A Compact Terahertz Multibeam Antenna Based on a Multimode Waveguide Beamforming Structure

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DOI:
10.1109/TTHZ.2023.3327563

A Compact Terahertz Multibeam Antenna Based on a Multimode Waveguide Beamforming Structure

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***Abstract*—In this letter, a fully metallic terahertz (THz) multimode-waveguide-based multibeam antenna operating at the band from 410 to 480 GHz is proposed. The antenna is composed of four waveguide feeders, a multimode waveguide beamforming network, four grooved waveguide phasers and a flare radiation aperture. It is realized by using high-precision Computer Numerical Control (CNC) machining technology. The measured results demonstrate that the reflection coefficients of all feeding ports are below −10 dB across the operating band. Multiple beams at the scanning range of ±32° are obtained with a scan loss less than 2 dB at 425 GHz. Wideband radiation characteristics with a maximum gain above 15 dBi and a gain fluctuation below 3 dB are realized from 410 to 480 GHz. The measured and simulated results agree very well. The antenna offers a compact and easy to implement solution for THz frequencies.**

***Index Terms*— Terahertz, multibeam antenna, multimode waveguide, grooved waveguide phaser.**

I. Introduction

MULTIBEAM technology that can meet the requirements of high gain and wide space coverage has attracted much attention in recent years because of its application potential in fifth-generation (5G) millimeter-wave (mmW) communication [1]. Passive multibeam antenna is a competitive solution for its balance in performance and cost [1, 2]. More recently, terahertz (THz) technology has been considered to play an increasingly important role in the sixth-generation (6G) wireless communication [3, 4]. The cost-effectiveness of the passive multibeam antenna solution is particularly relevant for THz since lower implementation cost and wider multiple beams coverage [5, 6] have been important design drives.

Several excellent solutions have been proposed on THz beam steering antennas by passive methods, most of which are based on quasi-optical lens-type beamforming networks [7]–[10]. The dielectric lenses, especially high-resistivity silicon lenses with relatively low dielectric loss, are widely employed in THz antenna systems [7], although the difficulties in integration and low beam overlapping levels limit its application scenarios. In recent years, by using high-resistivity silicon etching, a Luneburg lens antenna which improves the 1-D beam scanning performance has been realized at the band above 300 GHz [8]. However, the connection with standard interface such as waveguide is still a practical problem to be solved. Several metallic lens antennas with waveguide interfaces have been reported. An E-plane-focused parallel plate waveguide (PPW) lens antenna has been realized using CNC [9], but the mechanical beam scanning limits its flexibility. In [10], a terahertz Luneburg lens antenna manufactured by 3D printing and magnetron-sputtering has been proposed. However, its internal plastic and column structures with large depth-width ratios make it short of reliability and difficult to be fabricated with cost-effective CNC technology. The presented multibeam network structure in this letter can be easy to fabricate together with the waveguide feeders and flanges by using the same machining process, which make it convenient to be connected with the components and instruments with waveguide interfaces.

Due to the advantages of low loss, manufacturability and reliability, rectangular waveguide structures are still a popular choice for transmission lines and components at THz band. However, to the best of the authors' knowledge, there is no reported work on THz multibeam network based on compact waveguide structure. In the mmW band, passive multibeam solutions based on transmission-line signal distribution networks have been widely reported using Butler matrix [11, 12], Nolen matrix [13] or multimode waveguide (MMWG) multibeam networks [14]–[16]. The MMWG has the great advantage of compactness and can realize a 4-beam antenna with much smaller footprint and lower complexity. The MMWG multibeam network is always designed with the help of necessary phase compensating transmission lines for better directional beams, which is similar with the means in the design of Rotman lens [17, 18], another kind of popular multibeam network. However, the MMWG network with closed waveguide structure and without dummy ports is totally based on the MMWG transmission theory rather than the quasi-optical theory in Rotman lens. Recently, the reported MMWG antennas are mainly based on substrate integrated waveguide (SIW) technology which is hard to be scaled up to THz band. A more viable alternative is the use of the fully metallic air-filled MMWG for multibeam antennas operating above 300 GHz.

Fully metallic waveguide structures have been used in THz transmission lines [19, 20], filters [21], functional networks

This work was supported by the National Natural Science Foundation of China under Grants 62271047, 61901040 and 12173006 and the U.K. Engineering and Physical Science Research Council under Grants EP/P020615/1. (*Corresponding author: Hongda Lu*).

