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A Review of Broadband Low-Cost and High-Gain Low-Terahertz Antennas for Wireless Communications Applications

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ABSTRACT Low-terahertz (Low-THz, 100 GHz-1.0 THz) technology is expected to provide unprecedented data rates in future generations of wireless system such as the 6th generation (6G) mobile communication system. Increasing the carrier frequencies from millimeter wave to THz is a potential solution to guarantee the transmission rate and channel capacity. Due to the large transmission loss of Low-THz wave in free space, it is particularly urgent to design high-gain antennas to compensate the additional path loss, and to overcome the power limitation of Low-THz source. Recently, with the continuous updating and progress of additive manufacturing (AM) and 3D printing (3DP) technology, antennas with complicated structures can now be easily manufactured with high precision and low cost. In the first part, this paper demonstrates different approaches of recent development on wideband and high gain sub-millimeter-wave and Low-THz antennas as well as their fabrication technologies. In addition, the performances of the state-of-the-art wideband and high-gain antennas are presented. A comparison among these reported antennas is summarized and discussed. In the second part, one case study of a broadband high-gain antenna at 300 GHz is introduced, which is an all-metal model based on the Fabry–Perot cavity (FPC) theory. The proposed FPC antenna is very suitable for manufacturing using AM technology, which provides a low-cost, reliable solution for emerging THz applications.

INDEX TERMS Antennas, low-terahertz, additive manufacturing (AM), high gain, Fabry–Perot cavity (FPC), low-cost, three-dimensional printing (3DP).

I. INTRODUCTION

A. DEFINITION OF LOW-TERAHERTZ (LOW-THz)

Generally, the conventional terahertz (THz) [1]–[3] wave refers to an electromagnetic (EM) wave with a frequency in the range of 0.1 to 10.0 THz (wavelength of 3.0 mm to

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30.0 μm), which coincides with the millimeter wave in the long wavelength band and the infrared light in the short wavelength band. However, there are very few research results and data related to the terahertz band, which is mainly limited by effective terahertz generation sources and sensitive detectors, so this band is also called the THz gap [4], [5]. With the development of a series of new technologies and new materials in the 1980s, especially the development of

ultra-fast technology, obtaining broadband stable pulsed THz sources has become a quasi-conventional technology. In the past few decades, some works have been conducted at low-terahertz (Low-THz) band [6], [7], which spectrum refers to the portion of electromagnetic (EM) spectrum from 100 GHz to 1 THz, and the corresponding wavelength is from 3.0 mm to 0.3 mm. In Low-THz band, the equipment requirements are not as high as high-THz requirements, and it maintains many characteristics of THz wave. Therefore, Low-THz has become a hot research field.

B. THE APPLICATION OF LOW-THz ANTENNA

Because of the unique and huge advantages of THz wave, it is considered as the optimal choice for a new generation of imaging systems. Like conventional imaging technologies at microwave or millimeter wavebands, THz imaging technology also adopts THz rays to illuminate the object to obtain information of the sample through the transmission or reflection of the object. What's more, imaging with higher resolution [8]–[11] can also be achieved by increasing the frequencies and bandwidth of incident waves. With this function, THz imaging is rapidly developed to meet the requirement of some commercial applications, such as THz medical imaging test [12]–[14], atmospheric and environmental monitoring [15]–[17], THz radar [18], [19], national security and anti-terrorism [20]–[23].

Since the data rate of mobile communication systems has been growing exponentially over the past few decades, substantial work has been done in this field. Previously, have been extensively applied for its unprecedented data rates, especially in the existing fifth generation (5G) wireless communication systems [24]–[27]. In addition, higher data rates are also required to serve the dramatically increase of wireless data traffic in the near future. To address this issue, wireless communication devices can carry more signals at THz band, which provide a potential solution to guarantee the transmission rate and channel capacity. In particular, technologies in Low-THz band are of great significance to the upcoming beyond-5G or 6G communication system [28]–[30]. Furthermore, technologies in THz band have an unparalleled advantage in space communications [31]–[33]. Because it is in a state of near vacuum in outer space, it is not necessary to take the influence of moisture into consideration. In this case, the message transmission rate is several hundred to one thousand times faster than current that of ultra-wideband technology, which allows THz communications to perform highly secure satellite communications with extremely high bandwidth.

Among all the communication systems, antennas are the most fundamental components, which take the responsibility of receiving and transmitting EM waves. Due to the large transmission loss [34]–[36] of Low-THz waves in free space, it is urgent to design a very high gain Low-THz antenna to compensate for additional path loss, thereby increasing the distance of the THz communication system and overcoming the power limitation of THz source generator [37]–[39]. Due

to the lack of efficient THz transmitting antennas and sources, it cannot yet be commercialized in the communication field recently.

C. MANUFACTURING OF LOW-THz ANTENNAS

With the continuous development of processing technologies, many new technologies have able to meet the processing requirements of Low-THz and the processing cost is greatly reduced. Additive manufacturing (AM) or three-dimensional printing (3DP) [40]–[43] is a technique for constructing objects by printing them layer by layer, based on a digital model file, using glutable materials such as powdered metal or plastic. 3DP is very suitable for structural parts of large size and complex shape. The precision of the 3D printing equipment can reach 0.01mm, but the powder metallurgy parts need to be sintered after being printed and formed. The shrinkage rate and high temperature deformation exist in sintering. High-precision parts still need to be fabricated with machining methods. Many manufacturing methods, such as computer numerical control (CNC) machining, electrical discharge machining (EDM), low-temperature co-fired ceramic (LTCC), and Printed circuit board (PCB), are able to meet the high precision processing requirements of different electronic devices or products.

Except for the processing technologies, new materials are also important for the processing and design of THz antennas. For insurance, graphene [44], [45] has a resistivity of only about $10^{-6}\Omega\cdot\text{cm}$, which is lower than that of copper or silver. It is currently the smallest resistivity material in the world. Due to its extremely low resistivity and the fast movement of electrons, it is expected to be used to develop a new generation of thinner, faster conductive electronic components. Nowadays, graphene has been used to design reconfigurable circuits or antennas [46]–[49] with its superconducting properties. On the basis of the emergence of new processing technologies and new materials, the research on Low-THz antennas has become more practical and meaningful.

This paper aims to provide a detailed review of recent development on Low-THz wideband and high gain antenna that utilizes different ways with corresponding manufacturing processes. Furthermore, a novel wideband high gain RCA is designed at 300 GHz. Scaled model is fabricated using AM and measured in anechoic chamber. Measurement results are discussed and compared to the simulation results, followed by conclusions in Section IV.

II. REVIEW OF WIDEBAND HIGH-GAIN LOW-THz ANTENNAS

To design Low-THz high gain antenna, some methods have been demonstrated. Up to date, many papers have been published on this topic, such as horn antennas [50]–[51], traditional planar antenna arrays [52]–[56], transmit-arrays (TA) or lens antennas [57]–[63], reflect-arrays (RA)[64]–[70], and resonant cavity antennas (RCA) [71]–[83].

