Compact High-Gain Si-Imprinted THz Antenna for Ultrahigh Speed Wireless Communications

Shu-Yan Zhu, Yuan-Long Li, Student Member, IEEE, Kwai-Man Luk, Fellow, IEEE, and Stella W. Pang, Fellow, IEEE

Abstract—A low-profile and high-gain Gaussian beam antenna (GBA) operating at 1 THz is demonstrated for the first time. Imprint and dry etching technologies in silicon are employed. A complementary antenna feed based on the magnetoelectric dipole is proposed for enhancing the radiation characteristics of the antenna. The microfabrication technologies are compatible with the Si-based integrated circuit manufacturing processes. The terahertz (THz) antenna is realized with over 20 dBi in antenna gain. With high-precision fabrication technologies, a highly efficient THz GBA with smooth morphology and much lower profile than conventional horn and lens antennas is developed. Moreover, the antenna has the characteristic of low sidelobe levels which is advantageous in many wireless applications.

Index Terms—Gaussian beam antenna (GBA), high gain, imprint technology, low profile, Si-based microfabrication, terahertz radiation.

I. INTRODUCTION

THF terahertz (THz) technology has attracted great interest due to its unique advantages [1]–[3] and great potential in many applications such as security inspection, medical imaging, and mobile communications. Driven by the demands of the faster data rate toward terabit-per-second (Tb/s) for future 6G networks, communications systems working at the THz band are highly desirable [4]. Antenna is one of the most important components in a wireless communication system to transmit and receive signals. Conventional THz sources have low output power, and THz waves have high propagating loss in air. Therefore, high-gain antennas are necessary for THz systems; otherwise, the distance of communications will be very limited [5], [6].

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The physical size of an antenna decreases with increasing operating frequency. Conventional manufacturing technologies for most microwave and millimeter (mm)-wave antennas will not be applicable at THz frequencies. The common horn and lens high-gain antenna operating at or above 1 THz is produced by metal milling or silicon (Si) etching technologies [7]–[10]. However, these antennas are bulky in size, with a thickness over 6 mm, and they cannot be easily integrated with planar circuits for realizing compact transceiver systems. Three-dimensional (3-D) printing technology has emerged as a promising candidate for fabricating reflectarray antennas operating between 100 and 400 GHz [11], [12]. However, the resolution of 3-D printing technology can only go down to tens of micrometers. Therefore, it is intractable to fabricate a 1 THz antenna with acceptable surface roughness using 3-D printing technologies.

Recently, microfabrication technologies were used to construct a low-profile wideband 2 × 2 magnetoelectric (ME) dipole antenna arrays operating at 1 THz by stacking multiple layers of SU-8 polymer together, each with thickness over hundreds of micrometers [13]. It is a great challenge to combine and align multiple SU-8 layers as breakage and deformation often occur during the process. The gain of the THz antenna array is 14 dBi, which indicates its high radiation efficiency. In this article, Si microfabrication technologies including deep reactive ion etching (DRIE) and imprinting were employed instead, which can provide precise dimensional control and smooth surface morphology. These technologies are compatible with Si-based integrated circuits (ICs) manufacturing technology, and the high-performance THz antenna can be integrated on the same chip with other components to form a THz device or system. In addition, applying the microfabrication technology in Si gives the advantage of providing more mechanically stable structures in Si due to its higher Young’s modulus compared with SU-8 for avoiding structural deformation [14], [15].

In comparison with horn antennas, lens antennas, reflectarrays, and cavity-backed antennas, the Gaussian beam antenna (GBA) is a promising candidate to achieve both medium/high-gain performance and a low-profile structure. GBAs with a spherical concave cavity and a partially reflective surface (PRS) have been realized at microwave or mm-wave by traditional manufacturing technologies such as metal milling, electroplating, or stacked printed circuit boards (PCBs) [16], [18]. However, these technologies cannot be
applied to build 3-D spherical concave cavity structures with micrometer size. The conventional photolithography for IC fabrication cannot also be used to generate a nonplanar 3-D curved structure. Stacking multiple ring layers with different diameters together could realize a spherical concave cavity structure, but many processing steps and high precision alignments are required, as well as having the problem of forming air gaps between different layers which could reduce the radiation efficiency.

