate mode [56].

As the thickness of the substrate increases, the higher order modes in the substrate also increase. However, these higher order modes are repeatedly radiated in the substrate and the energy radiated by the antennas is coupled. With increasing high-order modes, the coupling efficiency between the antenna and the substrate medium is increased. This situation results in the energy loss.

To weaken the surface wave effect, there are three optimization schemes [61]:

1) Loading the lens on the antennas, the antenna bunching property is used to increase the gain.

2) Reducing the thickness of the substrate, the high-order mode generation of electromagnetic waves is suppressed.

3) Replacing the substrate dielectric material with electromagnetic band gap (EBG), the spatial filtering characteristics of EBG can reduce high-order modes.

3.3 New material antennas

In addition to the above two types of antennas, there is another kind of THz antenna made of new materials. For example, in 2006, Jin Hao et al. proposed a carbon nanotube dipole antenna [62]. As shown in Figure 11(a), the dipole is made of carbon nanotubes instead of metal material. The infrared and optical properties of carbon nanotube dipole antennas are carefully studied in [62]. The general antenna characteristics of finite length carbon nanotube dipoles, such as input impedance, current distribution, gain, efficiency and radiation mode, are discussed. Figure 11(b) shows the curve of input impedance of carbon nanotube dipole antenna vs frequency. It can be seen from the Figure 11(b) that at the higher frequency band, the imaginary part of the input impedance has multiple zero points. It shows that the antennas can realize multiple resonance points with different frequencies. Obviously, the carbon nanotube antenna exhibits resonances within a certain frequency range (lower THz frequencies), while is strongly damped outside of this range.

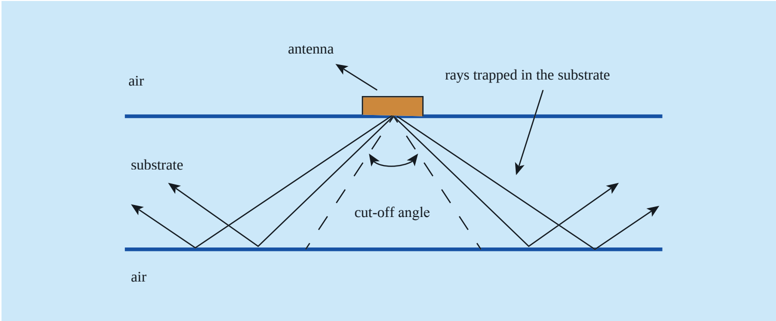


Fig. 10. *Schematic diagram of antenna surface wave effect.*

In 2012, Samir F. Mahmoud and Ayed R. AlAjmi proposed a new THz antenna structure based on carbon nanotubes [63], which consists of a bundle of carbon nanotubes wrapped in two dielectric layers. The inner dielectric layer is a dielectric foam layer and the outer dielectric layer is a metamaterial layer. The specific structure is shown in Figure 12. By testing, the radiation performance of the antennas is enhanced compared with single-walled carbon nanotubes.

The new material THz antennas explored above are mainly three-dimensional. In order to increase bandwidth and fabricate conformal antennas, the planar graphene antennas are more popular. Graphene has excellent dynamic continuous control characteristics, by adjusting bias voltage, and products surface plasmons. Surface plasmons exist on the interface of positive dielectric constant substrate (such as Si, SiO_2, etc.) and negative dielectric constant substrate (such as precious metals, graphene, etc.) [64]. There are a large number of "free electrons" in conductors such as precious metals and graphene. These free electrons are also called plasmas. Due to the inherent potential field in the conductor, these plasmas are in a stable state without external disturbance. When the incident electromagnetic wave energy is coupled to these plasmas, the plasma deviates from the steady state and vibrates. After the conversion, this electromagnetic mode forms a wave that propagates in the form of transverse magnetic mode at the interface. According to the Drude model's description of the plasmon dispersion relationship on the surface of the metal, the metal cannot naturally couple with the electromagnetic waves in the free space and convert the energy. It is necessary to use other materials to excite the surface plasmon wave [65]. The surface plasmon wave attenuates quickly in the parallel direction of the interface between the metal and the substrate, and a skin effect occurs when the metal conductor conducts electricity in a direction perpendicular to the surface [66]. Obviously, because of small dimension and skin effect at the high frequency band, the performance of the antennas deteriorates sharply, which cannot meet the requirements of the THz antennas. On the contrary, graphene can achieve a large range of light absorption and light regulation. At the THz frequency band, the in-band transition of graphene dominates, and the collective oscillation of plasma gives graphene excellent surface plasmon material properties. The surface plasma of graphene not only has higher binding and lower loss [67], but also supports continuous electrical tuning [68]. Moreover, graphene has complex conductivity at the THz frequency band. Thus the slow wave propagation is associated with the plasma mode at the THz frequency. These characteristics fully demonstrate the feasibility of using graphene to replace metal materials at the THz frequency band.

For example, [69] has presented an equivalent circuit model for graphene-based THz antennas by using the partial element equiv-

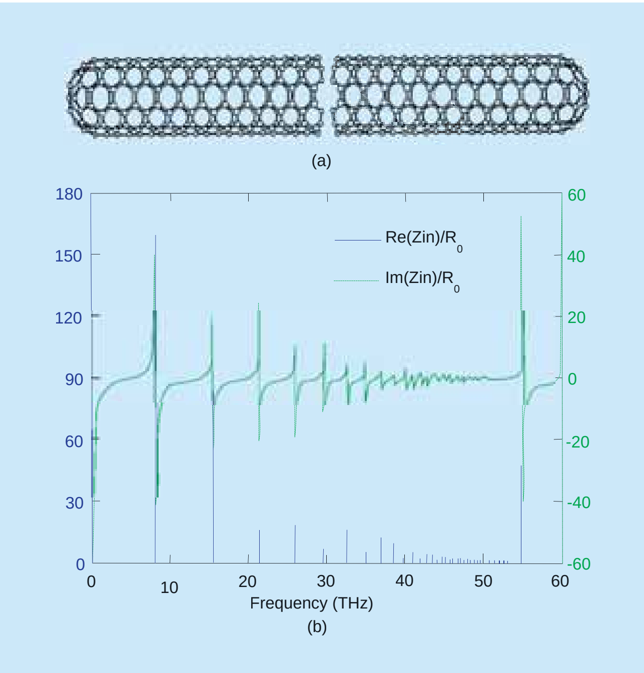


Fig. 11. *(a)Carbon nanotube dipole antenna. (b)Input impedance versus frequency curve [62].*

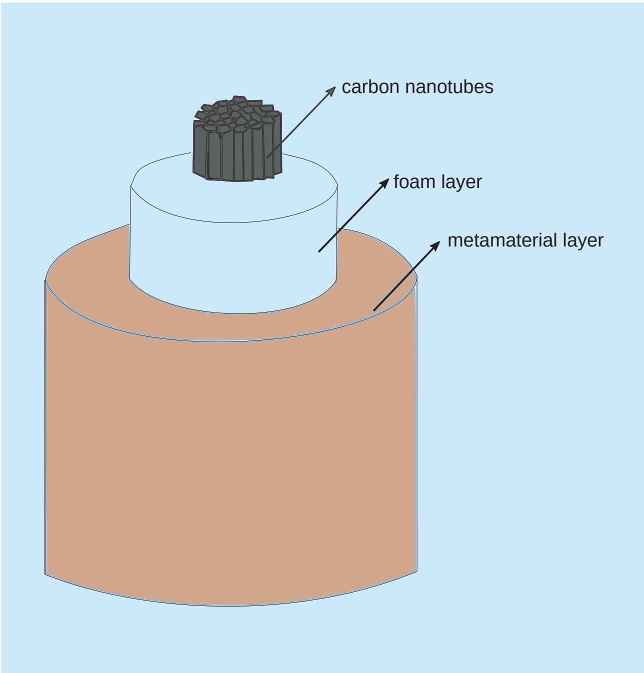


Fig. 12. *New carbon nanotube antenna geometry [63].*

alent circuit method, which can obtain the EM features of graphene in the EM field. [70] has made a detailed exploration on how to accurately make graphene nano-antennas. It is shown that under the condition that the width of surrounding incision is equal to the wavelength of plasma, the nano-antennas manufactured by focusing ion beam (FIB) technology can show the same performance as the independent antennas. This technology is very helpful for making fractal or logarithmic period antennas. By comparing the plasmonic and nonplasmonic solutions, the graphene fabry-perot cavity leaky-wave antennas is given in the [71]. The reported structures belong to Fabry-Perot cavity antennas, whose radiation mechanism relies on the excitation of cylindrical leaky waves with an ordinary (i.e., non-plasmonic) sinusoidal transverse modal profile. It shows higher radiation efficiencies than those of alternative graphene-based radiators based on the excitation of surface-plasmon polaritons. Based on the polarization behavior of graphene surface plasmon, [72] proposed a new type of ribbon antenna, and the structure is shown in Figure 13. It also proposed the band shape for the propagation characteristics of plasma waves in graphene. The design of the tunable frequency band of the antenna provides a new way of studying the propagation characteristics of the new material THz antennas.

In addition to exploring a single new material THz antenna element, a graphene nano-patch THz antenna is designed as an array [73] and used to construct a THz multi-input multi-output antenna communication system. The antenna structure is shown in Figure 14. Based on unique properties of graphene nano-patch antennas, the antenna elements have micron-scale dimensions. The chemical vapor deposition directly synthesizes different graphene images on a thin nickel layer and transfers them to any substrate. This design concept facilitates the design of different antenna arrays. By selecting the appropriate number of components and changing the electrostatic bias voltage, we can effectively change the direction of radiation and make the system reconfigurable. For example, [74] used the aperture-graphene and patch-graphene antennas to design circular-polarization splitters. However, this design has the challenge of low production efficiency. Obviously, we urgently need to improve the production technology of THz antennas to meet our production requirements for high efficiency THz antennas. In addition to optimizing antenna performance, an efficient wireless communication system was achieved by creating a graphene-based THz

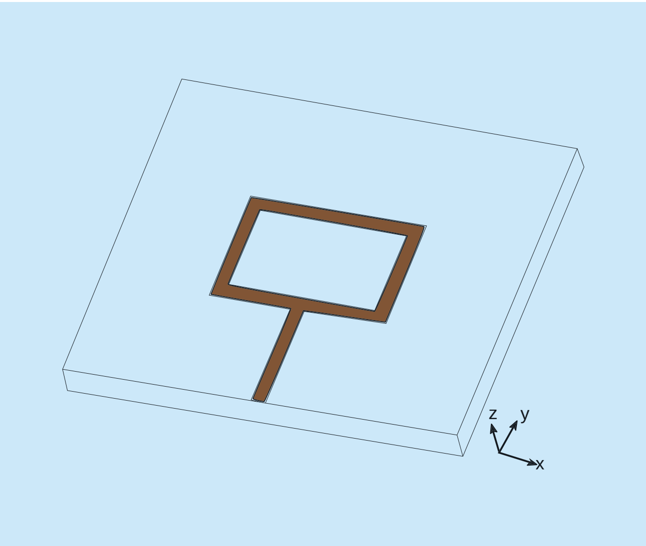


Fig. 13. *Schematic of the ribbon antenna.*

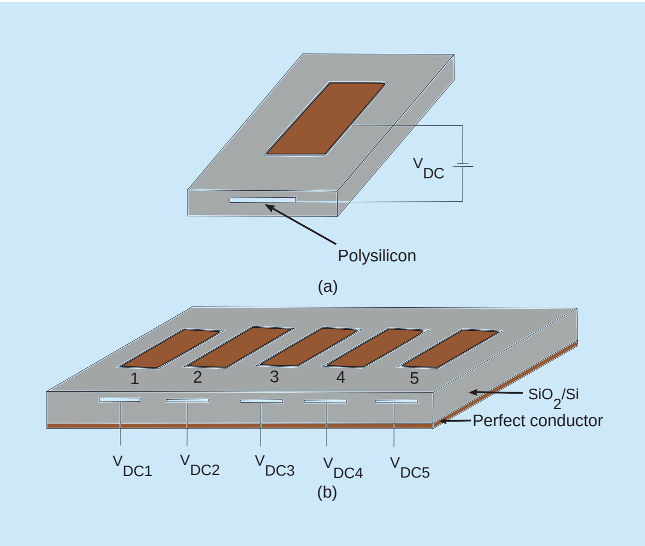


Fig. 14. *(a)Graphene-based nano-patch antenna element.(b) Graphene-based directional antenna array [73].*

reflective array and an accurate three-dimensional channel model [75].

The research of new materials is a relatively new direction. The innovation of materials is expected to break through the limits of traditional antennas and to evolve a variety of new antennas, such as reconfigurable metamaterial [76], two-dimensional (2D) materials [77]. However, this type of antenna, mainly depends on the innovation of new materials and the progress of process technology. In any case, the development of THz antennas requires innovative materials, precise machining processes and novel design structures to meet the high gain, low cost and wide bandwidth requirements of the THz antennas.

This section provides a brief introduction to the three basic THz antennas, which are metallic, dielectric, and new materials, and illustrates their differences, advantages, and disadvantages.