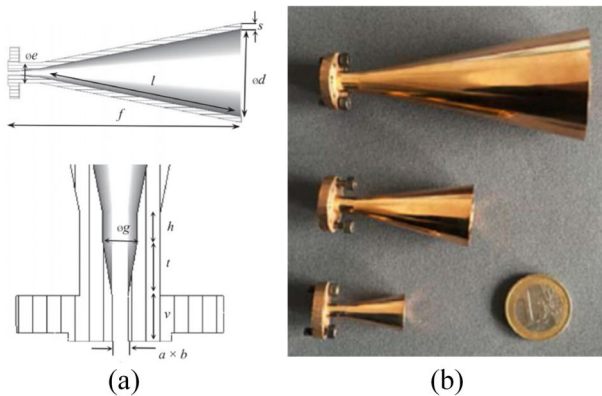


FIGURE 1. Conical horns fabricated by SLM Cu-15Sn in [50]: (a) overall view and the zoomed-view of the flange and rectangular-to-circular waveguide taper, and (b) photograph from the top: E-, D-, and H-band horns.

A. HORN ANTENNAS

The horn antenna is a widely used antenna, which has the advantages of simple structure, wide frequency bandwidth, and large power capacity. A reasonable horn size allows for good radiation performances, such as a fairly sharp main lobe, small side lobes and a high gain.

In Fig. 1 [50], three horns are printed by selective laser melting (SLM) Cu-15Sn 3DP technology. Balancing between the cost and the antenna performance, the manually polished Cu-15Sn is selected to develop a series of conical horn antennas at the E-band (60–90 GHz), D-band (110–170 GHz), and H-band (220–325 GHz). The waveguide interface on the flange is milled for better flatness. As a result, the measured antennas' impedance bandwidth ($|S_{11}| < -20$ dB) covers the completely operational band. The observed in-band gain are more than 22.5, 22.0, and 21.5 dB for the E-, D-, and H-band antennas, respectively. There exists a 0.5 dB difference between the simulated and measured gain at these three frequency bands.

Another 300-GHz step-profiled pyramid horn antenna is investigated on a LTCC multi-layer substrate [51]. Through drilling cavities with gradually expanding size on each layer, the shape of horn is formed which inherently has a stepped profile as shown in Fig. 2 (a). The dielectric layers are parallel to H plane in conventional dielectric loaded H-plane sectoral SIW horn antenna, which may lead to mismatching between the edge of the dielectric slab and air, and decreasing the operational bandwidth. In addition, the increase of dielectric and conductor loss in THz band will degrade the antenna efficiency. To overcome these issues, vertical SIW hollow structure formed by drilling cavities and metallic vias in stacked LTCC layers is proposed in this paper. Compared with H-plane SIW structure, the vertical SIW offers better antenna gain and symmetric radiation patterns in both E-plane and H-plane owing to flexibility in aperture design. Multiple metallic via design effectively reduces the leakage of EM wave between vias and metal layers. The vertically formed hollow structure can be fabricated without

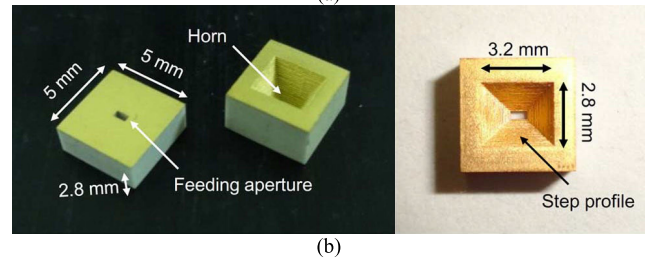
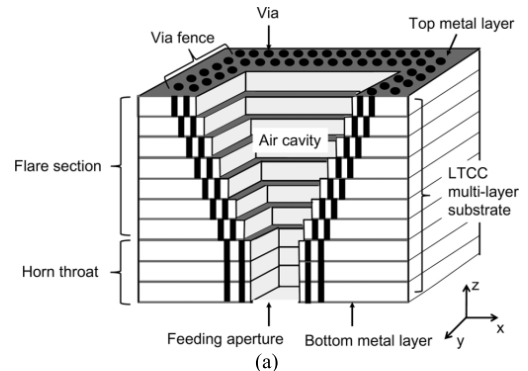


FIGURE 2. Schematic view of LTCC horn antenna in [51]; (b) side view and top view of fabricated LTCC horn antenna.

any special fabrication process. Experimental results show that the antenna has a peak gain of 18 dBi and 100 GHz working bandwidth from 230 to 330 GHz ($|S_{11}| < -10$ dB). Measured hollow LTCC waveguide insertion loss is 0.6 dB/mm, which is low enough to be applicable to 300GHz band.

B. PLANAR WAVEGUIDE ARRAYS

Planar waveguide array has been greatly developed since the middle of the last century. Because of its unique features such as easy control of the amplitude distribution in the antenna aperture surface, high utilization of the aperture surface, small volume, and easy realization of low or very low side lobes, it has been widely used in various fields like ground, ship-borne, airborne, and navigation.

In [52], a broadband high gain corporate-feed waveguide slot array with cavities is proposed using diffusion bonding technology for 120 GHz application. The wide bandwidth characteristic is achieved by the dual-resonance caused by slot self-resonance and external mutual coupling. An outer cavity structure is employed in the 4×4 element array for each radiating slot to adjust the mutual coupling, which enables all radiating elements to have similar characteristics in the array. As a result, high gain and efficiency are achieved over a broad bandwidth.

The multilayer slot array antenna is composed of feeding network in the bottom layer and radiating waveguide in the top layer, which is hard to fabricate using conventional technology such as machining or die-casting in 120 GHz band. Eventually, diffusion bonding of laminated thin metal plates is selected for the fabrication of the proposed multilayer antenna, which has the advantage of high accuracy (± 20 μ m) and low loss characteristics in high frequency.

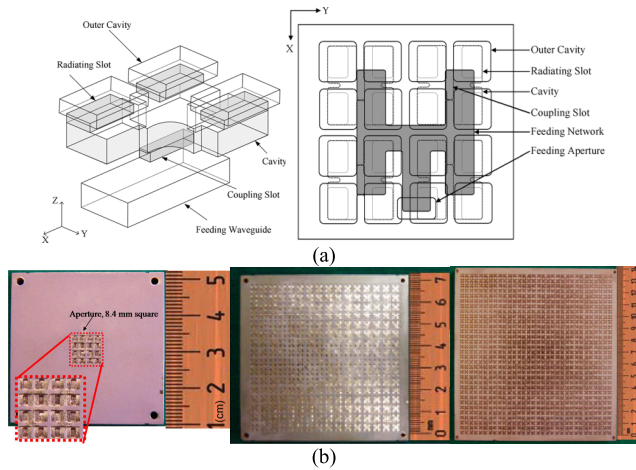


FIGURE 3. Waveguide slot antenna array in [52], [53]: (a) 2×2 -element subarray and 4×4 element array; (b) Fabricated 4×4 , 16×16 and 32×32 corporate-feed waveguide slot array.

It could also provide perfect electrical contacts between etched metal plates. The measured gain and efficiency is 21.1 dBi and 80.0% respectively. Furthermore, the 1dB-down gain bandwidth is 17.6%. Two larger-size slot arrays (16×16 , 32×32) of the same structure are presented in [53], which show higher gain of 38.0 dBi and 43.0 dBi. The fabrication of even larger and more complex structure would be difficult as the metal plates with large and complex patterns are easily deformed under high pressure and temperature during the fabrication process.

