Received June 2, 2020, accepted June 14, 2020, date of publication June 22, 2020, date of current version July 6, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3003853

Sub-THz Circularly Polarized Horn Antenna Using Wire Electrical Discharge Machining for 6G Wireless Communications

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This work was supported in part by the National Plan for Science and Technology (NPST), Saudi Arabia, under Project 13-ELE1184-02-R, in part by the European Union through the European Regional Development Fund, in part by the French Ministry of Higher Education and Research, in part by the Region Bretagne, through the CPER Project 2015–2020 SOPHIE/STIC, and in part by Ondes.

ABSTRACT A novel compact high-efficient circularly polarized conical horn antenna is realized with Wire Electrical Discharge Machining (EDM) technique operating at 300 GHz for 6G wireless communications is presented. The proposed antenna structure consists of three main components; a waveguide feed, a circular polarizer disk, and a conical horn. The waveguide feed is a standard WR-03 rectangular waveguide which feeds the whole structure. The circular polarizer disk is comprised of a crossed slot with unequal lengths which are perpendicular to each other. By adjusting the lengths of both slots, two orthogonal modes are excited in the antenna to produce circular polarization. The conical horn is mounted on the circular polarizer disk. The proposed antenna was designed and optimized using CST Microwave Studio and is validated experimentally by an inexpensive direct Wire-cutting EDM technique over the WM-860 frequency band. The fabricated circularly polarized horn antenna achieved a wide impedance bandwidth of 20 % from 270 GHz to 330 GHz with a reflection coefficient ≤ -15 dB. The measured results show that the 3 dB axial ratio of the fabricated antenna prototype has a bandwidth of 7 GHz from 309 GHz to 316 GHz with a minimum axial ratio of 1.15 dB at 312 GHz. The measured normalized radiation patterns show good agreement with simulated results for different frequencies in both the elevation and azimuth planes at broadside direction with good symmetry in both planes.

INDEX TERMS Axial ratio (AR), circularly polarized (CP), electrical discharge machining (EDM), horn antenna, sixth-generation (6G), terahertz (THz).

I. INTRODUCTION

Recently, the terahertz (THz) frequency spectrum spanning from 0.1 THz to 10 THz has been highly valued in different fields such as wireless cognition, imaging, spectroscopy, sensing, super-high precision positioning and future wireless communications [1]. Sub -THz frequency (100 GHz - 1 THz) band, which has not been allocated for specific uses yet, has an extremely broad atmospheric transmission window ($\sim$100 GHz bandwidth), with manageable losses, and will be ideal for building wireless links with ultra-high data-rates up to a terabits per second (Tbps) with super-reliability and minimal latency communications. All of these properties make the sub-THz spectrum ideal for sixth-generation (6G) wireless mobile communications [1].

At THz frequencies, the need for high gain antennas is very important in order to overcome high atmospheric absorption, and high path loss at these frequencies, which will affect the budget of the wireless link. The need for directive antennas for 6G wireless fronthaul/backhaul for cellular mobile radio networks is increased in case for applying point-to point high data rate wireless links according to fixed radio systems [2]. Moreover, circularly polarized (CP) antennas are required for any modern wireless communication systems due to their ability to avoid multipath fading, polarization mismatch between the antennas, and enhance the channel capacity of

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Feng.

the communication link. Therefore, it is important to develop front-end components focusing on CP THz antennas. For Sub-THz frequencies (i.e. 300 GHz), manufacturing errors become crucial with respect to antenna characteristics, so a simple structure, such as horn, is preferred. Horn antennas have been proposed at THz frequencies [3]–[8] with good radiation performance but no one has designed CP horn antennas at Sub-THz frequencies.

Recently, progress in Wire-cutting and die-sink Electrical Discharge Machining (EDM) technique in terms of accuracy and very precise control of the machining tools has made possible the fabrication of very delicate components needed for antennas at the millimeter wave frequency [9]–[11]. A directive and low loss antennas obeying the THz-wireless communication requirements can be obtained. Compared to conical corrugated horn antenna with 24 gold-coated silicon platelets at 330 GHz manufactured by using a deep reactive-ion etching (DRIE) process of silicon micromachining [12], our structure is very simple with three main components of brass and made economically by using metal cutting Wire EDM.

In this paper, we numerically and experimentally investigate a circularly polarized conical horn antenna for the WM-864 frequency (220 GHz-330 GHz) band, which has been fabricated by direct Wire-EDM machining in a single block of metal. The rest of the paper is organized as follows. Section II describe the basic concept of conical horn antenna design in terms of parametric study and its design factors for improving the antenna characteristics. Section III presents a fabricated prototype of the Sub-THz CP horn antenna. Finally, the measured reflection coefficient (S11), antenna directivity, axial ratio (AR), 2D radiation patterns in both principle planes, 2D AR, and the radiation pattern at different frequencies, which confirm the simulations are provided in Section IV. To the best of our knowledge, this is the first time a 300 GHz CP conical horn antenna have been successfully manufactured by direct machined using Wire-EDM in one block of metal. In comparison with the CP horn antenna proposed in [13] using EDM technology at 110 GHz, which is comprised of a series of hexagonal and transition waveguides, our proposed structure is considered to be much easier for design and fabrication at 300 GHz.