1) Metallic antenna: The metallic antenna has a simple geometry, is easy to process, relatively low cost, and has low requirements on the substrate material. However, the metallic antennas adopt mechanical adjustment method of the antenna position, which is easy to make a mistake. If the adjustment is not correct, the performance of the antennas will greatly degrade. The metallic antennas have small size, but is difficult to assemble with a planar circuit.

2) Dielectric antenna: The dielectric antenna has a lower input impedance, is easily coupled with a low-impedance detector, and the connection with the planar circuit is relatively simple. The geometry of dielectric antenna includes butterfly, double U, normal logarithmic and logarithmic periodic sinusoidal shape. However, dielectric antennas also have a fatal flaw-the surface wave effect which is caused by thick substrate. The solution is to load the lens, and replace the dielectric substrate with an EBG structure. Both solutions need to rely on innovation and continuous improvement of process technology and materials, but the excellent performance (such as omnidirectionality and surface wave suppression) can provide a new idea for the study of THz antennas.

3) New material antenna: There are currently new dipole antennas made of carbon nanotubes and new antenna structures made of metamaterials. New materials can bring new performance breakthroughs, but the premise is the innovation of materials science. At present, the research on new material antennas is still in the exploration stage, and many key technologies are still not mature enough.

In summary, different types of THz antennas can be selected according to design requirements:

1) If we pursue simple products and low production costs, metallic antennas can be selected.

2) If high-level integration and low input impedance are pursued, dielectric antennas can be selected.

3) If a breakthrough in performance is required, new material antennas can be chosen.

The above design can also be adjusted according to specific requirements. For example, two types of antennas can be combined to obtain more advantages, but the assembly method and design technology have to meet more strict requirements.

IV. Five Typical Terahertz Antennas

This section studies and analyzes the state-of-the-art THz antennas. Five 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.

4.1 Terahertz photoconductive antennas

The photoconductive antennas (PCAs) are used for the generation and detection of the THz wave. The innovation and development of the photoconductive antennas have an influence on the THz communication system and related fields. This section introduces the research background, working principle, typical photoconductive antennas and optimization scheme of photoconductive antennas.

1) *Background*: As far as the origin of photoconductive antennas are concerned, the THz wave traceback of femtosecond width was first proposed by Auston and Cheung [78] at Bell Labs in 1984. This design first developed the THz time-domain spectroscopy system. After more than ten years, this photon-based THz source method has become more and more popular, and has gradually developed into a new discipline. The generation and detection of THz waves have also made great breakthroughs. Table 3 shows the development history of the photoconductive antennas.

2) *Principle*: When a laser beam is irradiated on a photoconductive semiconductor (such as GaAs, InP, and so on.) switch, an electron-hole pair is generated therein. If there is an external electric field in the photoconductive switch gap, which is usually generated by the DC voltage, a current is formed. At this time, if the laser signal is a sufficiently short period of time, about 100 fs, the THz signal is generated by the generated photoconductive current. Figure 15 is a schematic diagram of the PCA.

The antenna model of the PCA basically includes an antenna gap, an electrode, and a photoconductive substrate. The antenna gap is the position where the laser pulse directly illuminates the photoconductive material. The laser pulses are focused on the gap between the electrodes and absorbed by the photoconductive substrate. Usually, in order to enhance the directivity and gain of the PCA, a lens is loaded on the PCA to increase the coupling efficiency and generate a THz wave in the normal direction.

The radiation performance of PCA depends mainly on three factors: the femtosecond laser pulse, the photoconductive substrate material, and the geometry of the antennas. Current laser pulses can reach femtosecond levels, and subsequent innovations need to go on evolving; the general requirements for substrate materials are shorter carrier lifetimes, faster carrier mobility, and higher resistivity [87]. The commonly used substrates of PCA are GaAs, GaP and ZnTe. For example, some researchers have designed a PCA antenna [88] with a wide frequency band (0.1--0.25 THz) by using GaAs. More effective optical materials are hot topics in the near future. The dipole PCA was firstly presented and the large aper-

Table III. *Development history of photoconductive antennas.*

Ref.	Year	Research progress
[78]	1984	Auston and Cheung first used the photoelectric conduction in Bell Labs to generate a THz wave with a femtosecond width
[79]	1988	Photoconductive dipole antenna generating 0.1-2 THz electromagnetic wave
[80]	1989	Exter et al. optimize PCA with sapphire lenses and parabolic mirrors
[81]	1990	Darrow et al. demonstrate a new method for producing a photoconductive antenna using directional electromagnetic pulses using a large aperture planar photoconductor
[82]	1992	Justin et al. proposed a correlation function based on the saturation characteristics of ultra-fast pulsed electromagnetic radiation generated by a large-aperture PCA. The function uses the saturation characteristic as the optical excitation flux
[83]	2008	Gabor M. et al. produced an astigmatic-type photoconductive switch based on LT-GaAs microlens array, and the measured energy conversion efficiency can be up to 1.35×10^{-5}
[84]	2013	Christopher et al. proposed a highly efficient photoconductive THz radiation source based on a logarithmic spiral antenna array
[85]	2014	Shang-Hua Yang et al. first fabricated a photoconductive THz radiation source in combination with a three-dimensional plasmon contact electrode. It sets a high 7.5% optical-THz conversion efficiency record
[86]	2015	Nezih T. Yardimci et al. designed a novel large-area photoconductive radiation source with higher optical-THz conversion efficiency
[90]	2017	Lucky Saurabh et al. designed and analyzed the bow-tie PCA with a return loss of -33.96 dB
[100]	2019	Alessandro Garufo et al. proposed a connected array of coherent photoconductive pulsed sources to generate mW average power

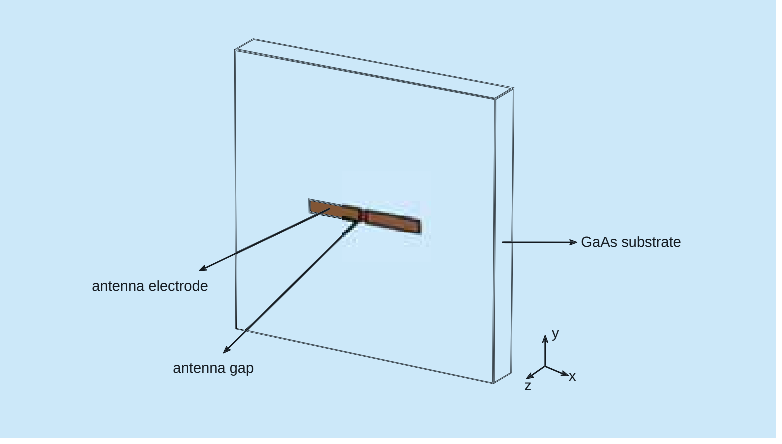


Fig. 15. *PCA schematic [87].*

ture PCA was followed. These two types have been widely studied and applied. The typical structures of these two antennas are analyzed as follows.

3) Typical photoconductive antennas: The geometry of the photoconductive antennas can have various shapes, and the representative ones are dipole antennas and large aperture antennas. Among them, the bow-tie PCA is a deformation of a dipole antenna, and the logarithmic-helical antenna is often used for a large aperture antenna integration.

- **Bow-tie photoconductive antennas:**

The bow-tie antennas can realize multi-band function, and have many advantages such as light weight, small size, simple structure, etc. There are many studies on the bow-tie photoconductive antennas. For example, [89] introduced a series of linear polarization PCAs and first proposed a bow-tie antenna deformed by a standard photoconductive dipole antenna. However, the antenna directivity is not strong enough. To improve the weak directivity of antenna, a silicon lens and an artificial magnetic conductor can be combined to achieve the demand. Then, a capacitive load dipole antenna is introduced, and the array is implemented. The measurement shows that the peak directivity of the binary array can be improved by 2 dB. In addition, a metal film cover layer is introduced, and the result shows strong directivity and high efficiency. Finally, THz grid antenna and arrays are designed. Figure 16 shows performance comparison of different bow-tie PCAs in aperture efficiency, radiation efficiency, and directivity.

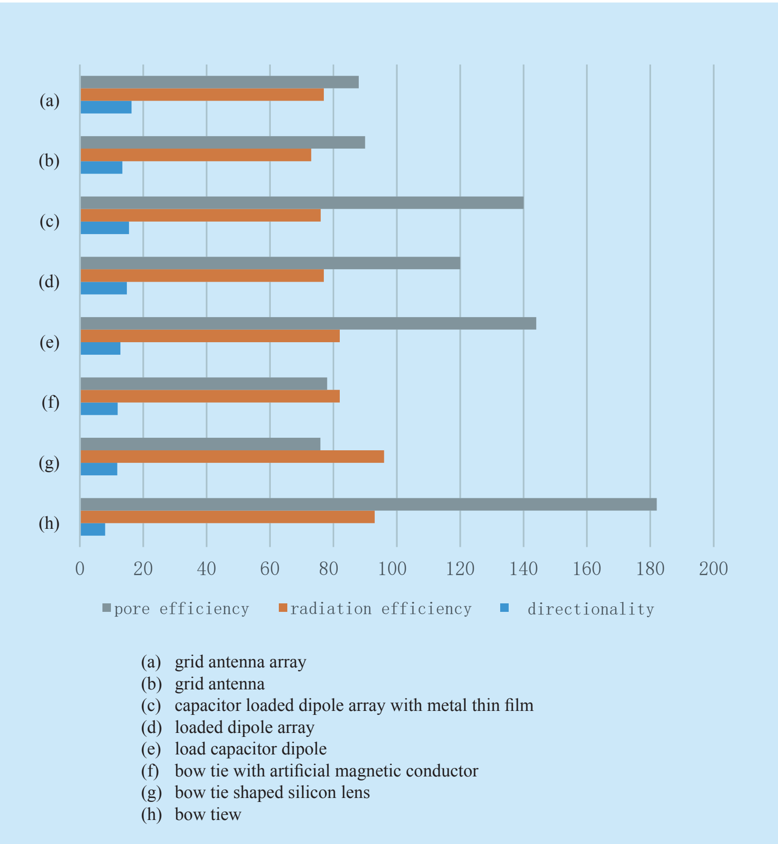


Fig. 16. *Performance comparison of different bow-tie PCAs.*

It can be seen from Figure 16 that the grid antenna array has the best directivity, and the bow-tie antenna is superior to other types of antennas in terms of radiation efficiency and aperture efficiency. These models have the advantages of high radiation efficiency, high directivity and high aperture efficiency, and they can be used as a reference for THz antenna designs. In 2017, Lucky Saurabh et al. [90] also designed and analyzed the bow-tie PCA for THz. By measurement, this antenna has a return loss of -33.96 dB at 1.64 THz and a maximum gain of 2.22 dBi at 1.25 THz. The design is simple and the antennas is a compact and miniaturized PCA.

It can be seen from the above analysis that the bow-tie photoconductive antennas have the advantages of simple structure, compactness, miniaturization, low cost, and so on. Improvements in size, substrate materials, and geometry can promote innovation in photoconductive antennas.

- **Logarithmic-helical photoconductive antennas:**

Log-helix antenna is a representative antenna that can be cut off to a finite size to obtain frequency independence. There are many studies on log-helix antennas, most of which are applied to large-area photoconductive emitters.

Some researchers have designed a series of photoconductive THz emitters with log-helix antennas, which can be used to generate high-power pulses [84]. Thus, logarithmic-helical photoconductive antennas have the potential to increase the output power. Logarithmic-helical antennas have low reactance advantages at the frequency of 0.1-2 THz [91]. In 2008, [92] began to use two full-wave electromagnetic solvers (HFSS and CST) to model the antenna and lens at 600 GHz, and the input impedance was calculated. Figure 17(a) shows the structure of the design. The influence of the lens on the input impedance of the antennas is experimently studied. It is found that the input impedance is basically constant at the 0.2-1 THz band. Regarding the logarithmic-helical antennas integrated lens, [93] conducted a numerical study on the lens integrated antennas in 2012, providing a solution to select a suitable feed and optimizing the THz broadband lens structure. [93] designed a logarithmic period and logarithmic spiral antennas with the same outer diameter and inner dimension. The structure is shown in Figure 17(b). By comparison, the logarithmic spiral antenna is superior in radiation efficiency and directivity and has a wide THz band with frequencies up to 5.0 THz.

Based on the above reserches, in 2017, the end-cutting type of THz antenna was studied in [91]. When the end of the spiral arm is sharp, the terminal reflects relatively less. But the mesh of the end portion is denser, which increases the workload of the computer. Therefore, the effects of several different end-cutting methods on the antenna performance are studied by simulation. By comparison, it can be found that the antenna with the tip operates at the range of 0.1-2 THz and its gain is up to 21.98 dBi. But the end cut-off antenna's operating frequency is 0.1-3 THz, and the computer efficiency can be accelerated. Oviously, the latter's function optimization is better. The antenna structure is shown in Figure 17(c).

In summary, the log-helical antennas have a constant radiation impedance and low reactance, so it is widely used in photoconductive emitters. The current operating frequency band is basically at the low frequency band of THz, and the research on high frequency band is still lacking. Future research needs to move toward higher frequency band of THz, so there is still a lot of work for log-helix antennas research.