Focus ion beam (FIB), electron beam lithography (EBL), thermal scanning probe lithography (t-SPL), and imprint lithography can all be applied to fabricate 3-D micro and nanostructures [19]–[23]. Among these techniques, imprint lithography is more suitable for producing 3-D spherical concave cavity structures over a large area with fast speed, accurate dimensional control, high throughput, and low cost. Typically, FIB, EBL, or t-SPL take many hours to form a large area of 3-D microstructures by direct-write patterning, while they lack good control of the exact profile of the spherical concave cavity structure. In contrast, a spherical glass bead can be used as a stamp in imprint lithography to fabricate the spherical concave cavity with accurate dimensions and smooth curvature within a few minutes. Multiple 3-D curved cavities could be imprinted simultaneously with multiple glass beads as stamps. In this article, imprint technology is applied to fabricate the 3-D spherical concave cavity, which is then integrated with a Si-based antenna feed to realize the THz GBA. This THz GBA comprises a Si-based ME dipole antenna as the feed, a spherical concave cavity structure together with a PRS as an open resonator cavity, and a 3-D printed holder to support the PRS. With the innovation of employing the ME dipole, a kind of complementary antenna, as the antenna feed, the measured gain of this GBA is 20.3 dBi at 1.04 THz. To the best of our knowledge, this is the first time a GBA is successfully developed that can work around 1 THz. The antenna also has small thickness of about 2.5 wavelengths in free space, enabling its suitability for on-chip integration with other electronic components to form a wireless system or device for future 6G and beyond communications.

II. DESIGN OF HIGH-GAIN THz GAUSSIAN BEAM ANTENNA

Open resonator cavity is usually used as an optical interferometer. By changing one of the reflective surfaces to a PRS, the cavity can radiate electromagnetic waves through the PRS into free space. When the height of the cavity is an integral multiple of wavelength, resonance occurs and a highly directive beam of radiation is generated. In comparison with the conventional Fabry–Pérot cavity with two flat mirrors, the open resonator cavity (or called the spherical Fabry–Pérot cavity), with two spherical mirrors or with one flat and one spherical mirror, could support higher order Laguerre–Gaussian beam modes. More importantly, the impedance bandwidth and the 3 dB gain bandwidth of the GBA can be efficiently enhanced by exciting the hybrid fundamental mode $H_{E_{11}}$ with two higher order modes. This operating principle was confirmed with a practical antenna design [16], [17].

As shown in Fig. 1(a), the proposed THz GBA consists of a metallized Si-etched ME dipole as the feed, a metallized spherical concave cavity as the reflective mirror, a 3-D printed holder, and a 20 $\mu$m-thick Si membrane as the PRS. The antenna is mounted above a metallic fixture with a WR-1.0 waveguide section at the center for convenience of measurement. Fig. 1(b) shows the side view of THz GBA as well as the top and side view of the ME dipole feed. Detailed parameters of the THz GBA are shown in Table I. According to the theory of open resonator with two spherical mirrors or one spherical mirror and one plane mirror, the resonant frequencies

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<th>Table I: Dimensions of THz GBA With Spherical Fabry–Pérot Cavity</th>
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of different higher order modes can be approximated by [24]

\[ f_{HE} = \frac{c}{2h_c} \left[ q + 1 + \frac{2p + l + 1}{\pi} \times \cos^{-1}\left(1 - \frac{h_c}{r_c}\right) \right] \]  

where \( p, l, \) and \( q \) are the radial, azimuthal, and axial mode numbers, respectively; \( c \) is the speed of light; \( h_c \) is the cavity height; and \( r_c \) is the radius of curvature of the reflective mirror.