II. ANTENNA DESIGN AND CONFIGURATION

The geometry of a conical horn antenna is shown in Fig. 1. To design a conical horn for a desired gain "G" of 20 dBi at a 300 GHz design frequency (free space wavelength $\lambda_0 = 1$ mmλ_0), we use the following procedure [14]:

$$a_i = \frac{3\lambda}{2\pi} \tag{1}$$

$$a_o = \frac{\lambda}{2\pi}\sqrt{10^{(G_{dBi}+2.91)/10}} \tag{2}$$

$$R = \frac{4a_o^2}{3\lambda} \tag{3}$$

$$\theta = \sin^{-1}\left(\frac{a_o}{R}\right) \tag{4}$$

$$L = \frac{a_o - a_i}{\tan\theta} \tag{5}$$

where "a_i" is the radius of the throat horn, "a_o" is the radius of aperture horn, "R" is the slant length, "θ" is flare angle, and "L" length of conical horn.

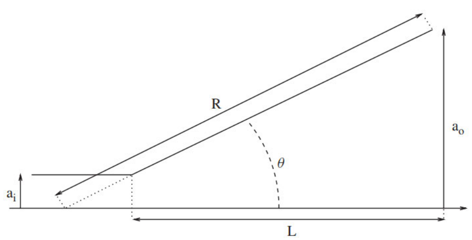

FIGURE 1. Conical horn geometry.

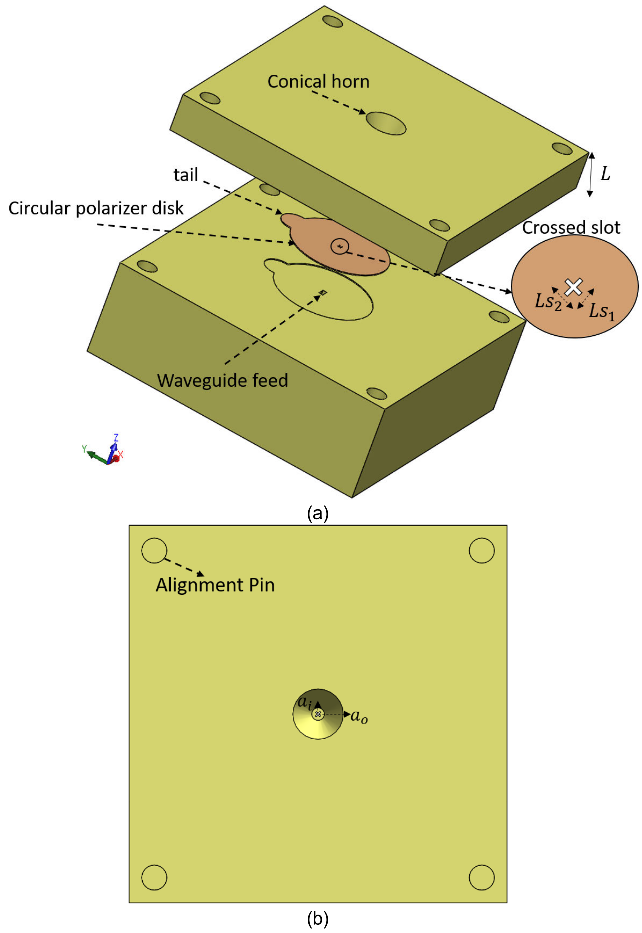

FIGURE 2. Structure of the proposed antenna (a) 3-D exploded view, (b) top view.

Fig. 2 illustrates the 3D geometrical view of the proposed antenna structure. The antenna consists of three components, which are waveguide feed, circular polarizer disk, and conical horn respectively. The waveguide feed is standard WR-03 rectangular waveguide works in WM-864 frequency band. This component, rectangular waveguide, works as feeding for the whole structure without using a transformer section from

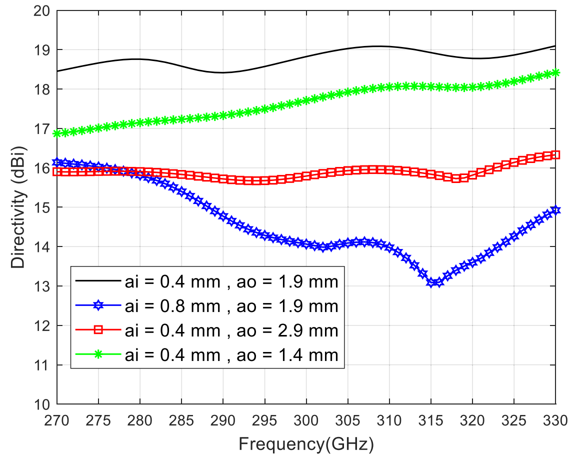

FIGURE 3. The directivity versus frequency for different dimensions of conical horn antenna.