4) *Optimization*: Based on the above reserches about the background, working principle and typical examples of PCA, it can be seen that the broadband THz source can be applied in the fields of communication, imaging, spectroscopy and security. However, current photoconductive antennas still have challenges, such as large material loss, low photoelectric conversion efficiency, and low output power. The current research mainly includes loading silicon lenses [94], [95], us-

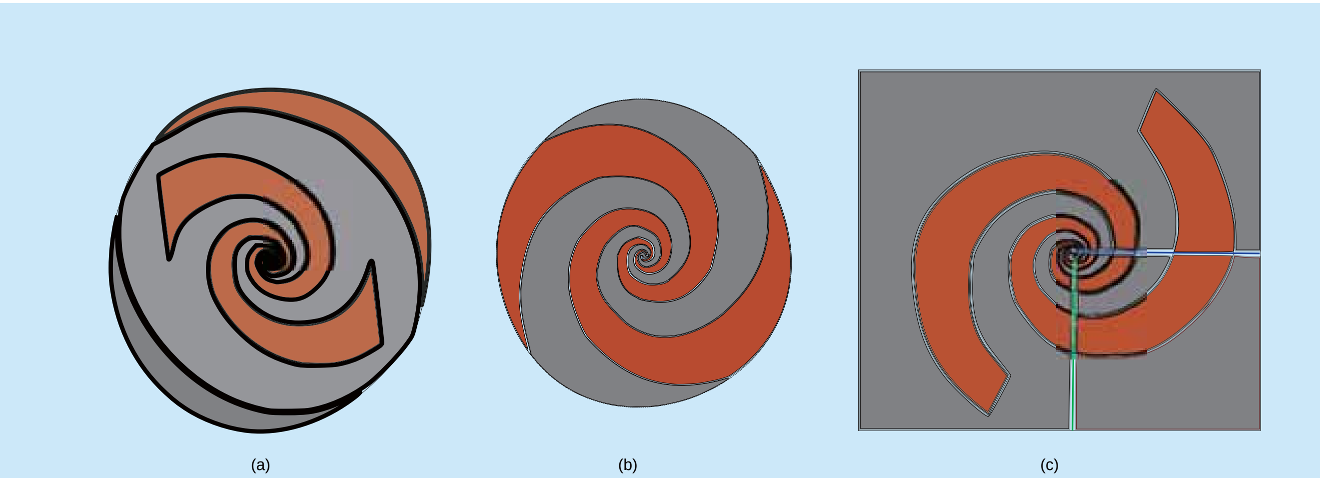


Fig. 17. *Geometry of three logarithmic-helical antennas: (a) loading lens, (b) self-complementing, and (c) end truncated.*

ing plasmon resonance [96], using photonic crystals [97] and so on. These methods can be used to improve the efficiency and directivity of photoconductive antennas.

[94] introduced a full-dielectric element lens. It can be seen that the element lens exhibits high transmission efficiency and almost collimated performance at 1 THz, and can also complement each other in detection. Compared to conventional ultra-spherical silicon lenses, the lenses proposed in [94] are lighter, thinner, and have enhanced collimation capabilities, which can pave the way for the development of high performance integrated light-conducting THz antennas. [95] proposed a leak lens for the weakness of dispersion and low radiation efficiency of photoconductive antennas. The structure is shown in Figure 18(a), which is designed to overcome the problem of scattering and poor radiation efficiency. [96] achieved plasmon resonance by establishing different metal arrays, which can solve the problem of low output power of photoconductive antennas. The structure is shown in Figure 18(b). [97] proposed a defective photonic crystal substrate, and the geometry is shown in Figure 18(c). The substrate consists of a two-dimensional array of holes drilled into a solid substrate to improve the radiation characteristics of the THz photoconductive antennas.

To further explore the THz photoconductive antennas, a novel equivalent circuit for pulsed photoconductive sources is introduced for showing the coupling between the photoconductive gap and the antennas [98], [99]. Photoconductive antennas with different geometries are fabricated and measured for validation, as showed in Figure 19.

By the above reseraches of PCA, we have a general understanding of PCA. The innovation of PCA is of great significance to the development of THz technology. However, the current PCA has disadvantages such as low conversion efficiency. It is still in the development stage in the areas of substrate materials, geometric structures and new technologies.

4.2 Terahertz horn antennas

In a high-speed THz communication system, the horn antenna can be used as a stand-alone antenna or as a feed source for a lens antenna or a transmitting antenna. Due to its simple structure, good performance, low cross-polarization and wide frequency band, horn antennas have been widely used in high-gain THz antennas. Since the frequency of the THz wave is very high, the path loss of the THz wave is much more serious than that of the millimeter wave in free space. Therefore, the THz base station antennas require a very high gain to overcome the distance of the THz

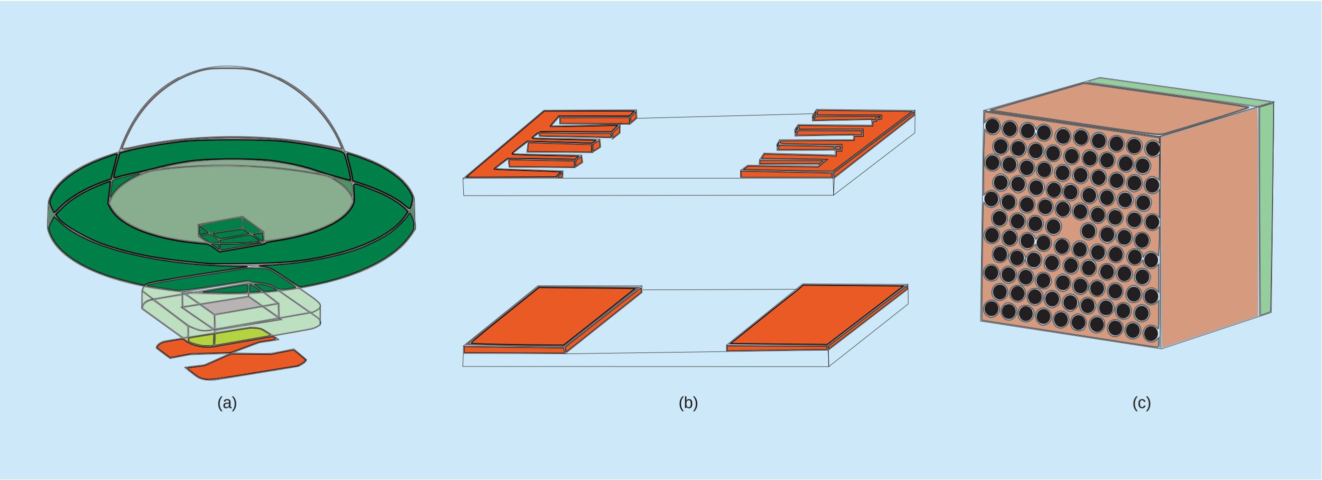


Fig. 18. *Three optimized PCA schematics: (a) PCA loaded lens [95], (b) comparison of two PCA electrode structures [96] and (c) photonic crystal substrate [97].*

communication system or additional path loss for performance. Therefore, the study of THz horn has great potential for gain improvement.

In recent years, there have been many achievements in the development of high-gain THz horn antennas. For example, Nacer Chahat et al. proposed a multi-angle horn antenna fabricated on an oxygen-free copper metal block [101]. As shown in Figure 20(a), the antenna operates at 1.9 THz, and the optimized directivity can reach 31.7 dB, and the cross polarization level is lower than -22 dB.

However, this horn antenna is composed of many parts, which requires high manufacturing cost, long time, and complicated assembly. Thus, in 2016, Kuikui Fan et al. proposed a new highly integrated radiating structure [102] with a horn antenna combined with an E-plane horn and a double H-plane reflector for high radiation gain, excited by standard WR2.2 waveguides. The THz horn antenna is used as the main feeder of the proposed antennas, and the structure is shown in Figure 20(b). At the same time, a prototype was built using low-cost commercial milling technology. This horn antenna operates at the 325-500 GHz band, with an antenna gain of more than 26.5 dBi, especially at 500 GHz with a maximum gain of 32.0 dBi, and with a high radiation efficiency of more than 43.75%. It is clear that the horn antenna can be used as a reference prototype for low cost and high performance. Some researchers have designed three high-gain antennas (rectangular horn, Cassegrain and offset paraboloid type) operating at 300 GHz, where the gain of the horn rectangular horn is 25 dBi, and the prototype is shown in Figure 20(c) [103].

The above three horn antennas are single-band, while the multi-band horn antennas with rich spectrum information are popular in communication systems. But the THz horn antenna is very small and difficult to manufacture. In response to this phenomenon, Xiannan Wang et al. developed a dual-band horn antenna operating at 94 GHz and 340 GHz [104]. As shown in Figure 20(d), the geometry is composed of a corrugated conical horn and a strip of tapered media. The conical horn operates at 94 GHz, and the media strip is inserted to allow the horn to operate at 340 GHz, simultaneously. The design has the advantages of low cross polarization, high port isolation, and large frequency ratio. In addition, the gain of the two bands can be adjusted independently. The design is simple to

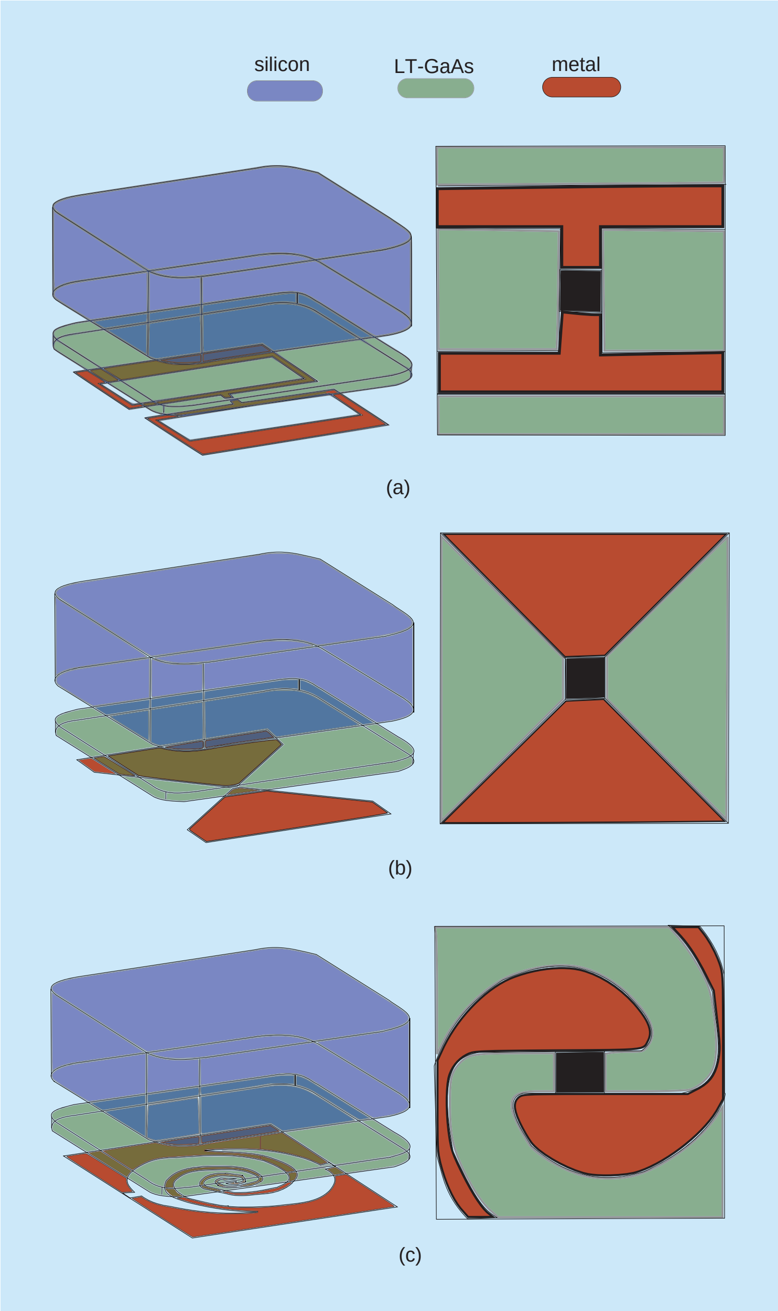


Fig. 19. *PCA geometries and structures [98]: (a) H-dipole antenna, (b) Bow-tie antenna, and (c) Logarithmic spiral antenna.*

assemble and easy to manufacture. A H-plane dielectric horn antenna operating in 750-1000 GHz has been proposed in [105]. It shows a good performance and is compatible with the planar circuit integration and Si fabrication, but has a larger size and low gain. For further study, a circularly polarized horn antenna can be achieved by selecting properly sized hexagonal waveguide [106].

From the above research results of the horn antennas, it can be seen that the current mainstream trend is focused on developing the low-cost, high-gain, compact, and multi-band horn antennas. If the horn antennas are not properly processed, some current will outflow, which will affect the performance of the horn antennas. Therefore, the following content concerns an optimization process for the THz horn. At present, the optimization schemes are typically the corrugated and loaded lens antennas.

1) ***Ripple treatment:*** The corrugated horn antenna can be obtained by engraving the corrugated groove on the conical horn with a suitable process. Different process treatments and different structural designs can achieve different effects. The corrugated horn antenna improves the pattern and reduces the cross-polarization level compared to a conventional horn antenna.