As a brief review, the higher order modes can be separated into two series where the series A and series B \( TEM_{pl} \) modes of the same order have the same resonant frequency so they can be combined to synthesize the linearly polarized \( TEM_{pl} \) modes. However, in the improved open resonator theory by Luk and Yu [25], when \( l > 0 \), it was discovered that there is a frequency difference between the series A and series B \( TEM_{pl} \) modes of the same order and, hence, they cannot be superimposed together and there is no linearly polarized \( TEM_{pl} \) modes. A new mode designation for the open resonator was proposed with the \( HE_{11} \) mode designated as the fundamental Laguerre–Gaussian beam mode instead of \( TEM_{00} \) mode [26].

In this article, it is found that both the fundamental \( HE_{11} \) mode and the \( HE_{12} \) higher order mode can be excited in the THz GBA when the conducting plane mirror is replaced by a PRS. This is attributed to the reduction in \( Q \) factors of the two neighboring modes. The cross-sectional magnitude and phase distributions at different axial positions are shown in Fig. 2. It can be observed that the magnitude distribution slightly below the PRS changes from a Gaussian distribution with one peak to a distribution with two symmetrical peaks around the center frequency, which confirms the excitation of both \( HE_{11} \) and \( HE_{12} \) modes. The magnitude and phase distributions at the location slightly above the PRS are relatively uniform and stable over the operating frequencies, which indicates that the mixed \( HE_{11} \) and \( HE_{12} \) modes could also generate a high-gain beam with low sidelobe level (SLL). In our design, the fifth-order cavity was chosen, which means that the height of the cavity is set to be five halves of a free-space wavelength, and the resonant frequencies of the \( HE_{11}, HE_{12}, \) and \( HE_{13} \) modes are 1.02, 1.06, and 1.1 THz, respectively. The calculated frequencies of different modes also correspond to the minimum points of \( S_{11} \) with some tolerable frequency deviation caused by cavity perturbation. The electric field (E-field) distributions of different \( HE_{1, p+1} \) modes are shown in Fig. 3. Although the higher order mode could widen the bandwidth, the out-of-phase \( E \)-field across the aperture will cause gain reduction and high SLL. In this article, the \( HE_{11} \) and \( HE_{12} \) modes are excited together so a tradeoff between wide bandwidth, high gain, and low SLL can be achieved.

Conventional GBAs based on the open resonator were fed directly by an open-ended waveguide and their SLL was about \(-15 \) dB in the H-plane and \(-10 \) dB in the E-plane [16], [17]. As shown in Fig. 4(a), the radiation pattern in the E-plane is different from that in the H-plane if a WR-1.0 waveguide is used. The SLL in the E-plane of the GBA can be very high. To solve this issue, an ME dipole feed is proposed, which can reduce the difference in the E-plane and H-plane radiation patterns. As shown in Fig. 4(b), the ME dipole exhibits nearly symmetrical E-plane and H-plane radiation patterns over a wide bandwidth, which is achieved by combining an electric dipole with a magnetic dipole. The structure of this 1 THz ME dipole can be found in [13]. Besides, the ME dipole can help to reduce the SLL, improve the front-to-back ratio, and increase the gain of the THz GBA. As shown in Fig. 5, the peak SLL and the front-to-back-ratio of the GBA, fed by an ME dipole, are reduced by around 2.1 and 3.1 dB, respectively. Especially at 1.03 THz, the SLL of the radiation patterns in both E-plane and H-plane is less than \(-17 \) dB. Fig. 6(a) shows the gains versus frequency of the GBA fed by an ME dipole and an open-ended WR-1.0 waveguide. It can be seen that the gain curve of the GBA fed by an ME dipole
within the working bandwidth from 1.02 to 1.07 THz has about 1.3 dB enhancement in average and becomes more stable over the operating frequencies. Although using the ME dipole feed does not help to improve the impedance matching or return loss of the GBA and theoretically the gain of an open resonator antenna is mainly related to the reflectivity of a PRS, the gain is also affected by the feed as the field distribution inside the cavity can be modified. As shown in Fig. 6(b), the gain of the ME dipole was about 2 dB higher than that of a WR-1.0 waveguide, which can help to reduce the spurious radiation from the open cavity and effectively increase the gain of the GBA. The maximum gain of the GBA fed by an ME dipole increased to 21.3 dB at 1.03 THz theoretically.