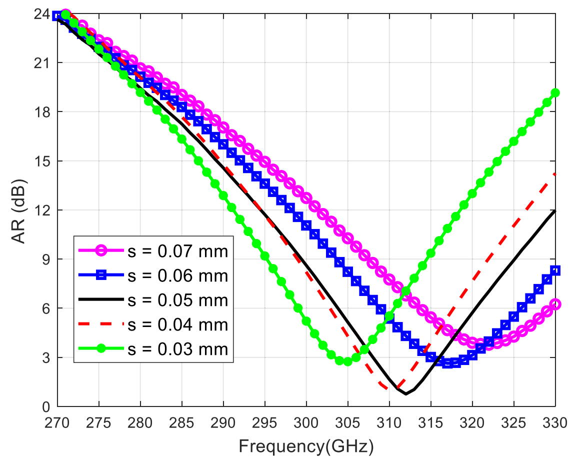

FIGURE 4. The axial ratio (AR) versus frequency for different lengths of crossed-slot antenna.

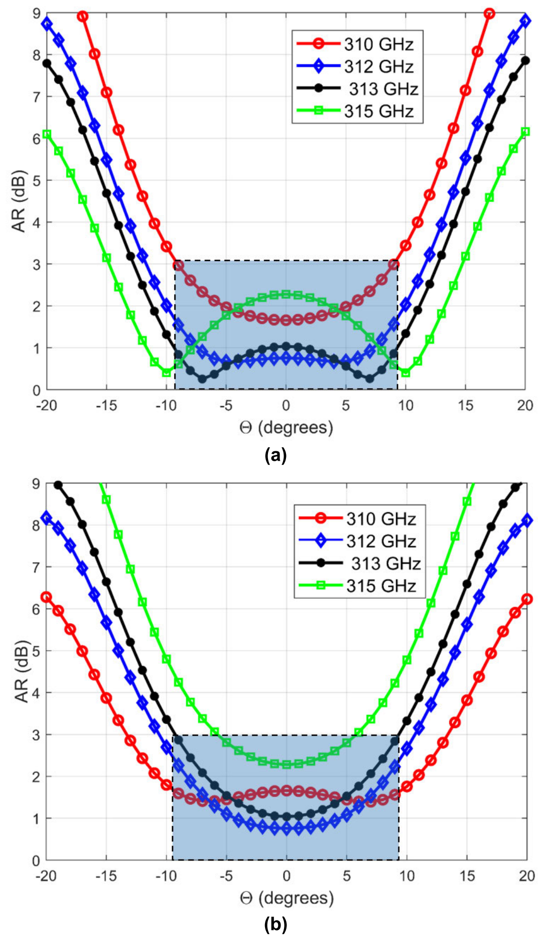

FIGURE 5. The simulated AR vs theta angle in (a) azimuth-plane, and (b) elevation-plane at different frequencies 310 GHz,312 GHz,313 GHz, and 315 GHz.

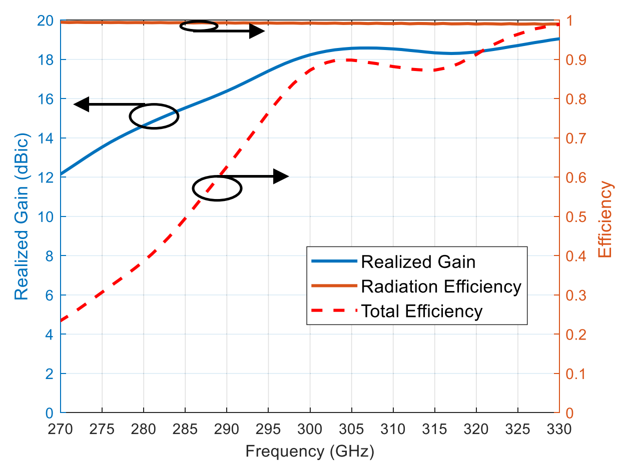

FIGURE 6. The simulated realized gain, radiation efficiency, and total efficiency versus frequency of the proposed antenna.

rectangular waveguide WR-03 to the circular waveguide in the input of conical horn.

The circular polarizer disk with a tail as shown in the Fig. 2(a) is crossed-slot antenna with unequal sub-wavelength lengths of $Ls_1 = 0.51$ mm, $Ls_2 = 0.46$ mm and a width of $W_s = 0.1$ mm, with thickness of 0.1 mm.

The conical horn element is a smooth walled conical horn antenna which is easier to manufacture at high frequencies (i.e. 300 GHz) compared to a corrugated walled which becomes complicated in terms of manufacturing process. For our desired gain of 20 dBi, the dimensions of the conical horn antenna were calculated by using (1-5). We found the optimum dimensions for the radius of horn throat is $a_i = 0.4$ mm, the radius of horn aperture $a_o = 1.9$ mm, and the conical horn axial length $L = 4$ mm.