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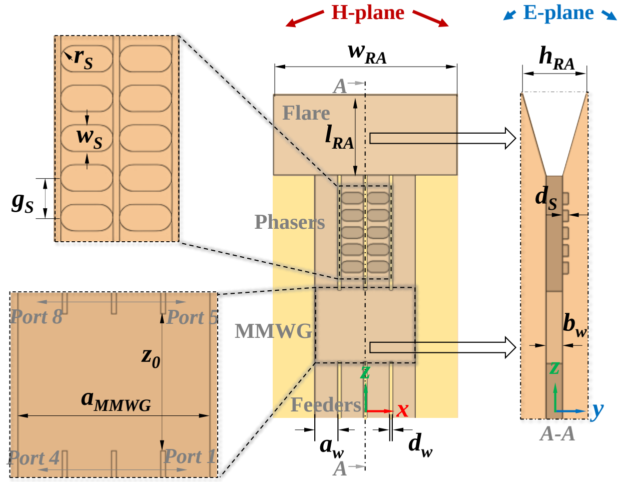

Fig. 1. Geometry of the MMWG-based multibeam antenna.

TABLE I
DIMENSIONAL PARAMETERS OF THE PROPOSED ANTENNA

Parameter	Value (μm)	Parameter	Value (μm)
a_w	400	g_S	300
b_w	280	d_S	100
d_w	50	r_S	100
a_{MMWG}	1750	w_{RA}	3200
z_0	1250	l_{RA}	1400
w_S	200	h_{RA}	1080

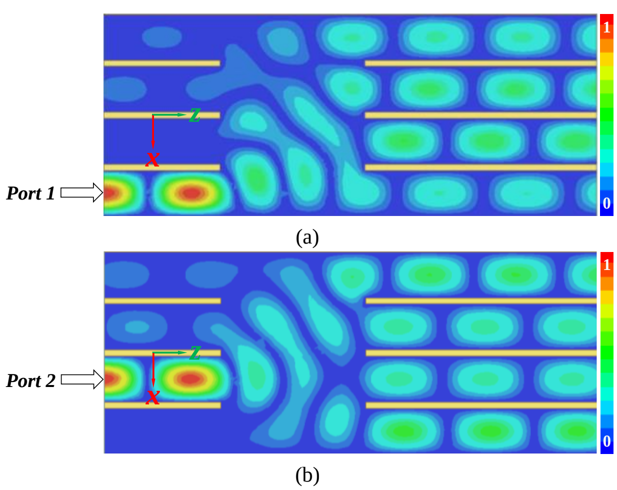

Fig. 2. Electric field distributions in the MMWG fed by (a) port 1 and (b) port 2.

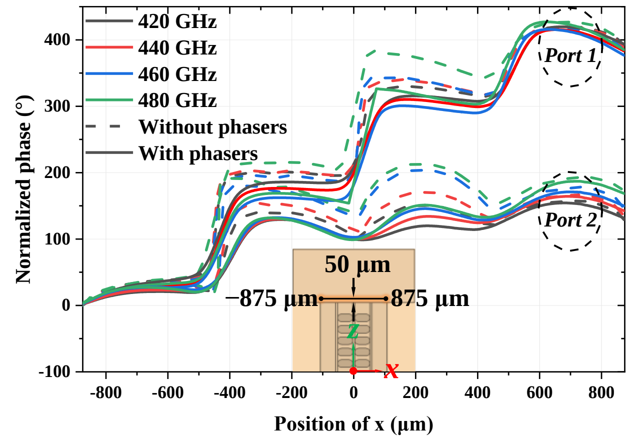

Fig. 3. Phase distributions at the output ports with and without waveguide phasers at different frequencies.

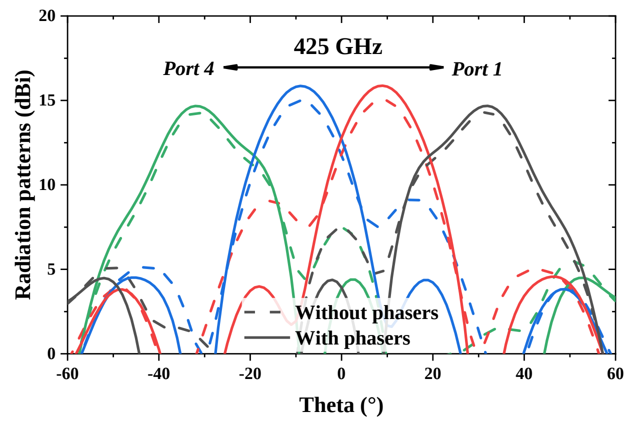

Fig. 4. Comparison of the radiation patterns at 425 GHz for the antennas with and without waveguide phasers.