Deep reactive ion etching (DRIE) process is explored for the fabrication of a corporate-feed slotted waveguide array antenna in [54]. The 16×16 array is constituted by five silicon plates (M1 to M5) as shown in Fig. 4 (a), which forms the corporate feeding network and radiating part. Standard rectangular waveguide WR-3 is used to feed the array through a coupling slot etched in M1. The feeding network, which distributes the coupled power equally, is etched in M2. The cavities in M4 excites radiating slots etched in M5. For 350 GHz band, etching accuracy of thin silicon plates is critical to antenna performance. To solve the requirement for accuracy, DRIE process with etching accuracy of lower than $\pm 5 \mu\text{m}$ is developed for the fabrication process. After etching, the plates are gold-sputtered and bonded with diffusion bonding process by applying high pressure with high temperature. The top and side views of the fabricated antenna prototype are shown in Fig. 4 (b). The average effective conductivity of the gold-sputtered plates is $1.6 \times 10^7 \text{ S/m}$ and loss per unit length is 1.1 dB/cm. The array achieves a realized gain of 29.5 dB at 350 GHz and 44.6 GHz of 3-dB gain bandwidth, while the impedance bandwidth ($|S_{11}| < -10 \text{ dB}$) is 7.57% within a range of 338.2 to 364.7 GHz.

C. LENS ANTENNAS OR TRANSMIT-ARRAYS

Lens antenna absorbs many optical information engineering techniques and are used in a wider range of applications in communications and military. According to the theory of

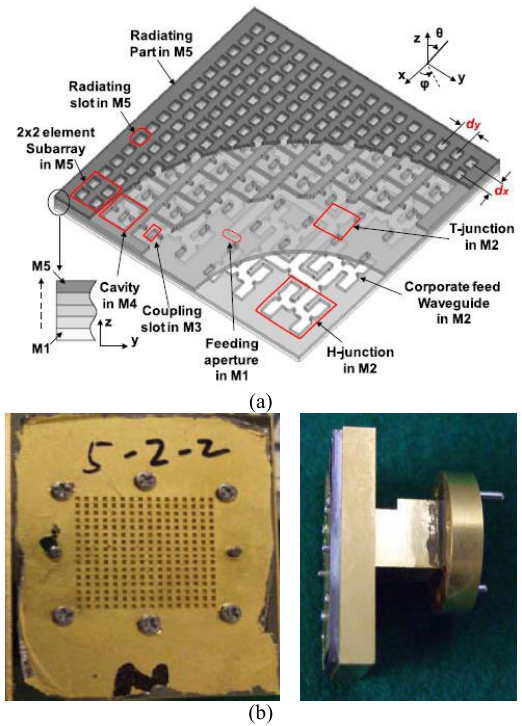


FIGURE 4. Waveguide slot antenna array in [54]: (a) Configuration of 16×16 slotted waveguide array (b) Top view and lateral view of fabricated array.

geometric optics, a spherical wave, which is radiated from a point source at the focal point of the lens, will condense through the lens to form a plane wave. This is the general idea of lens antenna design. During the transmission process, refraction occurs when waves pass through different media that are not parallel. The lens, which are mounted in front of the radiator, can concentrate the radiation energy and narrow the beam.

The authors in [57] present four different dielectric lens operating at V-band and H-band. Fig. 5 presents the lens fabricated by polymer-jetting 3-D printing technology. The 3-D printer has a fundamental resolution of $42 \mu\text{m} \times 42 \mu\text{m} \times 28 \mu\text{m}$ in x-, y-, and z-axes, respectively. The antenna fixture and lens are printed together, which can avoid assembly alignment errors. The fabricated V-band antennas are shown in Fig. 5 (a), the measured peak gain is ranging from 19.4 to 23.5 dBi (50-70 GHz). The measured beam directions at 50, 55, 60, 65, and 70 GHz. are -34° , -29° , -24.8° , -22° , and -19° , respectively. The fabricated H-band lens are shown in Fig. 5 (b), due to the uncertainties in dielectric property and loss of open-ended waveguide (OEW), the measured gain shifts downward by about 20 GHz and suffers from a 2-dB drop compared to the simulated results. The measured beam directions at 225, 250, 275, 300, and 325 GHz are -33.3° , -28.5° , -24.8° , -22° , and -19° , respectively.

Recently, the same research group in city university of Hong Kong designed another 3-D printed circularly polarized (CP) lens at H-band in [58]. Fig. 6 shows the lens fabricated

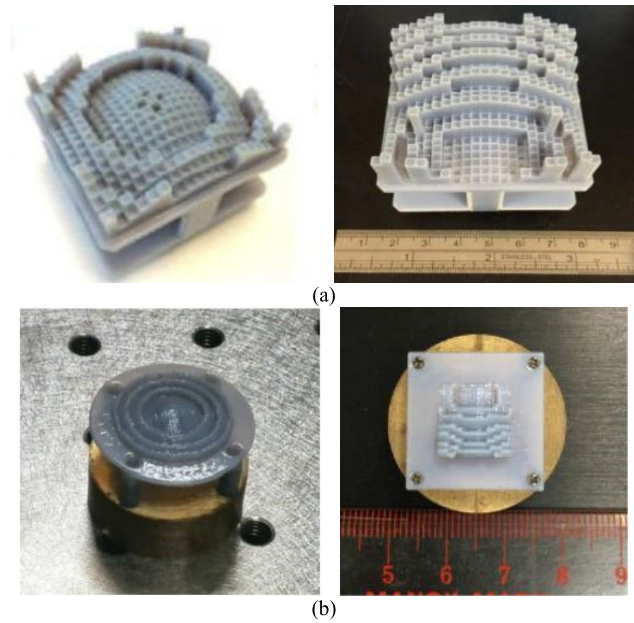


FIGURE 5. Fabricated lens antennas in [57]: (a) Lens antennas at V-band: left picture with fixed beam, right picture with scanning beam; (b) Lens antennas at H-band: left picture with fixed beam, right picture with scanning beam.

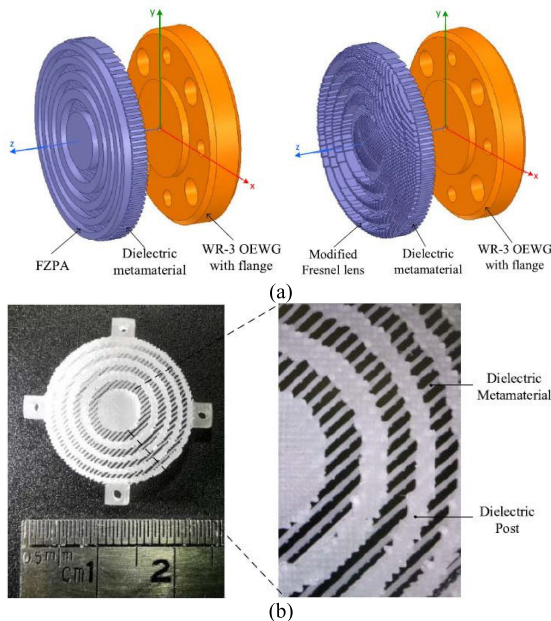


FIGURE 6. Lens antenna in [58]. (a) Designed 3-D models; (b) Fabricated lens antenna.

by in-house developed 3-D printing method with rapid prototyping technology. Considering the transmission phase of the dielectric post is sensitive to its height and the 3-D printer provides the highest resolution of $25 \mu\text{m}$ along the z -axis. The reflection coefficients of the designed antenna are smaller than -13.0 dB ranging from 265 to 320 GHz. The average gain of this CP lens is around 25 dBic, and the peak gain reaches to 27.4 dBic at 300 GHz, corresponding an aperture