The aperture "a_o" and throat "a_i" radii of the conical horn plays a very important role in the performance of the antenna such as directivity. We studied the effects of different dimensions of conical horn antenna in terms of directivity with respect to frequency as shown in Fig. 3. As the flare angle increases (in our study i.e. a_o), the directivity for an assumed horn length ($L = 4$ mm) increases until it reaches a maximum, beyond which it begins to decrease. The decrease

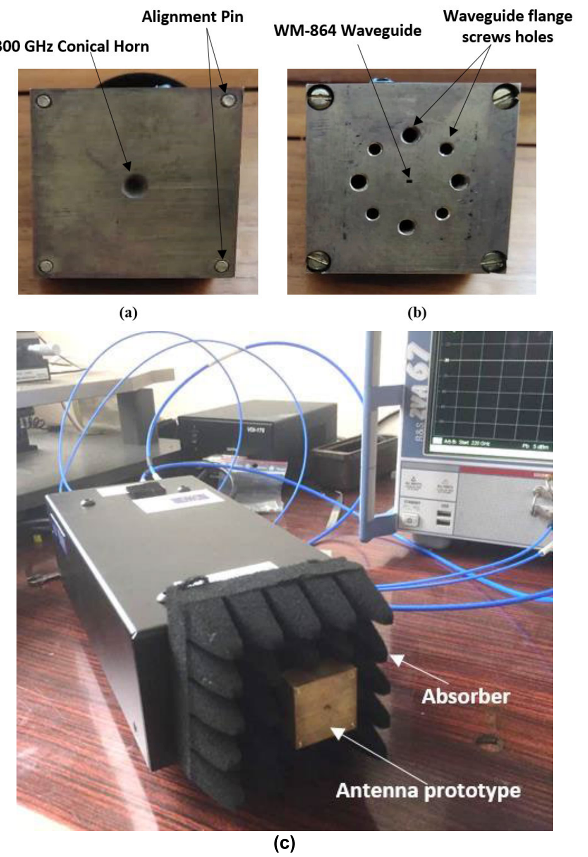

FIGURE 7. Pictures of the 300 GHz CP conical horn prototype fabricated by wire-cutting EDM (a) antenna prototype (top view) (b) feeding of antenna prototype (bottom view), and (c) antenna prototype with absorber mounted on a standard UG-387 waveguide flange.

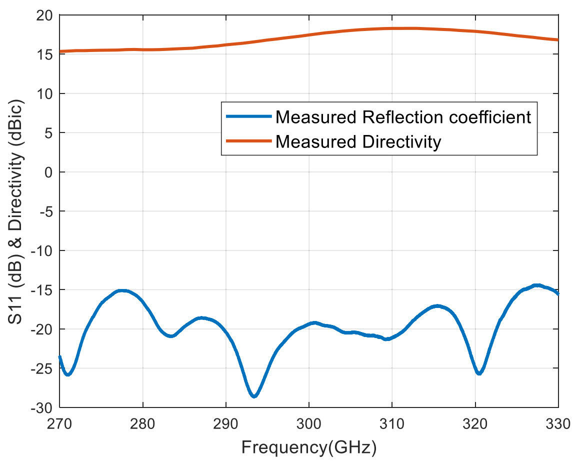

FIGURE 8. Measured reflection coefficient (S11), and directivity for the prototype of the 300 GHz CP horn antenna.

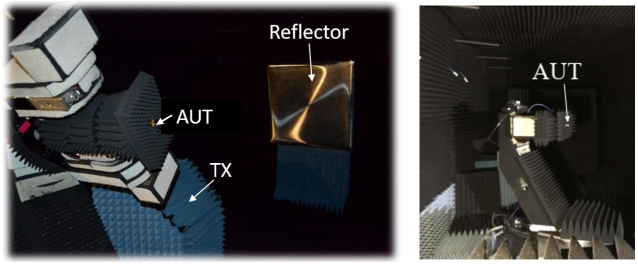

FIGURE 9. Antenna radiation pattern far-field measurement setup at IETR.

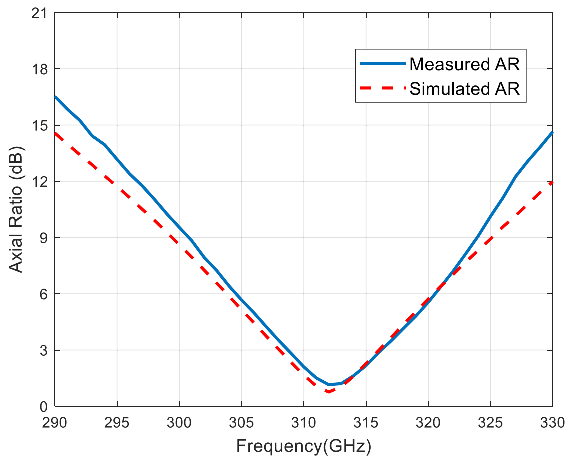

FIGURE 10. Axial ratio (simulated and measured) of 300 GHz CP conical horn antenna.