The working principle of the corrugated horn is to influence the distribution of the internal electromagnetic field through the corrugated wall [107]. Figure 21(a) shows the undulated wall. The corrugation can change the field propagating by the waveguide. Figure 21(b) shows the electric field of the corrugated horn antenna in the aperture, with an almost linear field in the antenna aperture. Obviously, the corrugated horn has two major advantages. On the one hand, the longitudinal current can be well suppressed by the ripple, and on the other hand, the magnetic field is sharply weakened near the corrugated groove.

There have been many studies on new technology of corrugated horn antennas. For example, in 2014, Takuro Tajima et al. used low-temperature co-fired ceramic (LTCC) technology to design corrugated horn antenna [108]. The antenna operates at 300 GHz and uses a cavity in a multi-layer LTCC substrate and a surrounding via barrier to form a feed hollow waveguide, which is shown in Figure 22(a). Due to the vertical configuration, the corrugated and stepped profile of the horn antenna is designed to be close to a smooth metal surface. The antenna has a peak gain of 18 dBi, a bandwidth of 100 GHz, a return loss of more than 10 dB, and a very small antenna size that allows the horn antenna to be integrated into the transceiver. One of the innovations of this design is the hollow structure,

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

Fig. 20. *Four THz horn antennas: (a) multi-angle horn[101], (b) E-plane horn [102], (c) rectangular horn [103] and (d) dual-band horn [104].*

which is relatively efficient compared to other LTCC antennas, and the use of ripples allows the horn antennas to exhibit better symmetry of the radiation pattern and a better Gaussian profile.

According to different corrugation loading modes, the corrugated horn antennas can be classified into three types: a radial trough corrugated horn, a scalar corrugated horn and an axial trough corrugated horn. The process of radial corrugation is too difficult and the opening angle of the scalar corrugated horn is relatively large. The axial trough corrugated horn can be processed on the outside of the horn, which is simple to manufacture. For example, in 2016, Lili Wang et al. designed a low-frequency THz H-plane horn antenna with an operating frequency of 191 GHz by loading axially slotted corrugations outside the horn of the H-plane flat-wall coaxial antenna [109]. The structure is shown in Figure 22(b). The antenna can weaken the interference of the wall current propagation on the radiation characteristics of the antenna, and effectively improve the directional radiation capability of the antenna. The maximum axial-ratio gain is 9.8 dBi with good directivity. The biggest highlight of the design is that the corrugations are designed on the outside of the horn and are easy to machine.

Even though the above horn antennas have been optimized in structure, at present, these antennas still have disadvantages such as high side lobes, low gain, and insufficient bandwidth. Corrugated horns can propagate high-order mode waves at the same phase velocity, which greatly expands the operating bandwidth. Thus how to design a corrugated horn with high coupling efficiency is essential. Yi-fan Jiang et al. [110] proposed a corrugated round-hole horn based on micro-electromechanical system technology. The structure is shown in Figure 22(c), which can achieve symmetrical beam radiation performance and reduce cross-polarization. The coupling efficiency of the antenna to the Gaussian beam is as high as 96%. In addition, some scholars designed a back-to-back corrugated horn operating at 0.22THz based on the characteristics of the corrugated horn [111]. The coupling efficiency is as high as 97.5%, and it can maintain more than 96% coupling coefficient at the 0.2 THz to 0.24 THz frequency band.

It can be seen from the previous analysises that the current frequency of the corrugated horn antenna is mostly between 0.1 and 1 THz, and the higher frequency band THz corrugated horn antenna has not been involved. Alvaro Gonzalez et al. designed and fabricated two different corrugated horns for the 1.25-1.57 THz band by directly processing a single piece of aluminum [112]. As shown in Figure 22(d), the first geometry is a long conical corrugation horn and the second geometry is based on the contours of nine different conical sections. Moreover, the measured results are basically consistent with the simulated results, which meets the application requirements of high beam quality, low cross polarization, and wide bandwidth. Thus this antenna can be used in the field of radio astronomy.

Different process techniques and corrugated designs can result in different effects. In any case, the above research results show high gain and low cross-polarization level characteristics of the corrugated horn antennas, diversified ripple loading mode, and operating frequency of the horn antennas.

2) ***Loading lens***: In addition to the structural design and process of the speaker itself, there is also an optimization scheme that loads the lens. The lens focusing characteristic can

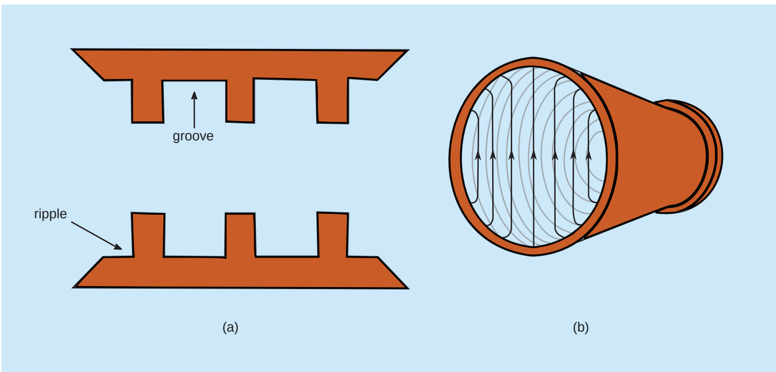


Fig. 21. *Corrugated horn working principle: (a) longitudinal section and (b) electric field line of corrugated horn[107].*

improve the directivity and gain of the THz antennas. Thus, loading the lens is a practical and universal method. The existing research results include: the THz band fuze antennas can be realized by loading the lens with the H-plane horn antenna [113]; loading the slotted Fresnel lens on the corrugated horn feed antenna can increase the antenna gain by 12.5 dBi [114]; loading a new type of "well" word stacking lens, whose process method and assembly are relatively easy with the operating frequency band of 320-380 GHz and the gain of higher than 26.4 dBi, can focus THz wave to meet the THz communication system's requirement [115]. There are also differences in loading different lenses with different geometry. For example, Yong Li and Ruiliang Song proposed a high-gain bow-tie antenna that can be loaded with a bullet-type silicon lens on an indium phosphide (InP) substrate [116]. By comparing the radiation characteristics of two different lens (hemispherical and bullet type) antennas, it can be concluded that higher efficiency, bandwidth and gain can be achieved when the on-chip antenna is equipped with a bullet-type silicon lens. The above four lens-loaded horn antenna prototypes are shown in Figure 23.

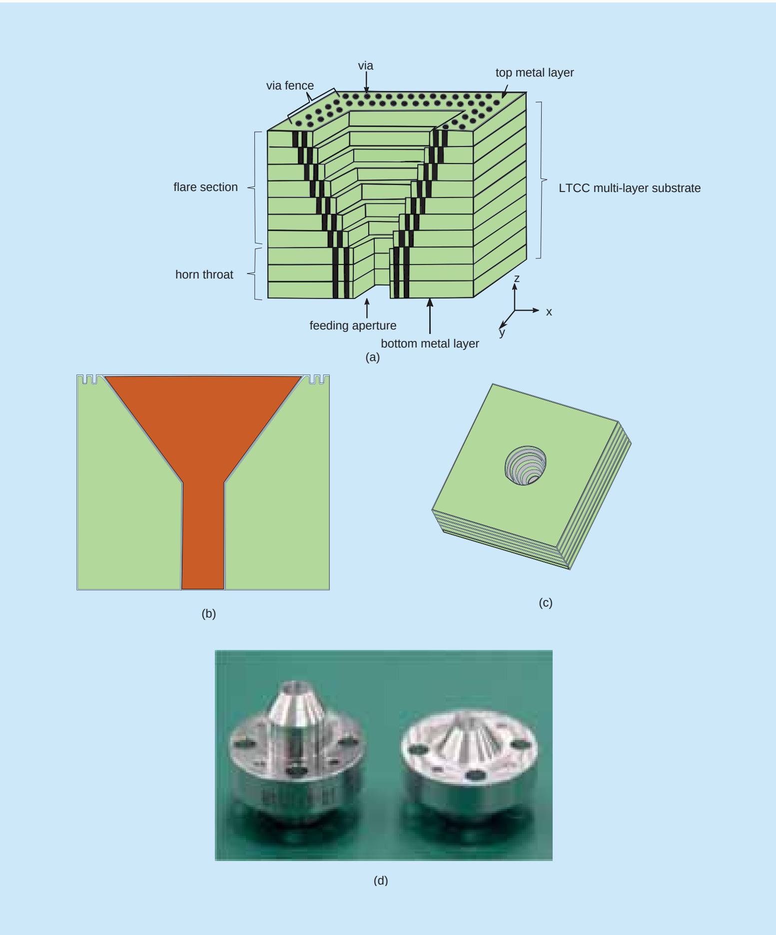


Fig. 22. *Four corrugated horns: (a) corrugated horns combined with LTCC [108], (b) horns loaded with axial grooved corrugations [109],(c) Multi-layer corrugated THz horn [110] and (d) processed based on aluminum materials Corrugated horn [112].*

Table 4 shows the performance comparison of several THz horn antennas. From Table 4, most of the horn antennas operate at the low frequency range of the THz wave, and the antenna gain can reach up to 35.5 dBi. These THz antennas can be realized by the ripple process and loading lens. By the above analysis of the horn antennas, we can understand the advantages and disadvantages of the horn antennas application at the THz frequency band, and propose two optimization schemes for the horn antennas. In addition, it is also possible to study deeply on the aspects of material, size, and geometry of the horn.

4.3 Terahertz lens antennas

The lens has focusing and imaging capabilities to improving the performance of the THz antennas, such as reducing sidelobe levels and cross-polarization levels, achieving in good directivity and high gain.

There are two common types of lenses: accelerating lenses and delaying antennas. They are classified by reducing and increasing the electrical length of the electromagnetic wave path [113]. The former's phase velocity is greater than the speed of light, and is typically an E-plane metal plate lens; the latter's phase velocity is less than the speed of light, and is representative.

The metal plate lens is formed by parallel arrangement of metal plates. The electromagnetic wave passes through matal plate lens as if it is transmitted in the waveguide. Since the refractive index has a great relationship with the metal plate spacing, the metal plate lens is very sensitive to frequency, which makes it unsuitable for THz antenna design. Since the metal plate lens need high precision and difficult process, there are few metal plate lenses used at the THz band. However, an artificial lens, named as a metal lens which meets the design requirements of THz antennas, has recently been developed.

The dielectric lens is fabricated using a low-loss dielectric, typically thick in the middle of lens and thin around lens with focusing and imaging characteristics. The dielectric lens can be fabricated in different shapes, such as ellipsoidal, hemispherical, over-hemispherical, and expanded hemispherical.

In general, as the thickness of the substrate increases, the energy will radiate more toward the dielectric layer. [56] has studied this phenomenon and used a dipole antenna as an example. Figure 24 shows the radiation power of a dipole antenna on a substrate with a semi-infinite thickness. The solid line is the antenna radiation when the dielectric constant of the medium is 11.7, but the dotted line is 4.

It can be seen from the Figure 24 that the dipole antenna radiates most of the energy to the dielectric layer. So the dielectric loss is very large, but conversely, if the energy radiated to the dielectric layer is used as the radiant energy. The energy of the layer is radiation energy, which can greatly improve the antenna gain and directivity. Therefore, the dielectric lens is used instead of the above-mentioned semi-infinite dielectric layer, and simulation result has almost no deviation, which meets the antenna design requirements.

THz lens antennas are relatively simple to manufacture, have low material requirements, are low in cost, and are easy to integrate [117]. In general, they are currently highly promising antennas that meet the design requirements of THz antennas. Two types of lenses are currently popular: silicon lenses and artificially fabricated metal lenses with retardation characteristics. Table 5 shows the research results

Table IV. *Performance comparison of several THz horn antennas.*

Ref.	Antenna type	f (THz)	Gain (dBi)	Return loss	Other
[101]	Multi-angle horn	1.9	N/A	N/A	Cross polarization level below -22 dB
[102]	Integrated E-plane horn and H-plane reflector	0.4125	>26.5	>20 dB	Radiation efficiency 43.75%
[104]	Dual frequency loading media horn	0.34	22.8	N/A	Sidelobe level below -25.4 dB cross polarization below -41.2 dB
[108]	Corrugated horn based on LTCC integration	0.3	18	<-10 dB	Radiation efficiency 90%
[109]	Corrugated horn	0.191	9.8	-35 dB	VSWR less than 1.5
[110]	Multi-layer corrugated THz horn	0.5	20.2	-13 dB	Coupling efficiency to Gaussian beam reaches 96%
[114]	Slotted medium type Fresnel lens antenna	0.35	Peak 35.5	<-20 dB	12.5 dB better than normal horn gain
[115]	Stacked lens antenna	0.35	>26.4	N/A	N/A
[116]	On-chip THz antenna	0.34	13.5	<-10 dB	90% efficiency

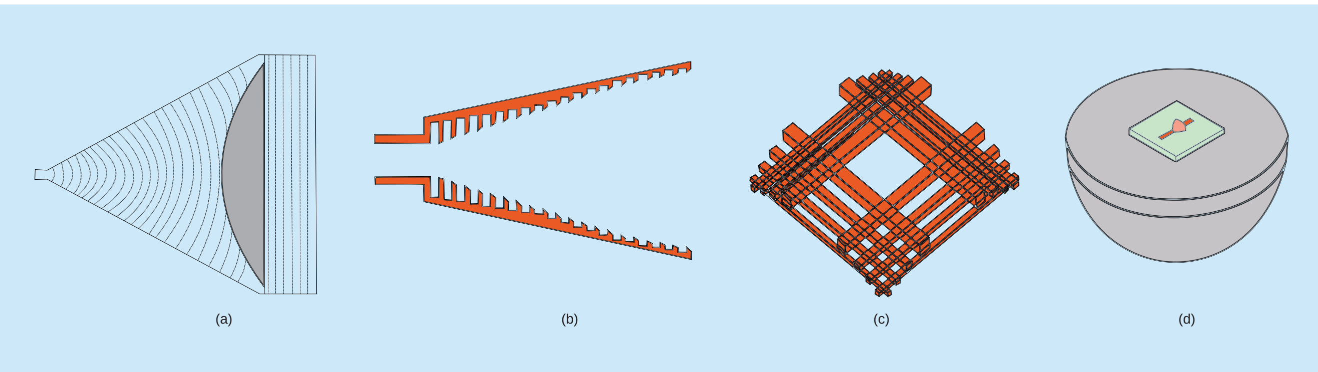


Fig. 23. *Four lens-loaded horn antennas: (a) fuze antenna [113], (b) corrugated horn [114], (c) "well" word stacked lens [115] and (d) bullet-type silicon lens [116].*

of THz lens antennas in recent years.