In addition to supporting more higher order modes, the spherical concave mirror could also help to correct the phase of the $E$-field across the aperture and improve the directivity. Fig. 7(a) and (b) shows the comparison of the simulated $E$-field magnitude distribution of the GBA with spherical and flat reflective surfaces. As shown in Fig. 7(a), the edge radiation in the GBA with flat surface is more noticeable. In comparison, the energy can be confined more in the spherical concave cavity of the GBA. The phase distribution of the $E$-field along the diameter of the aperture is shown in Fig. 7(c). The phase distribution of the GBA with a spherical concave cavity is more uniform due to less edge leakage and the radiating wave is more like a plane wave, resulting in higher directivity of the antenna than the GBA with flat reflective surface.

III. DEVELOPMENT OF IMPRINT TECHNOLOGY IN SI FOR THz GAUSSIAN BEAM ANTENNA

As shown in Fig. 8, the THz antenna feed was fabricated using optical lithography and Si dry etching technology.
Double side polished Si wafer with a 100 μm thickness was used as the substrate. The slot pattern with a 50 μm width and a 190 μm length was patterned by optical lithography and then used as an etch mask to etch through 100 μm-thick Si wafer using a Bosch DRIE process. This dry etching technology allowed thick layer of Si to be etched with vertical profile to achieve high aspect ratio microstructures. Subsequently, four pillar-shaped photoresist squares with a 60 μm width and 100 μm length, and a 100 μm thickness were patterned by optical lithography and then used as an etch mask to etch through 100 μm-thick Si wafer using a Bosch DRIE process. This dry etching technology allowed thick layer of Si to be etched with vertical profile to achieve high aspect ratio microstructures. Subsequently, four pillar-shaped photoresist squares with a 60 μm width and 100 μm length were aligned and patterned next to the Si slot by a high-performance mask aligner (Karl Suss MJB4; Garching, Germany). The photoresist was used as an etch mask to etch 80 μm-thick Si square pillars using the DRIE process. After removing the photoresist, 10/500/20 nm-thick titanium (Ti)/copper (Cu)/gold (Au) films were deposited on the top surface and sidewalls of the Si structure conformally by sputter deposition to metalize the Si THz antenna feed. Ti film was used as an adhesion layer and Au film was coated on the top to prevent Cu oxidation.

Fig. 9(a)–(c) shows the profiles of Si etched under different conditions. The top and back side of Si slot. (f) Top view and (g) tilted view of Si THz antenna feed.

Bosch process is based on cycling between deposition and etching steps to etch Si with fast rate without undercut while protecting the photoresist etch mask. As shown in Fig. 9(b), the Si etch rate and selectivity were improved to 4.2 μm/min and 147, respectively, by the DRIE Bosch process. The etch rate and selectivity were decreased to 3 μm/min and 108, respectively, but the etch profile became more vertical at 89°, which is suitable for the high-performance Si THz antenna feed with thickness over one hundreds of micrometers.

Fig. 9(d) and (e) shows the front and back sides of the Si slot, respectively. The measured Si slot had a 50 μm width, a 190 μm length, and a 100 μm thickness. As the slot was etched through vertically, the size of the front and back sides was the same. Top and tilted views of the Si THz antenna feed coated with 10/500/20 nm Ti/Cu/Au films are shown in Fig. 9(f) and (g). Due to the well-controlled etch profile and smooth etch condition, the etched surface of the Si THz antenna was smooth with high dimensional accuracy. No deformation was observed for the Si THz antenna since Si has a high Young’s modulus. The surface smoothness of the antenna is important to ensure high efficiency. Antennas in SU-8 polymer and Si before and after metallization were evaluated for their surface morphology using an atomic force microscope (AFM).