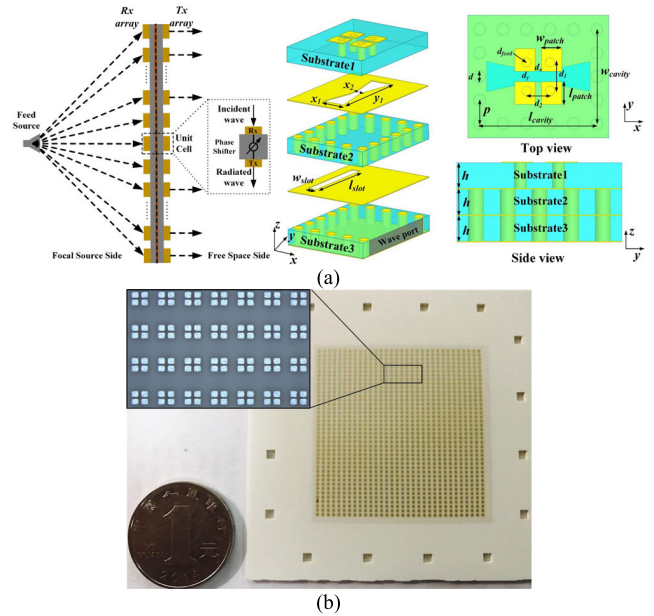


FIGURE 7. Wideband transmit-array in [59]. (a) Operation principle of a TA antenna and the designed radiation element; (b) Fabricated TA antenna.

efficiency of 15.4%. The measured 3-dB gain bandwidth is larger than 15.1% (275–320 GHz), and the 3 dB axial ratio (AR) bandwidth is larger than 18.8% (265–320 GHz).

Transmit-arrays (TA) schematized in Fig. 7 (a), which consist of an array of transmitting elements with independent phase adjustability, are one of the most attractive research areas in high-gain antennas due to the favorable features such as high gain, high aperture efficiency, low profile, and easy fabrication. Fig. 7 shows such a design reported at D-band in [59]. As shown in Fig. 7 (a), the proposed unit cell is composed of a pair of wideband magneto-electric dipoles, together with a substrate-integrated waveguide (SIW) aperture-coupling transmission structure for independent phase adjustability. This element provides a full 360° phase coverage and realizes nearly parallel phase response in a wide frequency range. A 40×32 array is fabricated by LTCC technology. The measured peak gain of the TA prototype is 33.45 dBi at 150 GHz with the aperture efficiency of 44.03%, and the measured 3-dB gain bandwidth is 124–158 GHz (24.29%).

D. REFLECT-ARRAYS

As with the principle of TA, reflect-arrays (RA) combine the advantages of reflector and array antennas. A dielectric reflectarray working at 220 GHz is reported in [64]. As shown in Fig. 8 (a), the reflectarray unit cell consists of a ground plane and a dielectric block. The reflection phase is obtained by adjusting the height of the block. Using the reflection phase computational algorithm, a dielectric reflectarray composed by 40×40 unit cells is designed and fabricated through 3DP technology. The maximum gain of 31.3 dBi and an aperture efficiency of 27.6% are obtained, and the 1-dB gain bandwidth is about 20.9% (220–246 GHz).

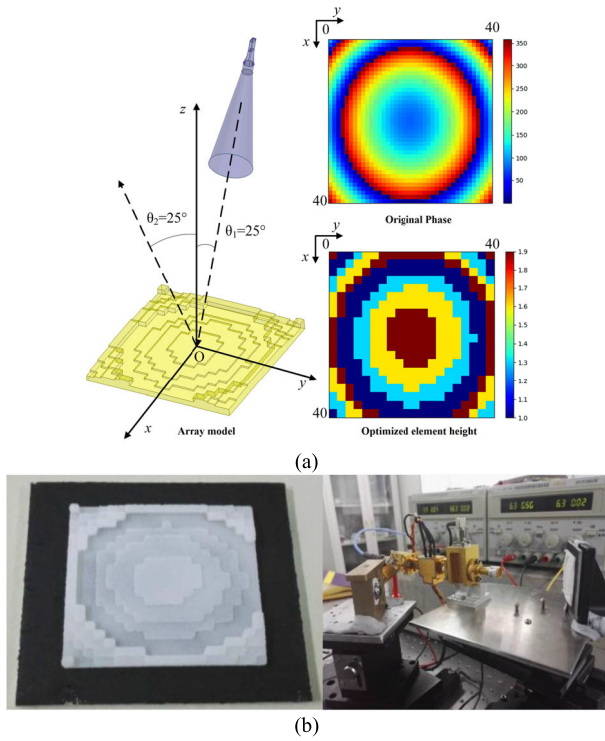


FIGURE 8. Wideband RA in [64]. (a) Designed dielectric reflectarray; (b) Fabricated RA antenna and the test environment.

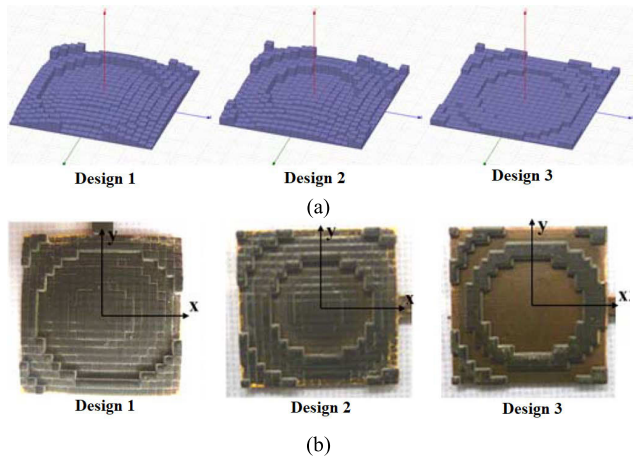


FIGURE 9. Three 3DP RAs in [65]. (a) Designed 3-D models; (b) Fabricated RA antennas.

The authors in [65] present another three different dielectric RAs operating at 100 GHz. Fig. 9 (b) presents the reflectarrays fabricated by Objet Eden 350 polymer-jetting rapid prototyping 3-D printer. The material loss and dielectric constant at 100 – 600 GHz are first observed using THz time-domain spectrometer system. Then RAs with different aperture phase distributions are studied to quantify the fabrication limits. The measured gain of the three prototypes at 100 GHz is 22.5, 22.9, and 18.9 dB, respectively. The proposed methodology is readily scalable and with the current material and fabrication technology, low-cost, high-gain antennas up to 1.0 THz can be realized.

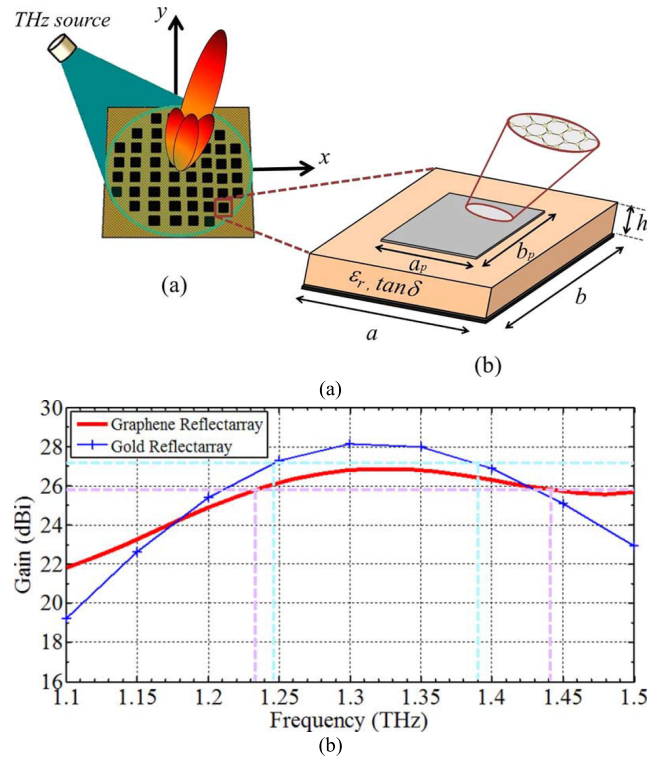


FIGURE 10. Wideband RA in [66]. (a) Designed dielectric reflectarray; (b) Fabricated RA antenna and the test environment.