It can be seen from Table 5 that the design concepts of [118] and [119] are similar, and they are integrated arrays of extended hemispherical silicon lenses fed by leaky waveguides. The integration is high, and the antenna prototype can be fabricated by laser micromachining. The lens in [120] is fed by a plane logarithmic spiral. By appropriately changing the length and diameter of the lens, the far-field radiation beam can be controlled and optimized to achieve the target bandwidth. The operating frequency is 0.625 THz, and the maximum directivity of 30.8 dB can be achieved, showing good radiation performance. Obviously, THz silicon lens antennas are typically used in integrated antennas or array designs to enable compact THz antennas. At present, a multi-beam antenna based on Luneburg lens is proposed [121]. The proposed lens integrated Luneburg and Maxwell fisheye, which is helpful for terehertz anti-interference communication system. In addition, a thin-film SUEX was conformally coated on silicon lens to reduce reflection loss to less than 4% [122].

Table V. *Research results of THz lens antennas.*

Ref.	Type	f (THz)	Fig.	Other
[118]	Silicon lens	0.545	25(a)	The antenna consists of an extended hemispherical lens antenna fed by a leaky waveguide that can be integrated with detectors such as sensors and schottky diodes
[119]	Silicon lens	0.55	25(b)	The antenna consists of an extended hemispherical silicon lens fed by a slot waveguide with high integration
[120]	Silicon lens	0.625	25(c)	The antenna is fed by a plane logarithmic spiral, and the maximum directivity can reach 30.8 dB
[123]	Metal lens	0.4125	25(d)	Maximum measurement gain is 27.6 dBi, return loss greater than 15 dB
[124]	Metal lens	0.4125	25(e)	Radiation gain is higher than 35.0 dBi
[125]	Metal lens	0.675	N/A	Gradient index convex lens THz antenna with full metal dielectric constant near zero
[126]	Metal lens	0.185	25(f)	Large diameter metal mesh lens

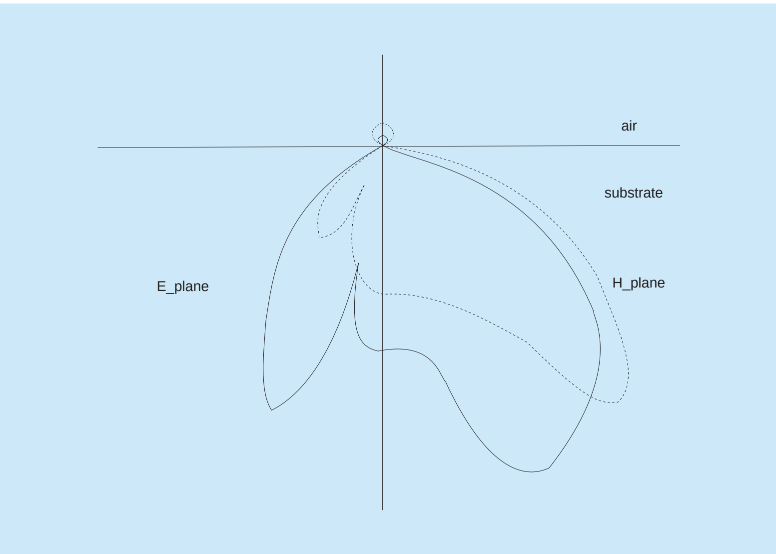


Fig. 24. *Radiation power distribution diagram of dipole antenna on dielectric layer [56].*

Man-made metal lenses can be designed asconformal or planar and are easy to manufacture. Thus, the research of metal lenses as novel antennas has been popular in recent years [123]-[126]. Both [123] and [124] use low-cost commercial metal milling techniques combined with metal lenses to make THz antennas with non-metallic structures, while [125] and [126] are all-metal THz lens antennas. An artificial metal lens can have a smaller area and a wider frequency bandwith compared to a conventional lens. The geometric structure of six representative THz lens antennas are shown in Figure 25.

In summary, the lens can optimize the performance of antennas with weak directionality and low gain (such as horn, waveguide, etc.), and its focusing characteristics can also reduce the side lobes and cross polarization levels, which provides a great design aspect for the THz antennas. At present, silicon lenses and metal lenses are widely used. Silicon lenses are often used for integrated antenna design. Metal lenses can be manufactured manually. Research on the combination of lenses with new technologies or other types of THz antennas requires further efforts. It is believed that future THz lens antennas can be designed in miniaturized size to meet low cost and high gain requirements.

4.4 Terahertz microstrip antennas

A microstrip antenna is designed by a thin dielectric substrate with a metal patch. The microstrip antenna is small size, light weight, simple to be manufactured, and wearable, and suitable for massive production. In recent years, there are many types of microstrip antennas developed, including T-type, slotted, stacked types, single-band and dual-band [127]-[133]. Since the substrate of the microstrip antennas is very thin and sensitive to frequency, the current research on THz microstrip antennas is concentrated at the low frequency range of THz (0.1-1 THz). This section classifies the microstrip antennas into two frequency bands for analysis.

For low-band THz microstrip antennas, the design is varied. The latest research results are as follows.

In 2017, Ge Zhang et al. [127] proposed an optimized THz microstrip antenna based on a dual-surface multi-channel open-loop resonator, as shown in Figure 26(a). On both surfaces of the antenna substrate, the same multi-way open-loop resonator connected to the feed line.

A T-shaped structure is generally adopted in dual-band microstrip antenna. In 2017, Wang Haijun et al. [128] studied a novel dual-frequency THz microstrip antenna, the structure shown in Figure 26(b). The antenna design is based on the principle of double T-shaped slits. The double T-shaped's radiation gap is loaded on the radiating metal patch, which can change the path of the surface circuit to achieve the effect of dual-frequency resonance.

M. Khulbe et al. [129] also designed a T-type dual-frequency microstrip antennas, but they improved the gain by optimizing the substrate volume. Unlike the substrate material in [128], [129] designed a dual-band coaxial feed slot microstrip patch antennas based on

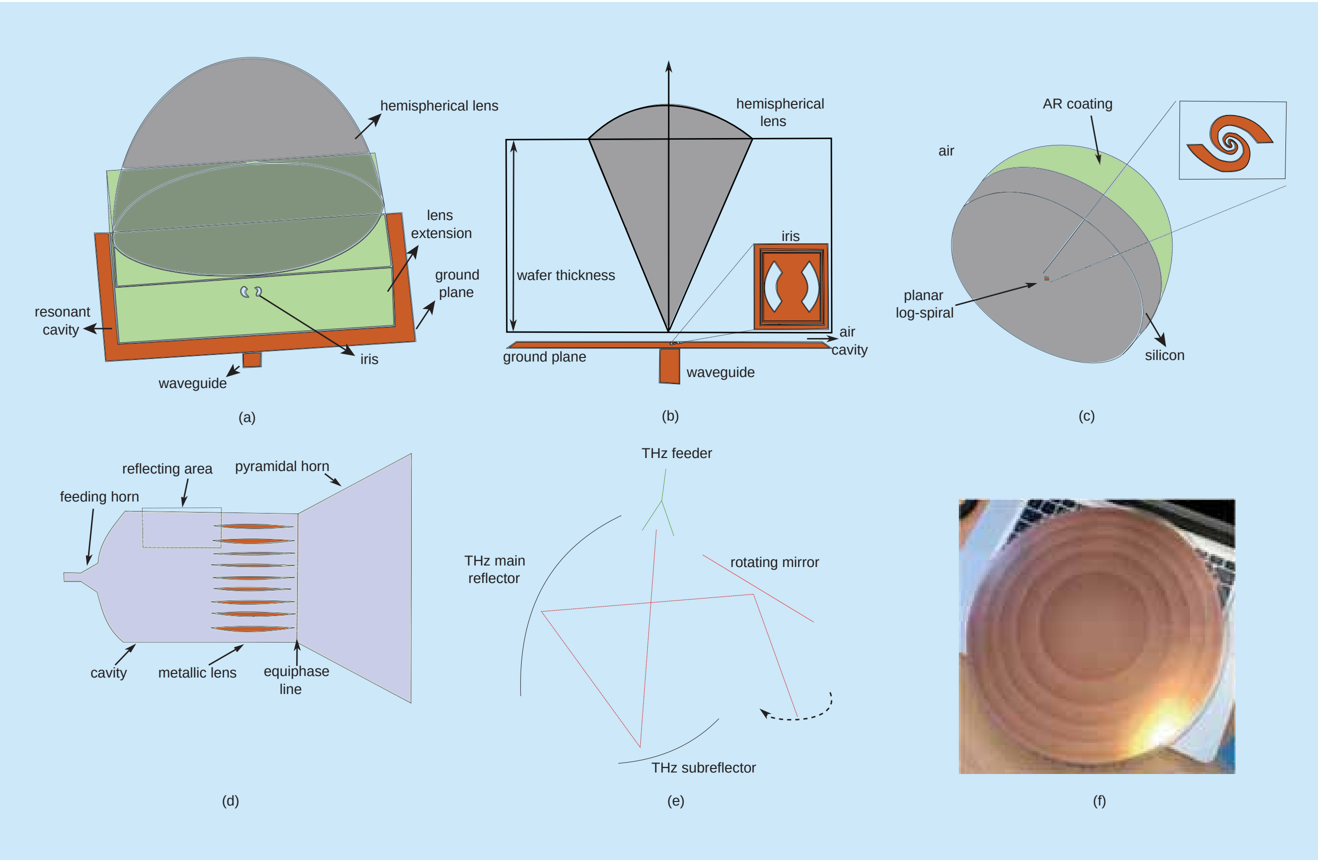


Fig. 25. *Six THz lens antennas: (a) extended hemispherical silicon lens [118], (b) extended hemispherical silicon lens deformation [119], (c) planar log-cycle fed silicon lens [120], (d) metal lens electric field distribution [123], (e) THz beam scanning antenna [124] and (f) metal mesh Fresnel lens [126].*

a T-shaped patch on an epoxy resin (FR-4) substrate, as shown in Figure 26(c). The slot is made by symmetrical cutting of copper, and the implementation of this structure provides better direction and radiation efficiency. This THz microstrip antenna can be used in a variety of applications such as fast and secure data transmission, biomedical applications, radar and THz imaging, nano-antenna applications and more.

The epoxy resin substrate used in [129] is relatively low in cost, and exhibits very low absorption loss, small suppression and high directivity to the human body at the THz band, and is very suitable for manufacturing a wearable microstrip antenna.