As shown in Fig. 10, before metal deposition, the surface roughness of Si was found to be 0.29 nm, lower than 0.35 nm shown in the SU-8 polymer. After the THz antennas were metalized with Ti/Cu/Au films, the surface roughness of the metal surface increased to 1.20 and 1.94 nm on Si and SU-8, respectively. Microfabricated THz antennas had much smoother surface morphology, in the order of 1–2 nm, compared with antennas made by 3-D printing or metal milling, which typically have surface roughness in the order of 0.38 μm. The smooth surface formed in the THz antennas substantially improves their performance in the THz range with low loss and high efficiency.

An important element for THz GBA is the formation of 3-D spherical concave cavity structure with height variation up to 100 μm. Conventional IC manufacturing processes are designed for planar devices and often limit to height of just a few micrometers. Although stacking multiple ring structures could result in a curved cavity, it requires very precise alignment and the curvature is formed by multiple steps instead of having a smooth spherical surface. To fabricate a smooth spherical concave cavity with high accuracy, imprint technology with glass bead was used [27]–[29]. As shown in Fig. 11, a glass bead was used as a stamp to imprint photoresist on glass. The imprint process was carried out at 95 °C and 5 bar for 10 min, and 395 nm ultraviolet (UV) exposure for 2 min [30]. After demolding the glass
Fig. 10. Atomic force micrographs of (a) Si, (b) Ti/Cu/Au on Si, (c) SU-8, and (d) Ti/Cu/Au on SU-8 surfaces. (e) Comparison of surface roughness for Si and SU-8 before and after Ti/Cu/Au deposition.

bead at 20 °C, a spherical concave cavity was generated in the SU-8 over the glass substrate. A femtosecond laser system was used to drill a 450 μm diameter circle at the central of the spherical concave cavity. Subsequently, 10/500/20 nm-thick Ti/Cu/Au films were deposited on the spherical concave cavity by sputter-deposition. The metalized cavity was then peeled off from the glass substrate and adhered on top of the Si THz antenna feed. The alignment between the curved cavity and the Si antenna feed was done under a long working distance microscope. A polymer holder with a 2 mm inner diameter and a 4 mm outer diameter was fabricated by 3-D printing, and it was placed on top of the metallized cavity. A 1-inch diameter undoped ultrathin Si membrane (Virginia Semiconductor Inc., Fredericksburg, VA, USA) with a 20 μm thickness was cut to a 3 mm diameter by a femtosecond laser with 850 μW power. The 3 mm diameter Si membrane was then placed on top of the polymer holder under the long working distance microscope. The three-layer unit with an SU-8 curved cavity, a polymer holder, and a 3 mm diameter Si membrane was fixed together using a thin layer of SU-8 polymer at 80 °C for 1 min and then cross-linked by UV exposure at 20 °C for 1 min.

During the imprint process, the PDMS polymer flowed and accumulated around the edges of the glass bead and hardened by annealing at 110 °C for 10 min. When the initial thickness of PDMS polymer was reduced to 16 μm, the diameter and depth of the PDMS cavity was reduced to 2020 and 73 μm, respectively. However, these dimensions were different from the desired spherical concave cavity structure and further decrease of PDMS thickness caused difficulty in peeling off the PDMS polymer from the glass as well as structural deformation.