With the rapid development of graphene preparation technology, graphene materials are also popular in THz high-gain antenna design. The work in [66] evaluates the feasibility of a fixed beam RA at THz band based on graphene and compares its performance to a similar implementation using gold for the first time. The designed graphene antenna operates at 1.3 THz and comprises 25448 electrically small unit cells. As shown in Fig. 10 (b), compared to a gold patches implementation, it exhibits better bandwidth and easier design thanks to the low sensitivity of the elements to the angle of incidence, but at the cost of increased loss. A 1-dB-gain bandwidth of 15% and 11% is achieved for graphene and gold RAs, respectively. The graph also reveals the lower maximum gain of the array made with graphene, which is due to the higher ohmic loss in graphene than gold at such frequencies. Since graphene complex conductivity can be efficiently controlled via electric-field biasing, RAs based on this material could potentially be dynamically reconfigured in the near future.

E. RESONANT CAVITY ANTENNAS

Resonant cavity antennas (RCAs) are excellent candidates to form planar structure, low loss, and high gain. RCA is constituted by suspending a partially reflective surface (PRS) above a ground plane at a predetermined height. There are many RCAs that work at X-band and Ka-band [71]–[77], but few works at the V-band [78]–[82], let alone the antennas that operate at THz band.

A novel wideband and high-gain RCA is presented in [78], which is achieved by FPC and printed ridge-gap waveguide

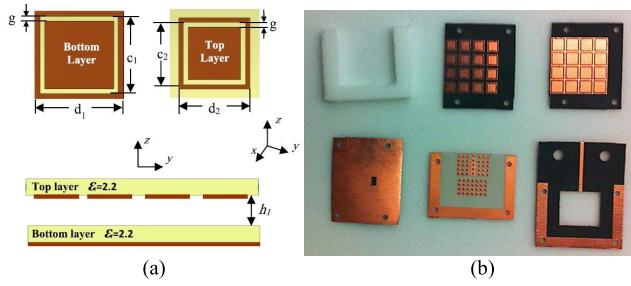


FIGURE 11. Fabry–Perot cavity in [78]. (a) Unit cell of the bottom and top layers of the PRS; (b) Fabricated prototype of the FPC antenna.

technologies. This work is the first one to utilize a PRS superstrate at 60 GHz to enhance the radiation characteristics. The FPC is formed by placing a dual-layer PRS above a slot antenna operating at 60 GHz, and fed by a printed ridge-gap waveguide. The structure of PRS is shown in Fig. 11 (a), it is a 2-D printed unit cell, and the unit cell is composed by two different frequency-selective surfaces (FSS) provides. This antenna is fabricated by PCB technology. The impedance bandwidth of the proposed antenna is 18.4%, (55.4-66.6 GHz). The maximum gain of 16.8 dBi is achieved.

Recently, the research group in city university of Hong Kong reported two RCAs operating at 60 GHz. This work introduces a new structure of PRS to realize gain enhancement. It is the first attempt to apply a fresnel zone plate (FZP) to a single-layer PRS. As shown in Fig. 12 (a), this antenna uses a substrate-integrated quasi-curve reflector and a FZP integrated PRS to form a FPC. With the quasi-curve reflector, multiple resonate modes are excited, providing a wide 3-dB gain bandwidth. This antenna is processed by low-cost and mature PCB technology. The antenna illustrates 17.8% impedance bandwidth from 54 to 64.5 GHz, and the 3-dB gain bandwidth is about 13.3 % (56-64 GHz). The measured peak gain is 21.0 dBi at broadside direction.

III. CASE STUDY: BROADBAND AND HIGH-GAIN FPC ANTENNAS FOR LOW-TERAHERTZ APPLICATION

A. RCA PRINCIPLE

Ray-tracing analysis explains the requirement for broadband performance of FPC [84]. As shown in Fig. 13, in order to produce high directivity within a range of frequencies, the resonant condition of the cavity should be satisfied within this range. Maximum boresight gain is obtained at resonant frequency f_r when

$$h = \frac{c}{4\pi f_r} [\phi_{PRS} + (2N - 1)\pi], \quad N=0,1,2,\dots \quad (1)$$

where ϕ_{PRS} is the phase of the PRS reflection coefficient, h is distance between PRS and ground. The resonant distance h is a function of the resonance frequency and the reflection coefficient of the PRS. The gain and bandwidth of the resonant structure can be increased by optimizing

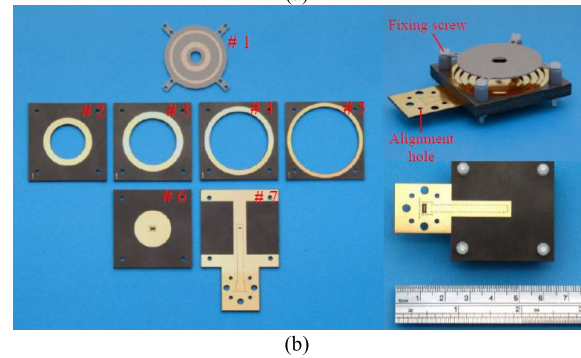
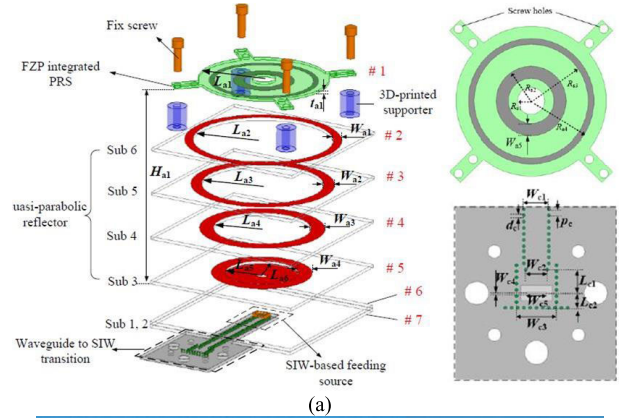


FIGURE 12. Fabry–Perot cavity in [79]. (a) Unit cell of the bottom and top layers of the PRS; (b) Fabricated prototype of the FPC antenna.

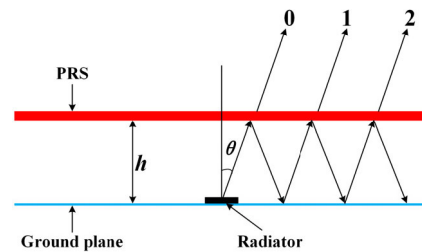


FIGURE 13. Schematic model of FPC PRS antenna.

the reflection characteristics (magnitude and phase) of PRS.