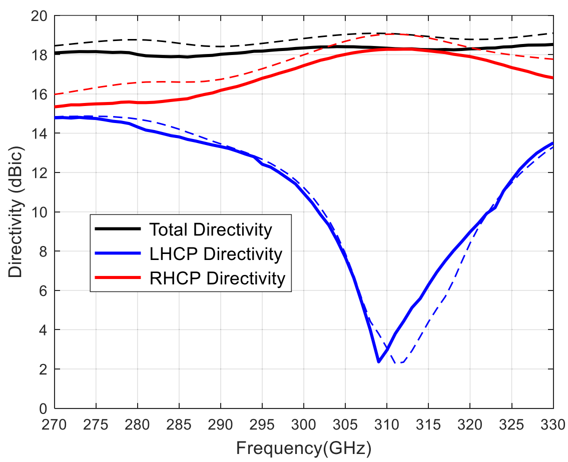

FIGURE 11. Measured (solid lines) and simulated (dashes lines) of total, RHCP, and LHCP directivities.

is a result of the dominance of the quadratic phase error at the aperture. From Fig.3 it's clear that a radius of horn aperture $a_o = 1.9$ mm and radius of horn throat $a_i = 0.4$ mm gives the highest directivity, which cover the desired bandwidth from 270 GHz to 330 GHz.

We noticed that the length of the crossed-slot of circular polarizer disk has a large impact on the AR as shown in Fig. 4. We fixed the length of slot 1 as ($Ls_1 = 0.51$mm) and change the length of slot 2 "Ls_2" by a fixed value of "s" with respect to Ls_1 (i.e. $Ls_2 = Ls_1 - s$). It is clear from Fig. 4 that a change in small value of "s" (20 μm) shifts the AR below 3 dB in frequency from 305 GHz to 312 GHz.

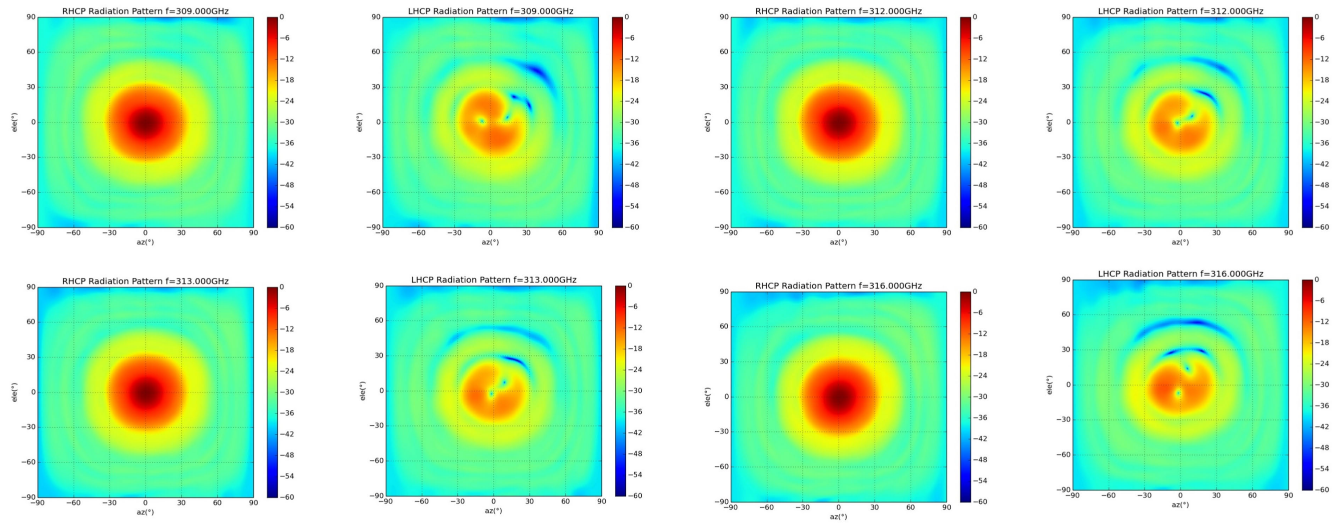

FIGURE 12. Measured normalized 2D co-polarization (RHCP), and cross-polarization (LHCP) radiation patterns of the proposed antenna at 309 GHz, 312 GHz, 313 GHz, and 316 GHz.

TABLE 1. Comparison between the proposed work with other latest CP Sub-Thz antenna.