In addition, in 2017, Liton Chandra Paul et al. [130] used a photonic band gap (PBG) substrate and a defective ground structure (DGS) to design a microstrip antenna with

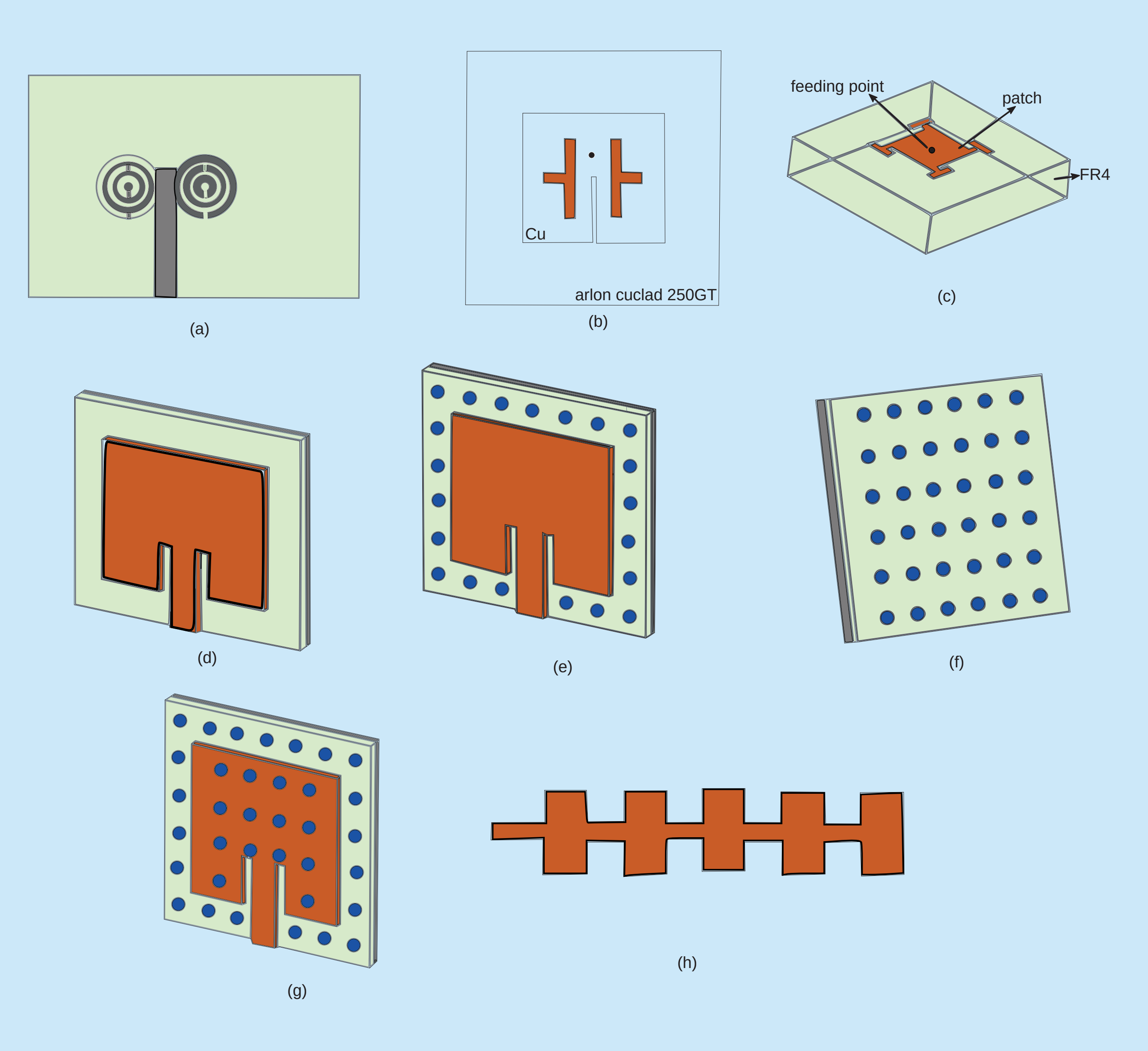


Fig. 26. *Schematic of the low-band microstrip antennas: (a) MSRRs microstrip antenna [127], (b) dual T-slot patch antenna [128], (c) FR-4 based T-type microstrip antenna [129], (d) RMPA [130], (e) RMPA based on PBG substrate [130], (f) PBG-based RMPA with DGS [130], (g) slotted RMPA [130] and (h) microstrip antenna array [130].*

wide broadband (26.4 GHz) and small size. The authors firstly designed a compact rectangular microstrip patch antenna (RMPA); then introduced a PBG structure as the substrate, in which case the antenna's performance was significantly improved over the previous one; the next step was to create defects in the ground plane, while optimizing the size of the defects; finally, some loop slots were made on the radiation patch to achieve the best results. Through optimizations, the gain and bandwidth were improved. This prototype of the antennas is shown in Figure 26(d)-(g).

Besides the single microstrip antenna, antenna arrays provide better directionality and gain. In 2017, Muhammad Saqib Rabbani et al. [131] used liquid crystal polymers as substrate operating at frequencies of 0.835, 0.635 and 0.1 THz. The geometry is shown in Figure 26(h). The design can be fabricated on a simple printed circuit board (PCB) for a variety of applications in medicine, which includes cancer detection by THz spectroscopy and vital signs detection by Doppler radar or vitro technology.

However, the microstrip antennas operating in THz band have a low gain, so the exploration of the THz microstrip antennas is mainly based on how to improve the gain.

In 2016, Gurnoor Singh Brar et al. [132] designed a THz stacked microstrip antenna using FR-4 substrate, as shown in Figure 27(a). The characteristics of the semiconductor are detected by employing the principle of suppression effect.

In 2017, Prince et al. [133] proposed a rectangular THz microstrip patch antenna with a slotted ground, as shown in Figure 27(b). The proposed antenna is made of copper and a rectangular groove is made on the ground. The antenna's return loss is very low, a gain of 4.254 dBi at the resonant frequency, which can be used to detect vitamins in biomedical applications. Obviously, the microstrip antennas in THz band also have low gain performance, and the optimization can be started from the aspects of material and structural design.

Based on the above analysis of the THz microstrip antennas, Table 6 gives performance comparison of several THz microstrip antennas. It can be seen from Table 6 that the radiation performance of the THz microstrip antennas needs to be further optimized. In summary, there have been many achievements in the research of microstrip antennas at the low frequency range of THz, but the research on THz microstrip antennas for high frequency bands is still in the development stage. The more serious characteristics are related to the fact that the choice of substrate has a great influence on the radiation performance of the antennas. Performance optimization is one of the most important research directions for future THz microstrip antennas.

4.5 Terahertz on-chip antennas

Due to the long transmission link and high loss, THz high frequency band signal on the chip will greatly attenuate. Meanwhile, in such a long link, it is hard to do have good impedance matching between different parts. Hence, it is both possible and necessary to integrate THz antennas on chip. The rapid development of packaging technology promotes the realization of THz on-chip antennas, such as CMOS- and SiGe-based packaging technology. Rectangular patch antenna is the most commonly used on-chip antenna structure, which is not only simple, but also easy to meet the design requirements of CMOS technology. Such as the rectangular patch of multiple frequency band is integrated on the same chip to realize

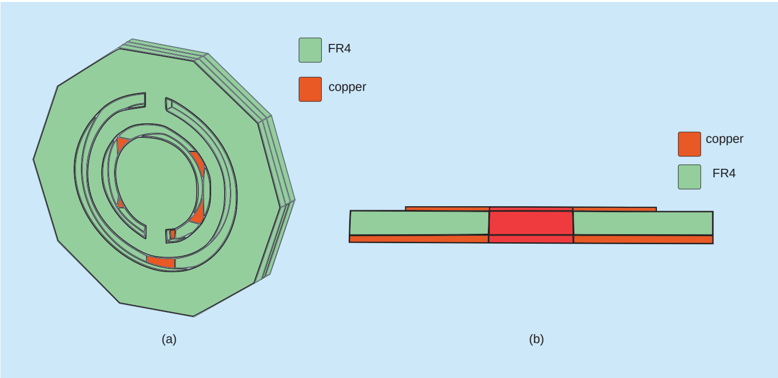


Fig. 27. *High-band THz microstrip antennas: (a) stacked microstrip antennas [132] and (b) slotted rectangular microstrip patch antennas [133].*

the frequency detection function, and the operating frequencies of the antennas were 1.6 THz, 1.9 THz, 2.6 THz, 3.1 THz, 3.4 THz and 4.1 THz [134]. However, rectangular on-chip antennas' feeder is too long or too narrow of cross section. Moreover, the area of the antenna on the rectangular plate is relatively large, the gain is relatively small and the bandwidth is too narrow, and the beam is not focused.

Some methods including loading dielectric and using array were proposed to improve the gain and bandwidth of on-chip antennas. For example, [135] presented a 0.34 THz on-chip 3-D antenna with 10 dBi gain and 80% radiation efficiency in 2015. Then, they presented two endfire on-chip antennas at 140 and 320 GHz by using a standard 0.13-μm SiGe BiCMOS technology [136]. Quasi-Yagi antenna concept is used with loaded dielectric, as shown in Figure 28. The later has a wider bandwidth and more compact structure.

Resonant cavity antenna has a large bandwidth, however its size is larger and the gain is lower [137],[138]. Such as the resonant cavity antenna designed by Shang Y. and Yu H., covers 0.239 THz to 0.281 THz, with a gain of -0.5 dBi. In practice, the higher order mode dielectric resonator (DR) would be a promising technology to improve the performance of THz on-chip antennas with simple assembly procedures and without additional area consumption [139], [140]. [141] has proposed a 270 GHz × 9 multiplier chain with on-chip dielectric-resonator antenna (DRA) with a 3-dB bandwidth of 33 GHz (from 0.258 to 0.291 THz) and the structure is shown in Figure 29.

Traditional on-chip antennas have become the first choice for THz antenna design, due to their advantages of low cost, small size, simple switching between circuits and easy to form arrays. For example, on-chip phased array can provide electronic beam steering and spatial power combining, as well as the capability for spatial filtering and multiple access [142]-[148]. Table 7 lists the performance comparison of THz on-chip antennas. The reason why the radiation efficiency of on-chip antennas is too low is that the inherent structure of on-chip antennas result.

This section provides a detailed analysis of several classic THz antennas (photoconductive antennas, horn antennas, lens antennas, microstrip antennas and on-chip antennas), including working principle, classification, performance comparison, and so on. The advantages and disadvantages of THz antennas are as follows.

1) For the photoconductive antenna, it

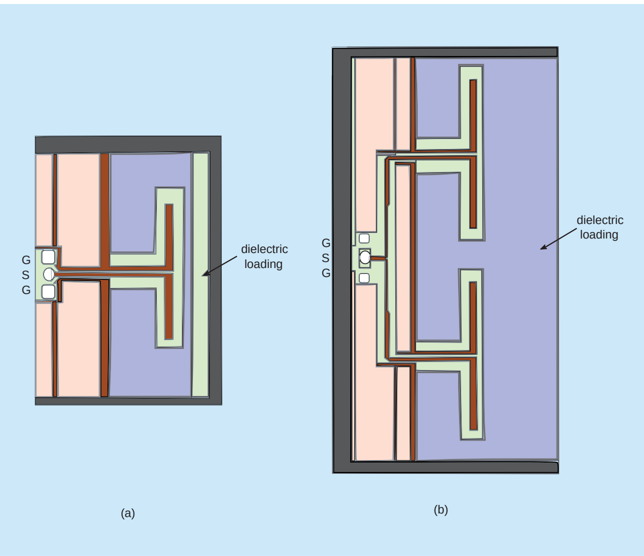


Fig. 28. *Micrograph of the on-chip antenna of (a) 320- and (b) 140-GHz antenna array [136].*

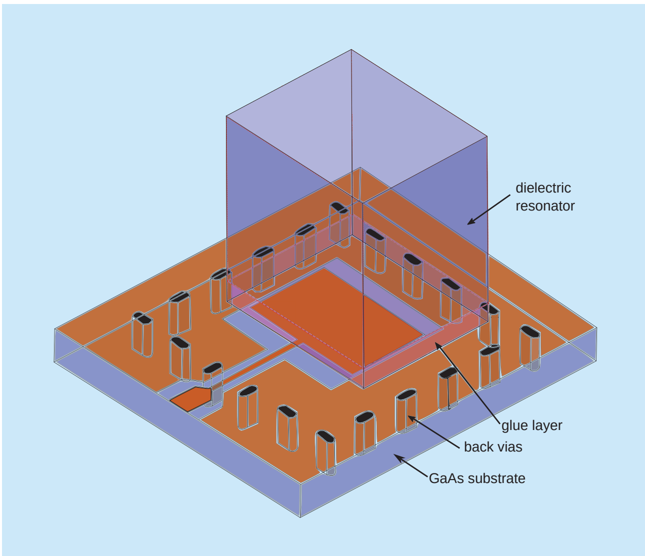


Fig. 29. *On-chip antenna structure with higher-order mode dielectric resonator [141].*

generates a THz radiation source. Its photoelectric conversion efficiency, output power, directivity, and gain have a great influence on the radiation performance of the THz radiation source. The more mature ones are dipole photoconductive antennas and large aperture photoconductive antennas, of which typical antennas are bow-tie and log-helix PCA. At present, PCA still suffers from the weakness of large material loss, low photoelectric conversion efficiency and low output power. It is necessary to optimize PCA, which can be achieved by loading silicon lens, plasmon resonance and photonic crystal. The idea of optimizing PCA is mainly from three aspects, such as antenna geometry, material selection and new technology. By innovation, it is hoped that the radiation performance of photoconductive antennas can be improved, which can promote the advancement of THz technology.

2) For THz horn antenna, it has the advantages of simple structure, low cross polarization and wide operating band, and high gain. But it is difficult to process in terms of integration and miniaturization, and the optimization can be achieved by corrugating and loading the lens. Although the complex rippled horn has better radiation performance compared to other horn antennas, it leads to complicated process, high precision requirements and high cost. Low-cost and simple-structured horn antennas are widely used, with better directionality and higher gain. At present, the THz horn antennas that have been applied are basically operating near 0.3 THz, and there are few horn antennas in high frequency bands of THz, which is related to the process technology of the horn. Another fatal flaw of horn antennas is that it is not easy to connect to planar circuits, and difficult to form antenna arrays.

3) For THz lens antenna, the lens can use its focusing characteristics to reduce the sidelobe level and cross-polarization level of the antennas, so that the antennas can obtain better directivity and higher gain. Currently the basic lenses are silicon lenses and metal lenses, which are used in integrated antenna design and small-area antenna design. The lens antennas are the most popular at the THz band. It has good directivity and high gain, and is very easy to connect with a planar antenna. However, the surface wave effect and dielectric loss of the lens antennas exist, and it is necessary to optimize its material and geometry in the near future.