To obtain maximum gain within a frequency range, the phase of reflection coefficient of the PRS should satisfy the following equation:

$$\phi_{PRS} = \frac{4\pi h}{c} f_r - (2N - 1)\pi, \quad N=0,1,2,\dots \quad (2)$$

Actually, the directivity of FPCA includes two sections, one is the directivity of feed antenna and the other is the directivity of PRS, which can be expressed as in (3).

$$D = D_{feed} + D_{PRS} \quad (3)$$

where D_{feed} is the directivity of feed antenna, and D_{PRS} can be calculated by formula (4),

$$D_{PRS} = 10 \log \frac{1 + R}{1 - R} \quad (4)$$

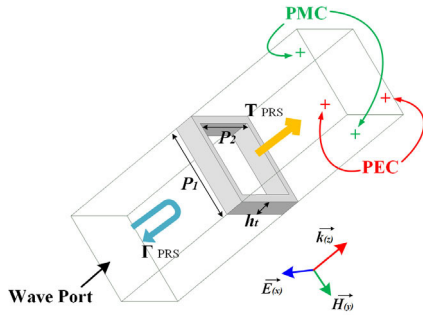


FIGURE 14. Unit cell of PRS.

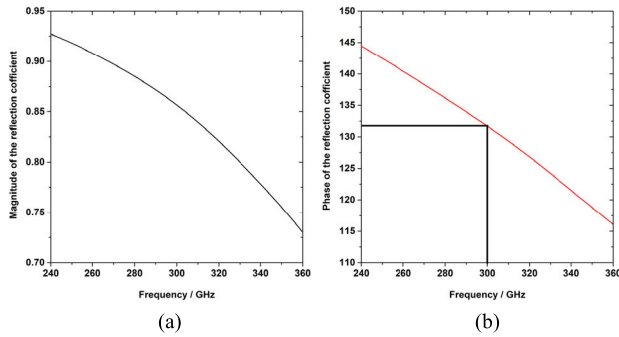


FIGURE 15. Simulated (a) magnitude (b) phase of the reflection coefficient.

B. ANTENNA DESIGN

Periodic metallic grid FSS is an ideal candidate PRS which can exhibit high reflectivity at the desired frequency. Fig.14 shows the designed PRS unit cell with geometrical parameters. Periodicity of the unit cell P_1 is 0.48 mm. The inner dimension and thickness are $P_2 = 0.4$ and $h_t = 0.1$ mm, respectively. The size of P_1 and P_2 is close to half wavelength at 300 GHz. In order to ensure the realization of processing, the width of square ring is 0.1 mm. The equivalent model of the periodic structure of the square ring is a high pass filter. From the frequency characteristics, it will reflect the low-frequency wave and transmit the high-frequency wave. High Frequency Structure Simulator (HFSS) is used to optimize the parameters of unit cell. The simulated magnitude and phase of the reflection coefficient are shown in Fig. 15. From the simulated result, the phase of PRS at 300 GHz is 132° , the distance between the feed antenna and the PRS layer h could be calculated by (1).

$$h = \frac{c}{4\pi f_r} [\phi_{PRS} + (2N - 1)\pi]$$

$$= \frac{300/300}{2} (\frac{132}{2\pi} + 0.5) \approx 0.433(mm)$$

The exploded view of the complete FPC antenna is shown in Fig. 16, which is composed of a WR3 waveguide feed port, a coupling slot, transmission cavity, two radiating slots and 5×5 metal PRS superstate. The metal wall is used to support the PRS layer on the top of radiating slots. Direct illumination

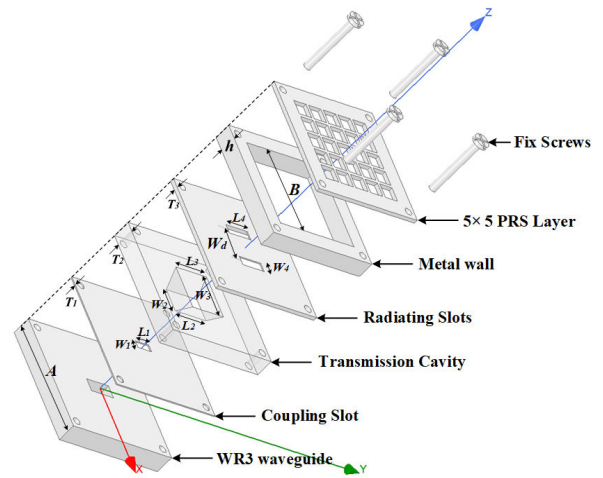


FIGURE 16. The exploded view of the proposed antenna $W_1 = 0.2$, $L_1 = 0.44$, $W_2 = 1.0$, $L_2 = 0.63$, $W_3 = 1.2$, $L_3 = 0.63$, $W_4 = 0.25$, $L_4 = 0.7$, $W_d = 0.95$, $T_1 = 0.03$, $T_2 = 0.55$, $T_3 = 0.03$, $A = 3.2$, $B = 2.4$, $h = 0.44$, unit: mm.

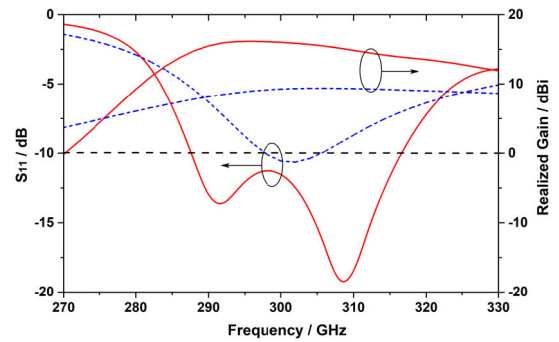


FIGURE 17. Simulated S_{11} and antenna gain with and without PRS.

of the PRS will lead to impedance mismatching, then to decrease the antenna efficiency. Therefore, a novel transition structure is used to realize impedance matching. A small slot is excited by the WR3 waveguide port. The middle layer adopts a trapezoidal cavity to transmit the wave from the coupling slot. On the top of the trapezoidal cavity, two identical, symmetrical parallel radiating slots are used to broaden the impedance matching bandwidth. Simulated return loss and gain of antenna with and without PRS are shown in Fig. 17. It can be seen that both the impedance matching performance and the realized gain are well improved. The antenna achieves a peak of 16.2 dBi at 295 GHz. As shown in Fig. 17, this transition layer will generate additional modes at the frequencies of 290 and 310 GHz, respectively.

Fig. 18 gives the E-field distributions and 3D radiation patterns of antenna with and without PRS at 300 GHz. Due to the large distance between two radiating slots, the antenna without PRS presents another two large electric fields at the low elevation angle. After add the 5×5 metal PRS superstate, the EM energy converges along the boresight direction.

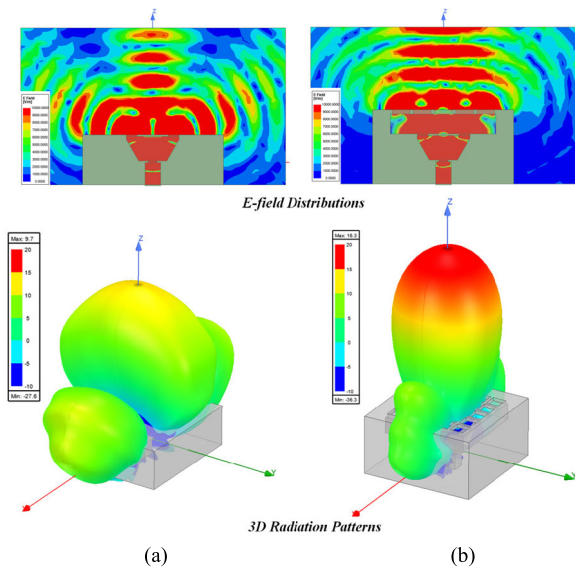


FIGURE 18. Simulated E-field distributions and 3D radiation patterns of antenna (a) without PRS, (b) with PRS.