Ref.	Antenna type	Frequency	3dB AR bandwidth	Max Gain (dBic)	Fabrication Technique	Remarks
[17]	Antipodal curvedly tapered slot	500 GHz	20 GHz	12.2	Silicon micromachining (Dielectric and metallization layers)	Low gain
[18]	Double-fan-shaped slot	500 GHz	10 GHz	12.5	Silicon micromachining (Dielectric and metallization layers)	Low gain
[13]	Hexagonal waveguide based horn antennas	110 GHz	~44 GHz	18	Wire-EDM (All metal)	Complex structure
[19]	Discrete dielectric lens	300 GHz	~55 GHz	30.8	3D printing (Dielectric layers)	Large size
This work	The proposed antenna	300 GHz	7 GHz	18.4	Wire-EDM (All metal)	Simple structure

The AR in azimuth plane is kept below 3dB on a range of angle theta "θ" up to $\sim \pm 10^\circ$ which covers the half power beam width (HPBW) equal to 18.5°, as defined in Fig. 5a. Also it is noted that in the elevation plane shown in Fig. 5b, the AR is less than 3dB over the whole main lobe, except for the highest value of frequency at 315 GHz. The maximum gain of the radiation pattern is equal to 18.4 dBic in both planes at broadside direction.

Fig. 6 illustrates the simulated realized gain, radiation and total efficiencies of the proposed antenna. The total efficiency is around 87.5%, radiation efficiency is 99%, and the realized gain is 18.5 dBic at 312 GHz.

III. FABRICATION PROCESS

There are three modern manufacturing technologies used to produce the antenna structure with very delicate components. These are Wire-cutting EDM, mechanical drilling, and laser-cutting. Wire-cutting EDM is a thermo-electrical process that uses a continuously moving metal wire (usually brass) used as an electrode (tool) to remove material by a series of sparks produced between the work piece and the electrode. A stream of dielectric fluid (deionized water) continuously flowing in the machining zone, is used to washed away tiny particles being eroded, regulate the discharge, and keep the wire and work piece cool. The wire and work piece must be electrically conductive [15], [16]. The waveguide feed and the conical horn were manufactured by wire-cutting EDM technique in a brass block with an electrical conductivity $\sigma = 35.86 \times 10^6$ Sm^{-1}. This Wire-cutting EDM is direct machining has features of simplicity and mechanical robustness, since the geometry of the proposed antenna is directly engraved onto the block of metal.We used mechanical drilling technology

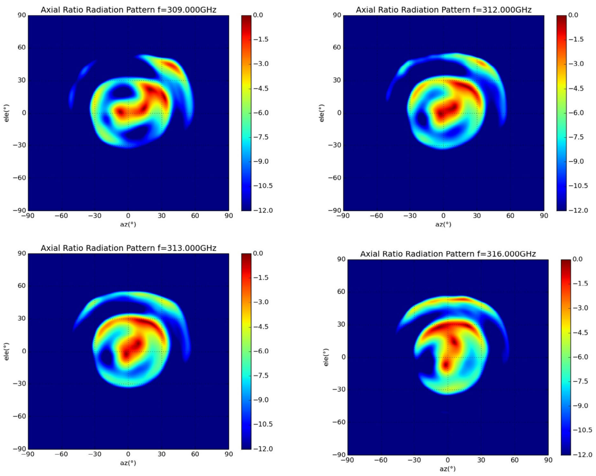

FIGURE 13. Measured normalized 2D axial ratio plots at 309 GHz, 312 GHz, 313 GHz, and 316 GHz.

for a novel footprint disk of circular polarizer with thickness of 100 μm and four hole alignments parts for the whole structure. Also in order to avoid the movement crossed slot in circular polarizer disk a small tail is provided as shown in Fig. 2 (a).A laser etching technique has been used to create crossed slot of circular polarizer disk in the proposed antenna as narrower as 100 μm (value of slot width) by using (LPKF ProtoLaser S 124102 laser machine). The infrared laser beam (λ = 1080 nm) is focused on the footprint disk of circular polarizer with thickness of 100 μm with the appropriate settings, such as laser scan speed (400 mm/s), laser spot size (25 μm $\times$ 25 μm) and fluency (10 W/spot). The final prototype of the fabricated proposed antenna is shown in Fig. 7. The circular polarizer disk with crossed-slot can be easily replaced by another disk with longitudinal slot; in this case the antenna will be linearly polarized.

IV. MEASUREMENT AND RESULTS

The measurement of 300 GHz CP conical horn antenna fabricated by Wire-cutting EDM showed that the reflection coefficient (S_{11}) less than −15 dB in the range of interest from 270 GHz to 330 GHz is as shown in Fig. 8. The measured right hand circular polarized (RHCP) directivity is 18.3 dBic at 312 GHz.

The far-field measurement setup based on a compact range millimeter-wave anechoic chamber facilities used at IETR is shown in Fig. 9.

The simulated and measured AR of the proposed antenna is shown in Fig. 10. The minimum measured AR at 312 GHz is 1.15 dB with the measured 3-dB AR bandwidth of 7 GHz between 309 GHz to 316 GHz being 2.3%. This shift in the frequency is due to the manufacturing tolerance. There is a good agreement between the simulated and measured results.