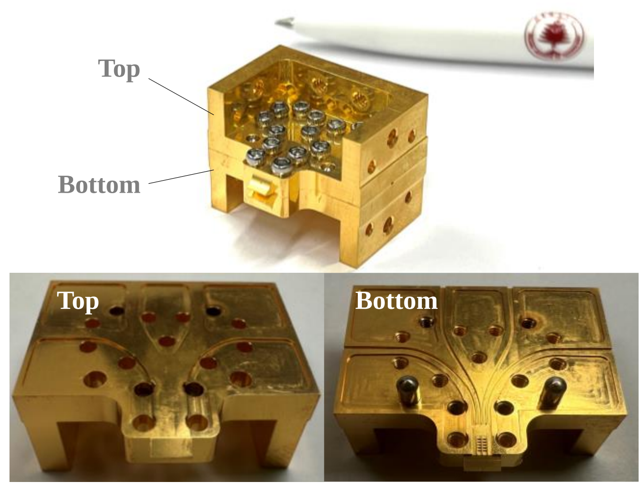

Fig. 5. Photographs of the prototype antenna fabricated by CNC milling.

[22], and antennas [23, 24]. Currently, to ensure the structural reliability and environmental robustness, CNC is still the most capable manufacture technique for THz devices and modules.

In this letter, a fully metallic MMWG-based THz 1-D scanning multibeam antenna that operates at the band from 410 to 480 GHz is presented for the first time. A four-mode waveguide signal distribution structure is used. A prototype is fabricated using commercial high-precision CNC machining and experimentally verified, showing high performance.

II. ANTENNA DESIGN

As shown in Fig. 1, the fully metallic THz MMWG-based multibeam antenna is composed of four parts: the waveguide feeders, the MMWG-based beamforming structure, the waveguide phasers and the radiation aperture. The beamforming network essentially has four input rectangular waveguides (RWGs) feeding the MMWG section with four output RWGs. This beamforming network is more compact and much simpler to implement at THz frequencies than the Butler or Nolen matrix. The dimensional parameters are given in Table I.

In this work, the concept is attempted at THz band by using an air-filled waveguide structure. The height of the MMWG,

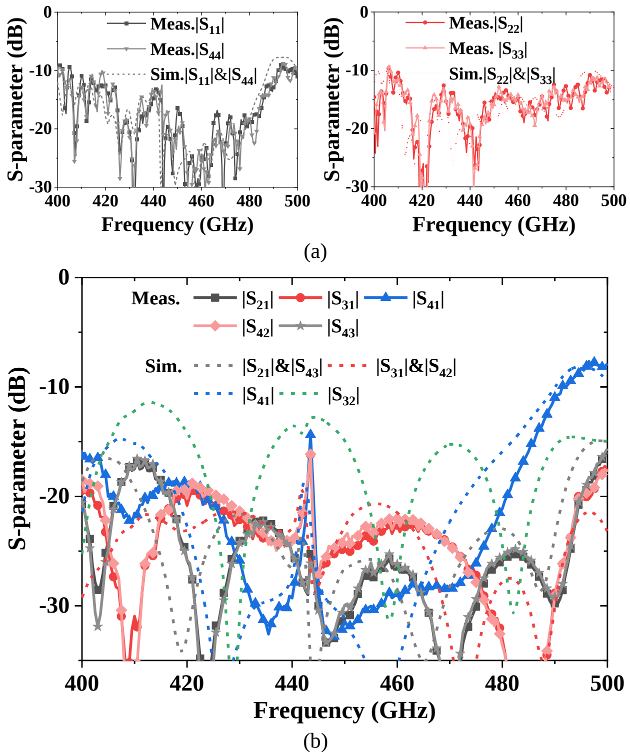

Fig. 9. Measured and simulated S-parameters (a) Reflection coefficients from 400 to 500 GHz, (b) Mutual coupling between ports from 400 to 500 GHz.