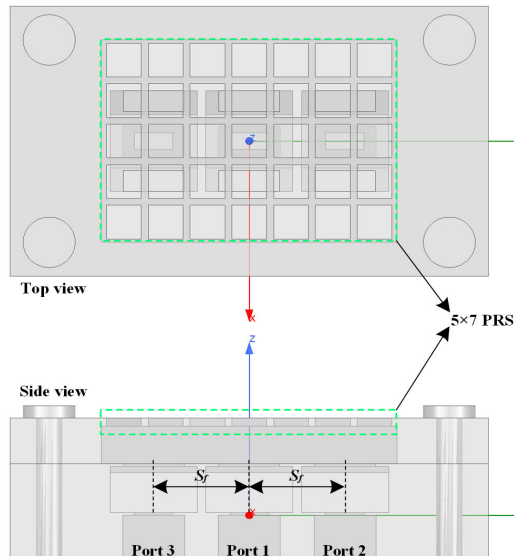


FIGURE 19. Configuration of proposed multibeam FPC antenna.

In addition, this antenna prototype is suitable for multi-beam applications. As shown in Fig. 19, a three-switched-beam FPC is designed by three feeding sources to realize switched-beam function. All the dimensions are the same as the antenna element as shown in Fig. 16. The offset distance between these three feeding sources (Port 1, 2, and 3), which are symmetrically placed, is $S_f = 1.1$ mm. When the feeding source is placed at a distance from y-axis ($S_f \neq 0$ mm), the phase distribution of the PRS will be changed. The simulated S-parameters of these three feeding ports is illustrated in Fig. 20. An overlapped impedance bandwidth from 290 to 320 GHz is achieved. When one port is excited, the other two ports are matched. As a result, the radiation pattern is tilted as shown in Fig. 21.

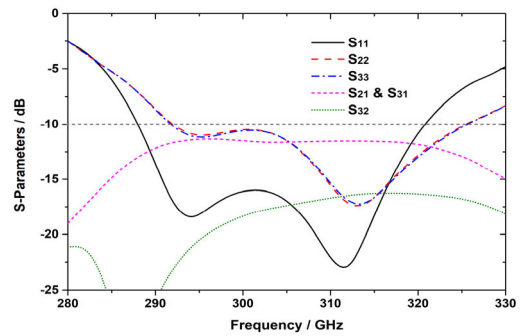


FIGURE 20. Simulated S-Parameters of multibeam FPC antenna.

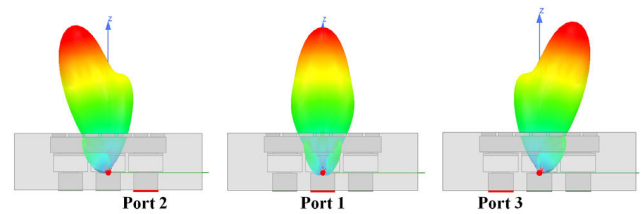


FIGURE 21. Tilted Radiation patterns with different feeding ports.

Fig. 22 shows the simulated radiation patterns at different frequencies (290, 300, and 310 GHz) with three beams. As shown in Fig. 21 (a), the peak realized gain at 290 GHz is 15.37 dBi with normal patterns and the peak gain of tilted patterns is 13.6 dBi with $\theta = 8^\circ$. While, when the frequency increases to 300 GHz, the boresight peak gain becomes 15.47 dBi, and the tilted patterns peak gain, which is 16.29 dBi, occurs at $\theta = 14^\circ$. As shown in Fig. 21 (c), as the frequency increases further, the phase change of PRS is more dramatic, which leads to the deterioration of normal patterns at 310 GHz, and the peak gain decreases to 12.20 dBi. However, the peak gain of tilted patterns is 15.54 dBi at $\theta = 18^\circ$.

C. FABRICATION AND MEASUREMENT

For 300 GHz FPC antenna design, almost none of the available AM or 3D techniques are capable of printing such fine structures. Therefore, this session mainly focus on the printing of scaled element at 30GHz. Based on the 300 GHz design, a scaled model operating at 30 GHz is simulated. As the whole antenna is made of metal, the values of antenna parameters are ten times than those at 300 GHz given in Fig. 16. The feeding rectangular waveguide adopts WR-28 with recommended frequency band of operation from 26.5 to 40 GHz.

There is a variety of AM processes. Here we use Metal Binder Jetting (MBJ), which is the most commonly used method for printing metallic structure. The 3D printer is ProX DMP 100 as shown in Fig. 23 (a). It is a high quality direct metal printing (DMP) system. During the fabrication, loose metal powder particles are melted together by

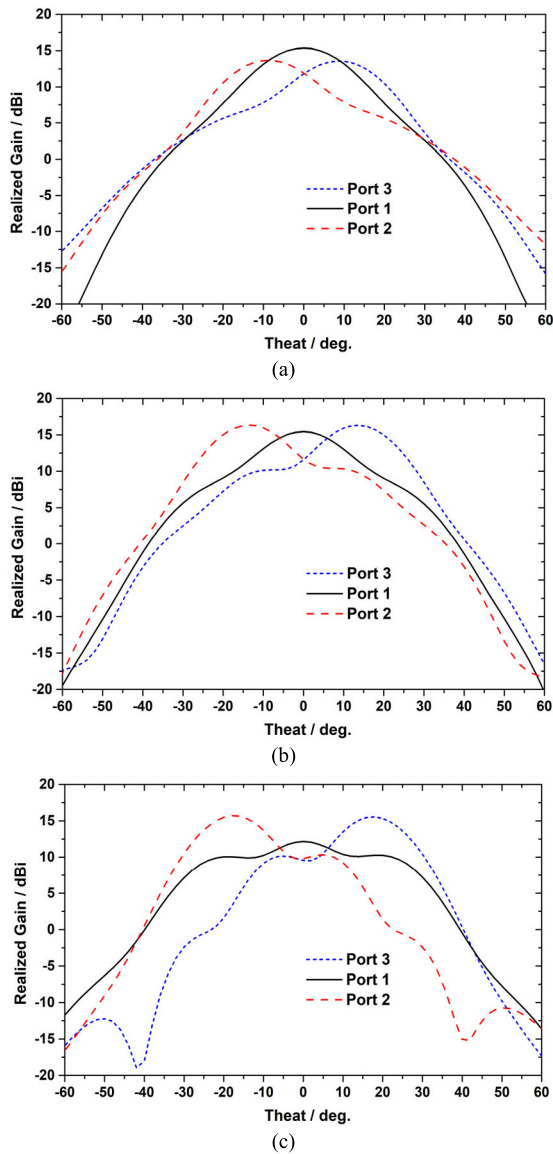


FIGURE 22. Radiation patterns of the proposed multibeam FPC antenna at (a) 290, (b) 300, and (c) 310 GHz.

a high-precision laser. The laser is directed to the powder particles according to the STL file of the antenna structure in order to selectively build up thin subsequent horizontal layers. Bonding the layers together forms the final metal parts as shown in Fig. 23 (b). MBJ process can create complicated and highly detailed design in a very short period. Moreover, it is cost-effective compared with traditional manufacturing technique.

This antenna is measured in an anechoic chamber using Anritsu 37397C VNA. Reasonable agreement between the measured and the simulated return loss is achieved, which is shown in Fig. 24. The difference mainly attributes to the surface roughness and tolerance during the fabrication process. The accuracy of the attachment of the waveguide-coax adapter to the WR-28 waveguide feed is another key factor with respect to the measured return loss.