The measured directivity of the proposed antenna is given in Fig. 11, which is obtained by integrating the 3D measured

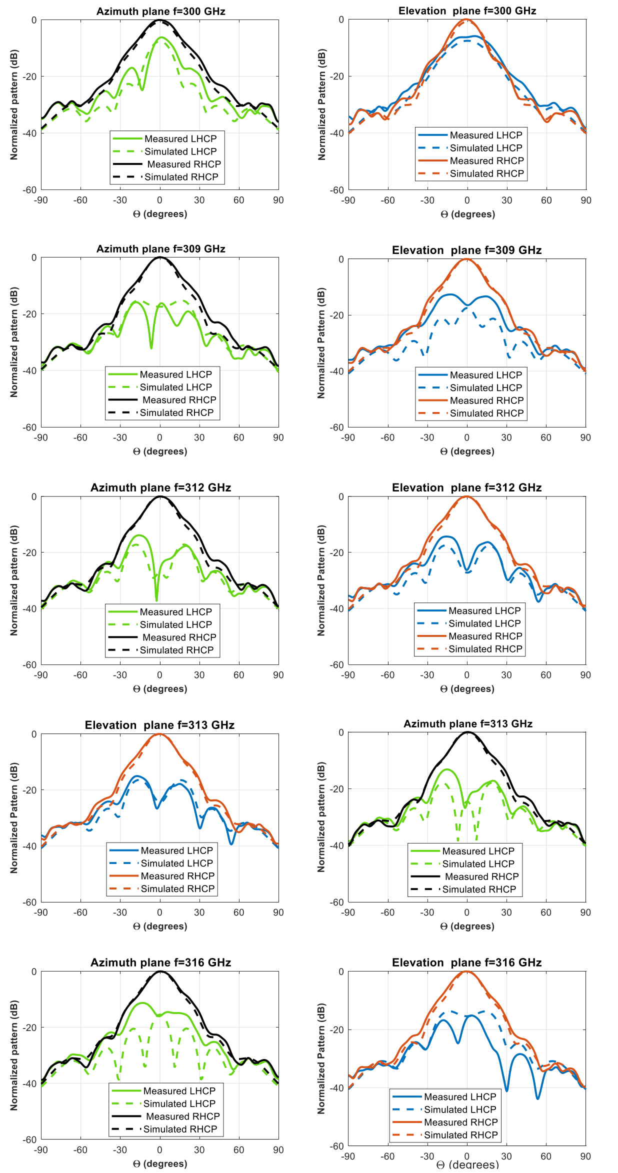

FIGURE 14. Measured and simulated normalized radiation patterns of the proposed antenna of the principle planes at different frequencies: f= 300 GHz, f = 309 GHz, f = 312 GHz, f =313 GHz, and f = 316 GHz.

radiation pattern of the antenna under test (AUT) over upper hemisphere. The measured broadside RHCP directivity reaches 18.3 dBic at 312GHz, while the simulated directivity is nearly 19 dBic. Also note that there is a good agreement between the simulated and measured results of the proposed antenna.

Fig. 12 shows the 2D measured far-field pattern of the proposed antenna in both principle planes (azimuth, and elevation), varying as a 2D plot with each point colored according to its normalized gain value in dB for the RHCP radiation pattern, and left hand circular polarized (LHCP) radiation pattern for different frequencies 309 GHz, 312 GHz, 313 GHz, and 316 GHz. It is noted that the antenna works as RHCP radiation pattern which is the co-polarization and LHCP radiation pattern which is cross-polarization. It's clear

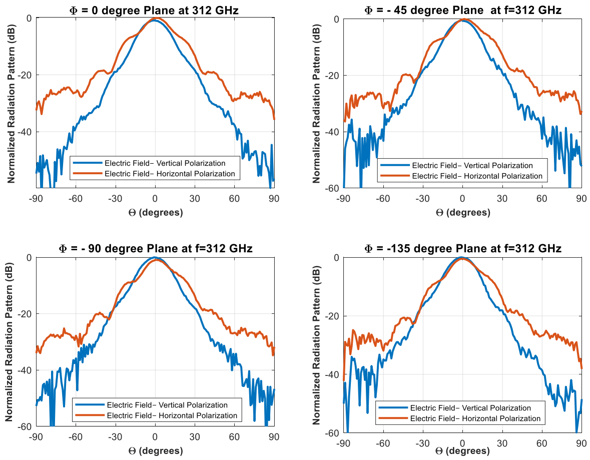

FIGURE 15. Measured normalized radiation patterns of the proposed antenna at different angles 0 degree, −45 degree, −90 degree, and −135 degree at 312 GHz.

from Fig. 12 that the measured normalized gain occurs at broadside direction, which is equivalent to azimuth (az = 0°) and elevation (ele = 0°).