In comparison, the SU-8 polymer with the same initial thickness resulted in a spherical concave cavity with smaller diameter and lower depth due to its higher viscosity (5485 centipoises for SU-8 2025 versus 3500 centipoises for PDMS mixed at 10:1 curing ratio). Besides, SU-8 is a more rigid polymer with Young’s modulus that is 2.6 × 10^4 times higher than PDMS, which prevents deformation of the microstructure or wrinkle formation during the peel off process. As shown in Fig. 12(b4)–(b6), the SU-8 2025 with an initial thickness of 16.5 μm generated a curved cavity with 1580 μm in diameter and 44 μm in depth, which satisfied the dimensions required for the THz GBA. Fig. 13 shows
Fig. 12. (a) Formation of spherical concave cavity by imprinting glass bead with a 14 mm diameter into polymer. (b) Micrographs of curved cavities with different dimensions due to various initial PDMS and SU-8 thicknesses.

Fig. 13. Micrographs of (a) curved cavity structure after imprint, (b) curved cavity with hole in center and coated with Ti/Cu/Au, (c) curved cavity structure stacked on top of antenna feed, and (d) top view of THz resonator antenna with a 20 μm thick and 3 mm diameter Si membrane above holder.

the micrographs of the THz GBA during different stages of fabrication. In Fig. 13(a), the 3-D curved cavity with the desired dimensions was formed after imprinting using the glass bead. After coating with Ti/Cu/Au, the 3-D curved cavity with a hole in center is shown in Fig. 13(b). Fig. 13(c) shows the curved cavity stacked on top of the Si antenna feed. The entire THz GBA was completed by placing a 20 μm thick, 3 mm diameter Si membrane above holder as part of the spherical concave cavity, as shown in Fig. 13(d).

IV. PERFORMANCE OF TERAHERTZ HIGH-GAIN GAUSSIAN BEAM ANTENNA

Fig. 14 shows the antenna measurement setup. A THz in-house far-field measurement system was used to measure the scattering (S) parameters. The system consists of a vector network analyzer (VNA, Agilent N8245A), a pair of Virginia Diodes Inc. (VDI) extenders, a monitor, and a manual turntable. Two VDI extenders were used as the THz sources operating from 0.75 to 1.1 THz. The fabricated THz GBA together with a supporting fixture was mounted on the WR-1.0 waveguide flange of the VDI extender (Tx). A WR-1.0 diagonal horn was connected to another VDI extender (Rx) as a receiving antenna and fixed on the manual turntable. The whole system was installed on a vibration-free platform to reduce possible errors. Before taking the measurement, the short-open-load-through calibration was performed by the VDI WR-1.0 calibration kit. Laser alignment was used to ensure that the fabricated antenna and the receiving antenna were at the same level. The metallic surfaces of the measurement system were covered with absorbers to reduce multiple reflection. The plot of the reflection coefficient as a function of frequency was directly read from the VNA. The plot of gain as a function of frequency was obtained by comparing $S_{21}$ of the antenna under test (AUT) and a commercial THz horn with 22 dBi gain, estimated by the manufacturer. When measuring the radiation pattern, the AUT was mounted on the turntable which could be rotated horizontally around the center point, and the angular movement was limited to ±60° with a precision of 1°. For far-field measurements, the distance between the AUT and the receiving horn was set at 80 mm, which is larger than the Fraunhofer distance of 60 mm.

Fig. 15 shows the simulated and measured reflection coefficients of the THz GBA. It can be seen that the simulated $S_{11}$ was below $-10$ dB from 1.02 to 1.08 THz. The trend of the measured $S_{11}$ matched well with the simulated results, but the measured $S_{11}$ was much lower in value. To investigate the reasons, the effect of having an air gap between the curved SU-8 cavity and the Si antenna feed was considered. Simulations with 50/100/500 nm gap were studied and the results reveal that $S_{11}$ of three gaps were the same as the ideal surface contact, which means air gap up to 500 nm is a tolerable variation. Another possible reason is that the metallic fixture could cause additional energy loss. To better understand
its influence on the antenna performance, the loss due to the metallic fixture was considered and added in the simulation model. The metallic fixture consisted of four location pins around the antenna and a bulky rectangular base with a waveguide slot in the center to connect the waveguide port on the Tx and the antenna. All the conductors were assumed to have finite conductivity in the model. The surface roughness of the machined metallic fixture and the microfabricated antenna was 1.1 \( \mu \)m and 2.0 nm, respectively, which were measured by AFM. As shown in Fig. 15, there is an obvious downward trend of the simulated \( S_{11} \) of the antenna when the metallic loss of the fixture was included in the simulation and it shows a better agreement with the measured results. Therefore, the difference may be mainly caused by metallic loss from the sample and the metallic fixture. In particular, the metallic loss due to the waveguide section of the metallic fixture is substantial.