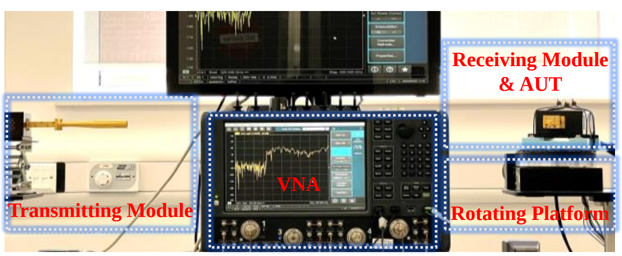

Fig. 10. Photograph of the test setup.

b_w, is the same as that of WR2.2 standard RWG, which is 280 μm. The width of the MMWG, a_{MMWG}, is chosen to be 1750 μm in order to support the transmission of four modes, TE_{10}, TE_{20}, TE_{30}, and TE_{40}, at the design frequency band from 410 to 480 GHz. This matches the overall width of the four input and output waveguides, each of which is 400 μm wide (a_w). For the convenience of measurement, the input waveguides are transferred to WR2.2 waveguides in the prototype. The thickness of the walls between the adjacent waveguides, d_w, is 50 μm. The length of the MMWG, z_0, is determined as 1250 μm using the method in [14]. Different from the quasi-optical devices, there is no unwanted scattering from the sidewalls in the beamforming network according to the MMWG theory. Fig. 2 illustrates the electric field distributions in the RWG-fed MMWG corresponding to different feeding ports. It indicates that the RWG-fed MMWG performs like a good signal distribution network although the phase outputs need to be further improved.

As shown in Fig. 2, the initial MMWG section cannot support the required phase gradients on the radiation aperture, causing poor gains and sidelobe levels (SLLs). To solve this

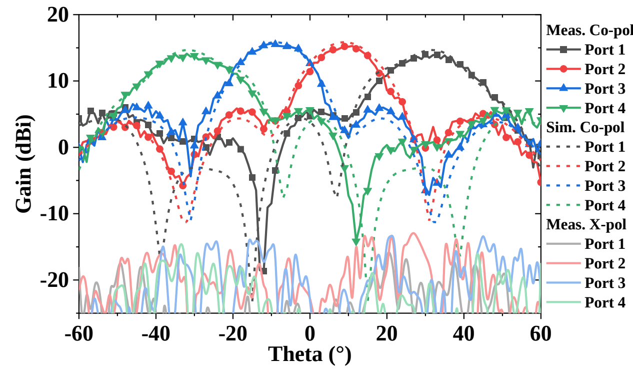

Fig. 6. Measured and simulated radiation patterns at 425 GHz.

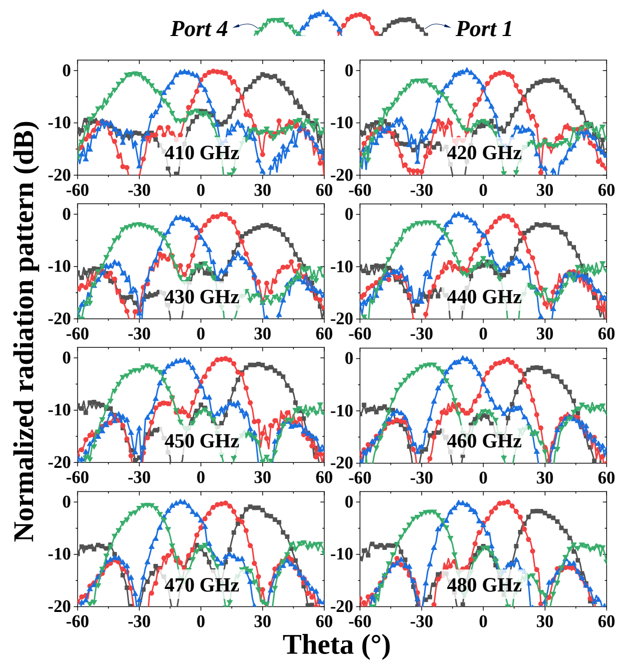

Fig. 7. Measured radiation patterns from 410 to 480 GHz.