4) For THz microstrip antenna, it has the advantages of small size, simple manufacturing, and easy to wear. Although many THz microstrip antennas have been developed, most of them are concentrated at the lower frequency band of THz. The gain is low and the bandwidth is narrow. The substrate material has a great influence on the electromagnetic

Table VI. *Performance comparison of several THz microstrip antennas.*

Ref.	Type	*f* (THz)	Bandwidth (GHz)	Gain (dBi)	Return loss (dB)	Substrate material
[128]	Double T-type slot microstrip antenna	0.3 and 0.76	12 and 31	7.13 and 3.71	-29 and -40	Arlon Cu-clad 250GT
[129]	T-type dual-frequency microstrip antenna	0.632 and 0.8702	50 ~ 80	Peak gain 8.2	N/A	FR-4
[130]	Slotted patch RMPA	0.703	26.4	5.235	-50.948	PBG and DGS
[131]	Microstrip antenna array	0.1	2.24	15.7	-26.04	Liquid crystal polymer
[132]	Stacked microstrip antenna	8.2	0.36	6.48	-38.85	FR-4
[133]	Slotted rectangular microstrip antenna	4.952	0.4445	4.254	-55.31	FR-4

Table VII. *Performance comparison of THz on-chip antennas.*

Ref.	Array Size	Radiation	*f* (THz)	Beam Steering(°)	Technology(f_{max})
[142]	4×4	DAR + Subs. Thinning	0.28	80/80	45 nm SOI CMOS (N/A)
[143]	1×8	Patch Antenna + Quartz Superstrate	0.39	75	45 nm SOI CMOS (0.26 THz)
[144]	1×4	Patch Antenna	0.5315	60	40 nm CMOS (0.3 THz)
[145]	4×4	Patch Antenna	0.338	45/50	65 nm CMOS (0.25 THz)
[146]	1×4	SIW Cavity Backed Patch	0.32	24/0	130 nm SiGe (0.3 THz)
[147]	2×2	Patch Antenna	0.344	128/53	130 nm SiGe (0.215 THz)

performance of microstrip antennas.

5) For THz on-chip antenna, it can solve the shortcomings of the mechanical antenna switching circuit, and is small, simple in fabrication, low in cost, easy to be intergrated and arrayed detector design, but it also has a lower gain and a narrower bandwidth. The main direction currently being studied is how to improve the gain and bandwidth of on-chip antennas.

In summary, the five typical THz antennas have their own advantages and disadvantages. Photoconductive antennas are mainly used to produce THz radiation sources. PCA uses femtosecond laser pulses to illuminate its antenna gap to generate THz signals. The improvement of photoelectric conversion efficiency is the key research direction in the future. The horn antennas are widely used at the low frequency band close to the microwave band, due to their good directivity, high gain and easy connection with the waveguide. The lens antennas can optimize the directivity of antennas due to their focusing characteristics. Since the lens antennas have excellent directivity, higher gain, and easy to connect with planar circuits, especially with the advantage of forming an antenna array, the lens antennas are very attractive. Microstrip antennas have small size and are widely used in mobile THz equipments. But their low directivity and low gain require further optimization in future. The on-chip antennas avoid the extra connection loss and packaging steps of the off-chip antenna system, and these additional operations result in loss of antennas' gain and overall size. On-chip antennas can be manufactured and assembled on a large scale with the latest CMOS technology. As technology matures, manufacturing costs will gradually decrease.

For the optimization of THz antennas, we can start from the antenna geometry, substrate materials and new fusion technologies. At the same time, significant gain can be obtained by creating an antenna array [149]. The reflectarray antennas are designed as potential solutions for high-gain THz antennas. The THz reflectarray antennas combine the advantages of the reflector antennas and the array antennas, and have excellent high-gain performance. THz reflectarray antennas include not only traditional microstrip reflectarray antennas, but also dielectric resonant reflectarray antennas, all-metal reflectarray antennas, and special material reflectarray antennas[150]. When the structure of the microstrip reflective array antennas is determined, the beam pointing direction is also determined, and the flexible scanning function of the beam cannot be realized. In order to realize the electronically controlled scanning function of the antenna beam pointing (so called reconfigurable reflectarray antennas), it is necessary to introduce a phase shifter that can operate in a high frequency band. The phase shifters currently used are mainly solid-state tuning devices (e.g., PIN diodes, varactor diodes). However, at the THz frequency band, these devices have parasitic effects and large losses. Therefore, the researchers realized the design of high-frequency phase-shifting devices by introducing media that can be tuned electrically. Commonly used materials are ferroelectric materials, liquid crystal materials and graphene.

The nonlinear nature of ferroelectric materials can be used to make capacitors with adjustable capacitance. But the driving voltage of ferroelectric materials is very high, and it generally needs to apply a bias voltage of more than 300 V to work. Liquid crystal is a dielectric anisotropic material. In the case of an external electric field, the arrangement direction of liquid crystal molecules will change with the size of the electric field, thereby changing its dielectric constant. [151] used liquid crystal as the circuit substrate and a reflectarray phased array with an operating frequency of 0.3445 THz was designed. The phase of the reflected wave of each element is controlled by applying an electric field, and the continuous scanning of the antenna beam is realized [152], [153]. However, the liquid crystal material is liquid, and errors caused by filling and manufacturing are unavoidable. The loss of the liquid crystal material at the THz band is relatively large, which limits the efficiency of the liquid crystal reconfigurable reflectarray antennas. Graphene is a two-dimensional carbon nanomaterial that can change the surface conductivity of graphene by a bias electric field. Graphene has higher tuning efficiency and lower dielectric loss at the THz band [154]. In 2018, Saber et al. proposed a frequency-adjustable reflectarray antennas based on graphene [155]. The transmitting element is composed of a split ring printed on the silicon dioxide dielectric substrate. The phase compensation of the element and the resonance point of the antenna are controlled by changing the length of the gap of the split ring and the surface conductivity of the graphene, respectively. The frequency graphene emission array antenna has good radiation performance. However, the current design of graphene-based reflective arrays is often limited by the preparation process of graphene.

In addition, some new materials, such as metamaterials, are also used in reflectarray arrays. Metamaterials are composite materials made of artificial structures, and their performance mainly depends on the artificial structures. For example, in 2016, Koziol et al. proposed the idea of using laser radiation to directly metallize to prepare metamaterials [156]. A high-energy laser beam was irradiated to the aluminum nitride ceramic body, and the surface of the aluminum nitride ceramic body obtained metallic aluminum to form a super material. In the same year, [157] designed a gold-polyimide-gold chiral metamaterial, etched the resonance ring on the metal layers on both sides of the polyimide, and used the coupling between the metal layers to generate chiral parameters. This makes the negative refractive index independent of the positive and negative of the dielectric constant and permeability. The chiral metamaterial has a wider frequency band. Obviously, with the continuous research and development of new materials, the electromagnetic performance of THz reflectarray antennas is expected to be improved, such as higher gain and reflection efficiency.

Actually, in the application of THz communication, different materials and structures are selected according to actual requirements achieve the high-gain reflectarray antennas. For example, [158] presented a 400-GHz folded reflectarray antenna with a peak gain of 33.66 dBi and an aperture efficiency of 33.65%. Despite all this, the current THz antenna is still in its development stage, and its functions in many aspects are not perfect enough. It is expected that the subsequent research will be innovative and thus promotes the realization of the THz high-speed communication system.

V. Process Technology of Terahertz Antennas

The THz wavelength is far smaller than that of millimeter wave. Hence, it is unreasonable to assume that the surface of antennas is smooth at THz frequencies. In fact, the metal surfaces should be considered as rough surfaces at the THz frequencies [159], which results in a decrease in the performance of the THz antennas. As is well known, antenna surface roughness is related to machining accuracy. Since many designs are limited by the process technology, the research on process technology is also important. Obviously, the development of THz antennas is inseparable from the development of process technology. The current popular process technologies including 3D printing technology and focused ion beam (FIB) technology are summarized as follows.

1) 3D printing technology is mostly used for printing waveguide or horn antennas [160]-[162], as well as THz lens [163]-[165], which has the advantages of rapid prototyping with low cost, high precision and miniaturization [166].

2) Focused ion beam (FIB) technology can overcome the disadvantages of traditional lithography technology and can be used for one-shot molding, especially for manufacturing complex antennas such as spiral antennas [167].

According to the development stage of process technology, it can be divided into traditional micro-mechanical THz process and new THz process technology.

5.1 Micromachined terahertz process technology

The micro-mechanical THz process technology is developed based on traditional machining technology. By improving and miniaturizing, the micro-system is used to control the machining program and the precision of the micro-mechanical THz process technology reach the micron level. In 1979, micromechanical technology began to be used in THz circuits. Micromechanical technology can provide accurate two-dimensional and three-dimensional structural control, demonstrating practical methods for producing various high-performance THz front-end components.

Micromachining technology is based on silicon technology, including lithography, laser milling and mold replication [168]. For example, researchers have designed and built a low-cost commercial milling technology [169] for high-gain antennas operating at 0.325-0.5 THz with an antenna gain of more than 26.5 dBi. In addition, the development of silicon micromachining technology can design a THz antenna [170] with beam scanning at 0.55 THz and a silicon microlens antenna [171] operating at 1.9 THz. It is beneficial to the miniaturization of the antennas, and the reliability and integration capability are improved, which has great application potential for the design of the planar THz array antennas. For example, the beam scanning array antenna designed by Kamal Sarabandi et al. [172] can perform frequency sweep at the frequency beam scanning of 0.23 to 0.245 THz with a gain of exceeding 28.5 dBi.

According to the development stages of micromachining technology, it can be divided into three categories: bulk micromachining, surface micromachining and metal micromachining. Bulk micromachining mainly uses etching technology to process silicon materials into the required products. Surface micromachining was initiated in the 1980s and mainly used in integrated circuit manufacturing, generally, with the sacrificial layer technology and the multi-layer stress-free thin film deposition technology. Metal micromachining is a follow-up development. It relies on X-ray applications and can process materials such as plastics, metals and ceramics.

5.2 New terahertz process technology

Although micromachining technology can achieve high accuracy, the process accuracy in higher frequency bands needs to be further improved, so new THz process technology has emerged in recent years.

The new THz process technology mainly includes electroforming, discharge, milling, thick photoresist, and etc.[173]. Electroforming refers to depositing a target material (metal or composite material) on a conductive original model, and then separating it from the original mold to obtain a desired product, which is often used to make a complex inner surface of a component, such as a corrugated horn. Discharge is the use of electrical energy to process a soft metal into a metal with a sharp structure. The milling process is to fix the original mold and rotate with high speed. The knife is machined on the mold to cut out the desired product shape. This process is relatively low in cost. It is a type of cold metal process and a technology commonly used in current THz antenna process. Thick photoresist SU-8 is a chemically amplified negative photoresist and is an innovation technique in THz antenna lithography.

Performance comparison of typical THz process technologies is shown in Table 8. According to the size of the milling cutter, roughing and finishing can be realized at the same time, and the process does not produce chemical waste. From the above analysis of the THz antennas, it can be seen that most of the current THz antenna manufacturing uses commercial milling technology because of its low cost, high efficiency and high precision, but the aspect ratio of the technology is the smallest over all technologies in Table 8.

The THz antennas are mainly processed by micro-machining, since the high THz band determines the small size of the THz antennas. The relatively complicated process of THz antennas depends on not only the antenna geometry but also the integration between antennas and circuits. Currently, there is no uniform manufacturing standard technology. Future THz antenna process techniques require high precision and low cost. It is hoped that the process techniques can be standardized.

Table VIII. *Performance comparison of typical THz process technologies.*

Name	Aspect ratio	Minimum convex groove size	Energy	Other
Corrosion	>20:1	>1.5	Chemical energy	Distinguish between wet (high speed) and dry etching (low speed)
LIGA	>70:1	>1.5	X-ray	X-rays need to be synchronized with the cyclotron
Electro-forming	10:1	N/A	Chemical energy	Concave mold made of chemically soluble materials
Discharge	>10:1	>150	Electric energy	Concave mold selects high conductivity metal material
Milling	2:1	>50	N/A	Production accuracy depends on the size of the milling cutter
Thick photoresist	>15:1	>1.5	Chemical energy	Using metal adhesion, related to alkaline processes

VI. CHALLENGES OF TERAHERTZ ANTENNAS

THz antennas are developed in the face of increasingly serious shortage of spectrum resources. Their broadband advantages carry the expectation of increasing the data transmission rate. However, by means of the above research and analysis, it can be found that the THz antennas faces many challenges: insufficient resonant frequency, lacking perfectly matched substrate materials, encountering bottleneck from low-cost manufacturing process techniques. These challenges come from the fact that the frequency of THz is higher than that of millimeter waves, and the corresponding antenna size is much smaller than that of millimeter wave antennas.