The radiation pattern was measured by the antenna measurement system, as shown in Fig. 14. The measured angle was limited to \( \pm 60^\circ \) due to the limitation of the system. Fig. 18(a) and (b) shows the simulated and measured radiation patterns of the GBA at 1.03 THz in the E-plane and H-plane, respectively. Without the mounting fixture, the antenna has \(-17.3\) dB SLL in the E-plane and \(-18.8\) dB SLL in the H-plane by simulation. With the fixture, there is a little deterioration in SLL but still lower than \(-16\) dB in all planes, again by simulation. The measured main beams in the E-plane and H-plane have a good agreement with the simulated results with and without fixtures, indicating that the THz GBA with a spherical curved cavity could achieve a highly directive radiation. The general trend of the measured SLL is the same as the simulated results, but the fluctuation in the curves is probably due to two main reasons. The first one is related to the power receiving by the antenna which is weak due to low source power and high propagation loss. Fig. 18 shows the normalized noise floor level (with long enough integration time) of \( S_{21} \) at 1.03 THz from the VNA measurement. As the noise floor level of the VNA was not much lower than the receiving power, the value of \( S_{21} \) could not be accurately measured. Another reason is that the coaxial cables connecting to the VDI extenders were very sensitive. When measuring the SLL, the cable could be over-stretched, and the accuracy was affected. The measured 3 dB beamwidths in the H-plane of THz GBA, two different cavities with surface variation over 5 \( \mu \)m were simulated, and the result is shown in Fig. 17. Through the simulation, it is found that the performances of the antenna are not sensitive to the curvature of the cavity within a few micrometers difference, so the variation of the fabricated cavity is tolerable. This further confirms that the differences between the simulated and measured gain curves, as shown in Fig. 16, are due to the metallic loss in the mounting fixture.
and the required dimensions of 1580 $\mu$m produce a spherical curved cavity with a very smooth surface that SU-8 2025 with an initial thickness of 16.5 $\mu$m can.

Imprint technology was developed to fabricate the 3-D curved cavity microstructures in Si with smooth morphology. Imprint technology was also used to fabricate the 3-D curved cavity microstructures in PDMS and SU-8 2025 polymers. It demonstrates that SU-8 2025 with an initial thickness of 16.5 $\mu$m can.

An ME structure in PDMS and SU-8 2025 polymers. It demonstrates that SU-8 2025 with an initial thickness of 16.5 $\mu$m can.

V. Conclusion

A high-gain and low-profile THz GBA has been realized by the imprint and dry etching technologies in Si. An ME structure in PDMS and SU-8 2025 polymers. It demonstrates that SU-8 2025 with an initial thickness of 16.5 $\mu$m can.

and the required dimensions of 1580 $\mu$m in diameter and 44 $\mu$m in depth. The spherical curved cavity and the PRS are separated by a 3-D printed holder to form the THz antenna. The measured peak gain of the THz antenna is 20.3 dBi at 1.04 THz, and the measured 3 dB bandwidth was 50 GHz, with SWR less than 2 from 1.02 to 1.07 THz. The measured main beam in the E-plane and H-plane matched well with the simulated results, confirming that low SLL and high gain can be achieved by this low-profile THz GBA.

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