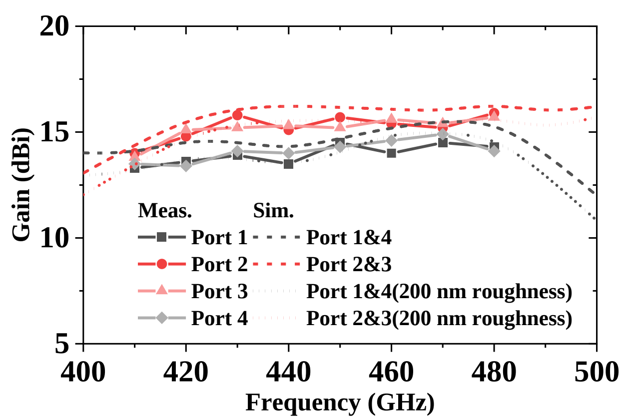

Fig. 8. Measured and simulated gains from 410 to 480 GHz.

problem, waveguide phasers that are easy to fabricate by CNC at THz band are employed for port 6 and 7 to provide proper phase compensations. The waveguide phasers are realized by adding grooves on the bottom of RWGs. According to the theory in [25], grooving the waveguide can be treated as introducing a discontinuity which can bring a phase delay into the original waveguide. In addition, for the convenience of CNC machining at THz band, the corners of the grooves are rounded to a radius of 100 μm.

Here, the equal-width grooved RWG sections which have been presented in [26] are introduced to realize a phase delay of 30° for port 6 and 7 at 425 GHz with about ±10° fluctuation in the operating band. Fig. 3 shows the influence of waveguide phasers on the phase distributions at the output ports of the MMWG at different frequencies. Here, x means the lateral distance to the center of the aperture. When port 1 is fed, the output phase gradient is clearly improved, showing uniform phase increments of 125°±5°. When port 2 is fed, compared with the initial output phase distribution, the modified one shows a better gradient about 40°±20°. Fig. 4 further demonstrates the effect of the phasers on the radiation patterns at 425 GHz. It is evident that the waveguide phasers bring higher gains and much lower SLLs.

III. Results and Discussion

The antenna prototype is fabricated by CNC machining technology. Fabrication accuracy of ±2 μm and maximum surface roughness of 200 nm have been verified by Alicona optical system. The UG-387 flanges and transitions between the waveguide feeders and the WR2.2 waveguides are also included in the block. A flared radiation aperture is added in front of the MMWG for the impedance matching with the free space and enhancing beam directivity in E-plane. The photographs of the antenna are shown in Fig. 5.

The S-parameters are measured by a vector network analyzer (Keysight N5247B PNA-X) with THz extenders (VDI WM570). The simulated and measured reflection coefficients and mutual couplings of the four ports are given in Fig. 6. The measured reflection coefficients are all below −10 dB in the range from 407 to 487 GHz and the mutual couplings are lower than −15 dB for most of the port pairs. It should be noted that ports 2 and 3 are relatively close, leading to a stronger coupling of −12 dB at some frequencies. Although it was not possible to measure all the mutual couplings such as that between port 2 and 3 due to their close proximity, the agreement between the existing measured and simulated results indicates the effectiveness of this design.

The test setup of the radiation performances consists of a transmitting module, a receiving module, a rotation platform, and the antenna under test (AUT) as seen in Fig. 7. Fig. 8 shows the radiation patterns at 425 GHz. The measured main beams agree very well with the simulation, at −32°, −10°, +10° and +32°. The cross-polarization patterns show a relative level below −25 dB. To verify the wideband performance of the antenna, the radiation patterns are measured across the band from 410 to 480 GHz and shown in Fig. 9. It is clear that the proposed antenna can provide satisfying multibeam radiations within the operating band. To evaluate the ohmic dissipation losses in the waveguide structures, the gain results with the effect of surface roughness are given in Fig. 10. The simulated ohmic dissipation losses caused by a 200 nm typical surface roughness is about 0.8 dB. The scan loss is below 2 dB in all cases. The gains are in the range from 13.3 to 15.9 dBi.

IV. Conclusion

A THz fully metallic MMWG-based multibeam antenna has been demonstrated for the first time. The prototype has been fabricated by high-precision CNC technology. The measured results demonstrate good impedance matching with the reflection coefficients lower than −10 dB from 407 to 487 GHz. A multibeam coverage range of ±32° at 425 GHz with a scan loss better than 2 dB has been realized. The wideband radiation characteristics indicate that the antenna can work well from 410 to 480 GHz. The good agreements between measured and simulated results verify the feasibility and reliability of this solution. The proposed multibeam antenna can be used independently or as a sub-array to meet the application requirements in the emerging THz multi-channel communications such as dynamic routing scenarios in 6G with proper protocols and algorithms.

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