6.1 Insufficient resonant frequency

From the above research, we can see that the resonance frequency of THz antenna designed by most researchers is generally between 0.1 and 1 THz. The reason for this is that the frequency band of this interval is close to the millimeter wave band. Thus the design of the antenna prototype can refer to the design idea of the millimeter wave antennas. However, this does not fully meet the design requirements for the resonant frequency of the THz antennas. We also need to use the frequency band between 1 and 10 THz. The phenomenon that the resonant frequency is not high enough is mainly resulted from the inherent defects of the THz antennas. As the resonant frequency is higher, the antenna size is smaller, the antenna loss is rapidly increased, and the radiation efficiency is greatly reduced. The other major challenge is that the macromolecular absorption increases greatly at the THz band. To solve this problem, high-gain antennas are required. The operating frequency is the challenge that the THz antenna design has to face in the future. In order to utilize the spectrum resources of the higher frequency band, an effective and reliable antenna with high operating frequency is very urgent.

6.2 Lacking perfectly matched substrate materials

Conventional millimeter-wave antennas generally use FR-4 or other dielectric polymers. When THz microstrip antennas continue to select such substrate materials, the loss is large and the gain is low [128]-[133]. Obviously, the traditional substrate material cannot fully match the resonant frequency requirements of the THz microstrip antennas. Incomplete matching of the substrate material can cause obstacles in designing many planar or conformal antennas at the THz band. In order to design a THz antenna with good radiation characteristics, two optional methods are to determine a suitable size of the substrate material according to the antenna resonance frequency and to find an alternative new material.

Traditional THz materials are represented by silicon-based materials, but their indirect bandgap properties determine that silicon-based materials are difficult to be applied to nonlinear devices and active devices. Subsequently, the emergence of semiconductor materials such as silicon carbide, silicon nitride, and gallium arsenide with a direct bandgap, are also made up for this deficiency. In addition, metamaterials are another potentially alternative new material [174], [175]. This is followed by the metasurface structure proposed by Yu N. in 2011 [176]. At the THz frequency band with a small wavelength, complex three-dimensional metamaterials normally stay in the stage of theoretical research and simulation. The metasurface benefits from the advancement of micro-nano process technology, and it is conducive to integration. However, most of the research on metasurfaces is to construct microstructures on physical structures to achieve metasurfaces, such as notched rings, I-shaped structures, etc. This discrete approximation will introduce discrete errors, especially at the THz frequency band. Graphene can form different equivalent refractive index regions by changing the bias electric field, avoiding the etching and other process of the graphene surface. This method can effectively avoid the phenomenon of electromagnetic wave scattering. Moreover, polymer materials such as polyimide with low refractive index and absorption at the THz range are used to achieve high transmission [177]-[180]. It not only allows both improved bandwidth and sensitivity, but also offers the additional benefits of increased efficiency and reduced cost.

6.3 Encountering bottleneck from low-cost manufacturing process techniques

Whether THz antenna manufacture uses micromachining or new process technology, it is necessary to meet the requirements of high precision and low cost. Although the current new process technology can meet certain THz antenna manufacturing requirements, most of them are of low efficiency and high cost, mainly because of the high-precision of process machines resulting in high equipment costs. Process technology is a key to accelerate the development of THz antennas. However, the high cost problem is an urgent problem to be solved in the future, and the THz process technology does not have a unified standard to evaluate machines' advantages and disadvantages. The antenna designer can only rely on experience to select the process technology solution.

VII. Future Research Directions for Terahertz Antennas

By the in-depth analysis of the THz antennas, the requirements of the THz antennas can be roughly clarified: good mechanical properties, high and low temperature resistance, acid and alkali resistance, small size, center operating frequency of around 1 THz, relative large operating bandwidth, the high gain, the low cost and the high radiation efficiency. In response to these, the future research directions of THz antennas mainly include the following aspects.

7.1 Miniaturization

The frequency of the THz antennas is relatively high, and the corresponding wavelength is relatively short, which determines the small antenna size. With the rapid increase of mobile devices, the demand for wearable mobile antennas also increases. The miniaturization of the antennas is an important research direction in the future.

At present, it is more suitable for miniaturization based on integrated THz antennas and THz microstrip antennas loaded with silicon lenses. Table 9 lists the size comparison of THz antennas.

As can be seen from Table 9, the THz lens antenna is loaded by a silicon lens with a radius of 5 or 6 mm, and the extended length depends on the performance of the antenna. For the current miniaturization demand, the radius of the lens can be selected to be less than 5 mm. However, we should take care to avoid deterioration of the antenna performance; the size of the microstrip antenna is relatively small, basically in the micron range. The microstrip antenna of [133] has the smallest size and the minimum return loss is -55.31 dB. However, its gain and directivity are only 4.084 dBi and 4.254 dB, which is lower than those of other types of antennas.

As can be seen from the above analysis, the design of the THz antennas tends to be miniaturized, especially for the THz microstrip antennas. This type of antenna can be used as a wearable mobile antenna. It is small in size, light in weight and easy to be manufactured. Its design size ranges from 1000×537.5×428.6 μm^3 to 23×19×1.5 μm^3, which shows the trend of miniaturization of THz microstrip antennas.

7.2 High gain

As an indispensable component in a wireless communication system, the performance of the THz antennas directly affects the communication quality of the entire system. In general, efficiency and gain are used to measure the antenna's energy conversion and radiation capabilities; main lobe width and directivity are used to evaluate the antenna's directivity radiation performance; and bandwidth is used to measure the antenna's available frequency bandwidth, etc.. The main obstacle to THz communication is the atmospheric attenuation. As the free space path loss is physically inevitable, increasing the gain of the transceiver antennas is used to compensate the free space path loss. Therefore, in THz communications, the larger operating bandwidth and atmospheric path loss require the antennas to have broadband, high gain, and high efficiency performance. Considering the wideband performance of THz waves, the realization of high-gain and high-efficiency THz antennas is a current research hotspot. For example, the current research work of THz silicon-based on-chip antenna technology mainly focuses on how to improve antenna gain and radiation efficiency. Because of the high dielectric constant of the silicon substrate, most of the energy is bound in the silicon substrate in the form of surface waves. However, the low resistivity of the silicon substrate causes most of this energy to be lost in the form of heat loss. As a result, the radiation efficiency of silicon-based on-chip antennas is usually low [135], [136].

The high-gain THz antennas can keep operating in a variety of harsh environments, and can reduce the impact of transmission loss, so high-gain antenna research is an inevitable trend in the future. At present, THz antennas suitable for high gain operation mainly include THz horn antennas and lens antennas, and Table 10 lists the gain comparison of THz antennas.

As can be seen from Table 10, the lens antennas can achieve a maximum gain of 35 dBi. The gain of typical THz horn antennas in Table 10 is basically about 25 dBi, and can be achieved as high as 35.5 dBi after loading the lens, while the microstrip antennas has the lowest gain, which is basically less than 10 dBi. However, the THz microstrip antennas array designed in [131] can achieve a gain of 15.7 dBi. Obviously, loading lenses and designing arrays are two solutions for designing high-gain antennas. In addition, [131] shows that the antenna array can greatly improve the

Table IX. *Size comparison of THz antennas.*

Ref.	Size	Other
[118]	The silicon lens has a radius of 6 mm, an extended Manufactured by deep reactive ion etching length of 150 μm, and a bottom silicon wafer of 30 μm	Manufactured by deep reactive ion etching
[119]	Silicon lens radius is 5mm, silicon wafer is 1mm	Laser process
[120]	The silicon lens has a radius of 5 mm and an extended length of 950 μm	/
[123]	28×30×20 mm^3	The waveguide wall is selected to be 0.1 mm
[125]	1000×537.5×428.6 μm^3	Lens focal length is 6 mm
[127]	653×430×8.17 μm^3	The substrate is Arlon Cuclad material
[128]	550×550×40 μm^3	The substrate is Arlon Cuclad material
[129]	0.6×0.6×0.138 mm^3	The substrate is FR-4 material
[130]	210×180×10 μm^3	The substrate is Rogers RO3003 material
[131]	3078×2489×100 μm^3	Manufactured using PCB technology
[133]	23×19×1.5 μm^3	The substrate is FR-4 material

gain of the antennas.

Of course, it is very difficult for THz antenna to achieve higher gain. The biggest difficulty is the design of the THz antenna array. Since the size of the THz antennas is very small, assembling the THz antenna array requires very high process precision and high quality materials. However, the current process technology can not meet the design requirements, so the gain of the THz antennas needs to be improved from the two aspects of process technology and materials.

7.3 High reliability and low cost

With the development of Internet technology, people pay more and more attention to personal privacy and information security issues, especially some important information related to national security issues. For current wireless communication security issues, THz antennas can be combined with encryption technology to improve antenna's reliability. The encryption technology can be clssified into traditional symmetric encryption technology and asymmetric encryption technology. The encryption algorithm has a small number of keys and is difficult to crack. If the THz antennas are combined with encryption technology, it is expected to increase the reliability of THz wireless communication.

In addition to reliability, low cost is also important, but currently, THz antennas have expensive manufacturing costs. From the above analysis, the machining process uses commercial milling technology and antenna material select low-cost materials such as silicon or FR-4, which is expected to reduce the cost of THz antennas. However, both approaches have certain defects and require further optimization in future. In short, it is hoped that through the innovation of materials and process technology, it is expected to manufacture a THz antenna with lower cost.

Table X. *Gain comparison of THz antennas.*

Ref.	Gain(dBi)	Other
[102]	> 26.5	Radiation efficiency exceeds 43.75%
[103]	25	Standard THz horn antenna
[104]	22.8	Making a dual-band THz horn antenna using a dielectric strip
[108]	18	The substrate is a multilayer LTCC material
[109]	9.8	Ripple horn antenna
[110]	20.2	Multi-layer corrugated THz horn
[114]	35.5	Loading lens
[115]	26.4	Loading stacked lenses
[123]	27.6	Lens antenna composed of metal waveguide
[124]	>35	THz beam scanning antenna
[91]	21.51~21.63	THz logarithm-helical antenna with truncated ends
[128]	7.13	Double T-type slot THz microstrip antenna
[129]	8.2	T-type dual-frequency THz microstrip antenna
[130]	5.235	Slotted patch antenna
[131]	15.7	THz microstrip antenna array
[132]	6.48	Stacked THz microstrip antenna
[133]	4.25	Slotted rectangular THz microstrip antenna

7.4 High integration

Due to the huge market demand and the improvement of silicon-based semiconductor process integration, THz antenna integration has been explored by many researchers. The integration of single or multiple antennas on the chip package can improve the antenna integration. Electromagnetic compatibility (EMC) is one of the biggest challenge in THz packaging systems. In fact, the compact massive antenna array is used to realize high-gain antennas. There is mutual interference between different elements in the array. Adding filter structure make the whole size of THz antenna modules bigger. There is a trade-off between the miniaturization of THz antennas and reduction of EMC. Besides, since the THz wavelength is smaller than the size of chips and modules, the high-precision process method is a great challenge for THz packaging technology.

From the above analysis of THz on-chip antennas in Section IV, the packaging technology (such as CMOS, SiGe, mHEMT and etc) is necessary for high integration. It is well known that the progress of highly integrated systems in recent years is attributed to CMOS technology. In fact, the 45 nm, 32 nm and 28 nm CMOS technologies offer an f_t and f_{max} greater than 300 GHz. This feature makes CMOS technology ideal for THz-wave circuit design. For example, [143] presented an eight-element 0.37--0.41-THz phased-array transmitter by using 45-nm CMOS silicon on insulator technology. This is one of the first paper of a phased array operating at 0.4 THz with wide bandwidth. Besides, [181] proposed a 0.525--0.556-THz radiating source in 28-nm CMOS technology. A dielectric lens antennas is mounted on top of the chip. A lumped model is developed by using a simulation-based modeling method for the transistor interconnect parasitics including the parasitic capacitances, resistances, and inductances.

Also, SiGe technology now has f_t and f_{max} in excess of 0.2--0.3 THz and with very high yields [182]. At the packaging system level, high integration is challenging. The CMOS and SiGe technologies have greatly changed THz-wave circuit design and expanded the application areas of silicon ICs in THz systems. To tackle complicated behaviors of electro-magnetic waves in integrated systems, the integration and packaging technology should be developed with new design and modelling concepts.

VIII. Conclusion

With the development trend of wireless communications, future spectrum resources are moving to the THz band, and the establishment of a THz wireless communication system can provide a higher data transmission rate. THz antennas are important devices for transmitting and receiving THz waves in communication systems. Meanwhile, the performance of THz antennas has a great influence on communication system quality. This paper carried out in-depth analysis of THz antennas, including research background, basic concepts, typical THz antennas and process techniques. Through analysis, it can be found that THz antennas currently encounter high cost, low gain and other challenges. Most of the THz antennas are still in the theoretical stage, and the practical products are rarely manufactured. Obviously, the future research task of the THz antennas is very heavy. We proposed key research directions as follows: (i) improving the antenna geometry to achieve miniaturization; (ii) optimizing the radiation performance of the antennas to achieve high gain; (iii) adding encryption technology to achieve high reliability; and (iv) using appropriate packaging technology to improve the integration of THz antennas.

Acknowledgement

This work is supported in part by the National Natural Science Foundation of China (NSFC) under Grants No. 61801299 and No. 61372077, and in part by the Shenzhen Science and Technology Program under Grants GJHZ 20180418190529516 and JSGG 20180507183215520.

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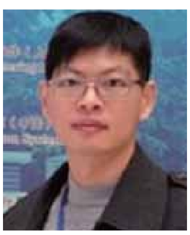

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