FIGURE 23. The printer and printed antenna.

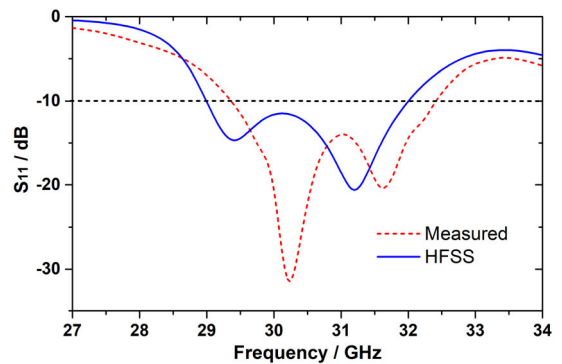


FIGURE 24. Simulated and measured S_{11} .

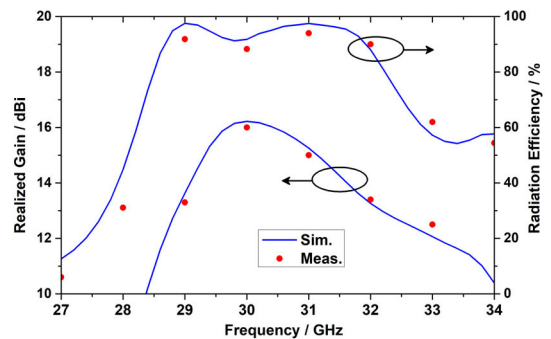


FIGURE 25. Simulated and measured antenna gain and radiation efficiency.

Fig. 25 compares the simulated and measured results of antenna realized gain and radiation efficiency. We can get the conclusion that the fabricated 3DP antenna has a good radiation performance. Compared with the simulated result, the measured result is slightly smaller from 28 to 31 GHz and higher from 32 to 33 GHz. A 3-dB-gain bandwidth of 10% is achieved. Both the simulated and measured antenna radiation efficiency are more than 88%. The small discrepancy attributes to the fabrication and assembly tolerances.

TABLE 1. Comparison among different Low-THz high gain antennas.

Ref.	Antenna Type	Antenna Size (mm)	Antenna Working Band	Fabrication Technique	Structural Complexity	Cost	3 dB Gain Bandwidth / %	Peak Gain / dB
[50]	Horn	$\Phi=21.34$	D-band	3DP (All metal)	Easy	Low	42.4	24.5
[51]		2.8×3.2	H-band	PCB & LTCC (Dielectric and metal layers)	Hard	High	24	18
[52-53]	Planar waveguide array	67.2×67.2 (32×32 array)	D-band	Diffusion Bonding (All metal)	Hard	High	11.9	39.1
[54]		11×11	H-band	Silicon & Diffusion Bonding (All metal)	complex	High	11.8	30.6
[57]	Lens	5.25×5.25	H-band	3DP (Dielectric layers)	Easy	Low	21.7	27
[58]		$\Phi=20$	H-band	3DP (Dielectric layers)	Easy	Low	15.1	27.4 (CP)
[59]	Transmit-array	40×40	D-band	PCB & LTCC (Dielectric and metal layers)	Hard	High	24.4	33.45
[64]	Reflect-array	28×28	H-band	3DP (Dielectric layers)	Easy	Low	–	27.4
[65]		30×30	W-band	3DP (Dielectric layers)	Easy	Low	–	22.5
[66]		$\Phi=2.52$	1.3 THz	Graphene	Easy	High	–	27
[71]	RCA	12×12	V-band	PCB (Dielectric and metal layers)	Hard	Low	12.5	16.8
[72]		$\Phi=39.6$	V-band	PCB (Dielectric and metal layers)	complex	Low	13.3	21
This Work		2.4×2.4 (Simulated)	H-band	3DP	Simple	--	9.9	16.2
		24×24 (Fabricated)	Ka-band	3DP (All metal)	Simple	Low	10	16

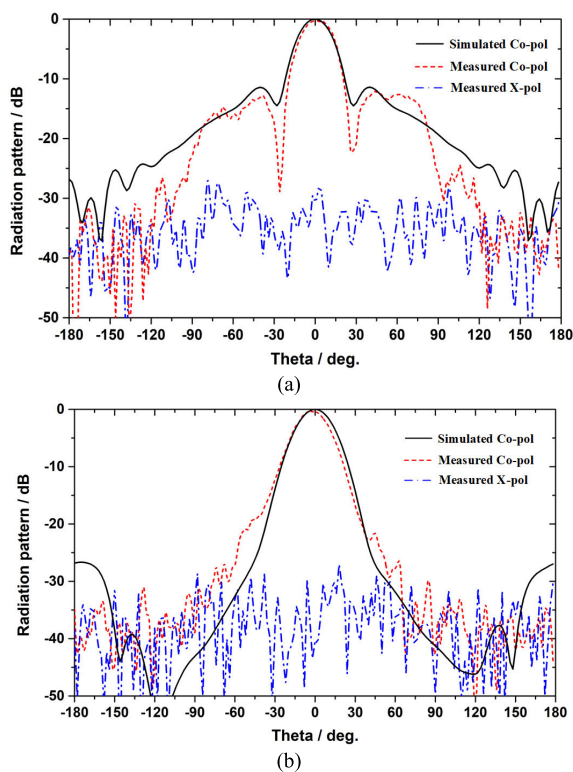


FIGURE 26. Simulated and measured normalized radiation patterns at 30 GHz. (a) E-plane, and (b) H-plane.

The normalized measured radiation patterns at 30 GHz in both E and H planes are shown in Fig. 26. The cross-polarization level is well suppressed, which is no greater than -30 dB in both planes. Sidelobe levels (SLLs) in E and H planes are less than -10 dB and -20 dB, respectively. Although the asymmetric fabricated structure causes slight asymmetry in the sidelobes, the main lobes keep good performances, agreeing well with the simulated results. The 3-dB beamwidth of both planes is in good agreement with simulated results.

IV. CONCLUSION AND FUTURE WORK

For Low-THz band, fabrication accuracy is crucial with respect to antenna performance. Traditional fabrication methods of THz devices can be an expensive and time-consuming effort. This paper reviews the current state of the art of wideband Low-THz antennas with corresponding manufacturing processes and different techniques used by researchers for gain enhancement. Then a novel FPC antenna element and three-switched-beam antenna are designed at 300 GHz. To validate the high-performance of proposed antenna, a scaled antenna element working at 30 GHz is fabricated using MJB process, which is fast and cost-effective compared with traditional manufacturing technique. Reasonable agreements are achieved between simulated and measured results. Table 1 gives a comparison among different high gain antenna

in Low-THz band. A detailed comparison from antenna type, antenna size, working frequency band, processing method, and radiation performance is illustrated in Table 1. The results show that our antenna is currently the first one antenna, which is achieved with very simple all metal RCA structure in millimeter-wave & Low-THz band using viable AM techniques to realize high gain and multi-beam radiation. The measured results proved that manufacturing parts have a high resolution. With the improvements of AM precision, some new printing technologies could be used to fabricate our Low-THz antennas in the near future, such as hybrid 3DP and 4D printing technology. The next step, our aim is to design and fabricate a Low-THz active phased array system, which will integrate some active circuits (oscillators, amplifiers) and passive circuits (filters) into one single chip. In addition, we will do some researches on Low-THz frequency scanning antennas.

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