Fig. 13 illustrates the 2D measured AR plots of the proposed antenna at 309 GHz, 312 GHz, 313 GHz, and 316 GHz. The AR is kept below 3 dB within the scope of the main beam between −10° to 10° at broadside direction for frequencies shown here in this figure (309 GHz, 312 GHz, 313 GHz, and 316 GHz, respectively). The AR reaches lower value near to 1 dB at 312 GHz, and 313 GHz as shown in figure by the black color in bar right the plot.

The measured and simulated normalized RHCP radiation patterns of the proposed antenna in both the azimuth plane and elevation plane at 300 GHz, 309 GHz, 312 GHz, 313 GHz, and 316 GHz are given in Fig. 14. It can be seen that, because of the symmetry of the antenna, measured radiation patterns of both planes are similar, and agree well with the simulated results. The normalized cross-polarization pattern plots (LHCP) of the proposed antenna are also given in Fig. 14. The maximum isolation between the co-polarization RHCP and its cross-polarization LHCP is more than 10 dB except at 300 GHz. The measured cross polarization levels are better than 20 dB below the main beam at the broadside direction at 312 GHz, and 313 GHz. The first sidelobe levels of the normalized RHCP radiation pattern is below −20 dB at the measured frequency.

The measured normalized radiation patterns at 312 GHz of the proposed antenna over a wide range of cut-plane observation angles at 0 °, −45 °, −90 °, and −135 ° are shown in Fig. 15. There is a good agreements of radiation patterns at different cut-planes of varied φ angles, which suggest that the proposed antenna has good CP radiations. The radiation pattern exhibits excellent stability with respect to the azimuthal angle φ (0°, −45°, −90°, and −135°), and good symmetry is also observed in the elevation planes. Similar results were also observed between 309 GHz to 316 GHz and the AR is below 3 dB. For brevity not all plots have been included.

V. CONCLUSION

A Sub-THz CP conical horn antenna fabricated by direct machining in one block of metal using Wire- EDM technique operating at 300 GHz was presented. Circular polarization was achieved by exiting two orthogonal modes though the crossed slot of circular polarizer disk of the proposed antenna. The antenna yields a measured impedance bandwidth of 60 GHz from 270 GHz to 330 GHz. The measured directivity of 18.3 dBic at broadside direction at 312 GHz. The measured 3-dB AR bandwidth of 7 GHz from 309 GHz to 316 GHz. Radiation patterns of the fabricated Sub-THz CP conical horn antenna have been measured and results agree well with the simulations. This antenna finds potential application in Tbps wireless communication at Sub-THz frequency band. Table 1 gives a comparison among different CP antennas in Sub-THz band. Some key parameters are listed, including working frequency band, 3dB AR bandwidth, maximum gain, and technology of fabrication. The results show that our antenna is currently the first one antenna, which is achieved with very simple all metal structure with a compact size in Sub-THz band using Wire-EDM techniques. The measured results proved that manufacturing parts have a high precision.

REFERENCES

[1] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, A. Alkhateeb, and G. C. Trichopoulos, "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019.

[2] M. Saad, F. Bader, J. Palicot, Y. Corre, G. Gougeon, and J.-B. Dore, "Beyond-5G wireless Tbps scenarios and requirements," French Funded Project-ANR-17-CE25-0013 BRAVE, Tech. Rep. BRAVE D1.0, 2018.

[3] T. Tajima, H.-J. Song, K. Ajito, M. Yaita, and N. Kukutsu, "300-GHz step-profiled corrugated horn antennas integrated in LTCC," *IEEE Trans. Antennas Propag.*, vol. 62, no. 11, pp. 5437–5444, Nov. 2014.

[4] Z. Wu, M. Liang, W.-R. Ng, M. Gehm, and H. Xin, "Terahertz horn antenna based on hollow-core electromagnetic crystal (EMXT) structure," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5557–5563, Dec. 2012.

[5] N. Chahat, T. J. Reck, C. Jung-Kubiak, T. Nguyen, R. Sauleau, and G. Chattopadhyay, "1.9-THz multiflare angle horn optimization for space instruments," *IEEE Trans. Terahertz Sci. Technol.*, vol. 5, no. 6, pp. 914–921, Nov. 2015.

[6] C. Lee, D. Gonzalez-Ovejero, M. Alonso-delPino, T. Reck, A. Peralta, I. Mehdi, and G. Chattopadhyay, "Corrugated (2×2) silicon platelets horn antenna array at 560 GHz," in *Proc. 42nd Int. Conf. Infr., Millim., Terahertz Waves (IRMMW-THz)*, Aug. 2017, p. 1.

[7] J. W. Britton, J. P. Nibarger, K. W. Yoon, J. A. Beall, D. Becker, H.-M. Cho, G. C. Hilton, J. Hubmayr, M. D. Niemack, and K. D. Irwin, "Corrugated silicon platelet feed horn array for CMB polarimetry at 150 GHz," *Proc. SPIE*, vol. 7741, Jul. 2010, Art. no. 77410T.

[8] J. P. Nibarger, J. A. Beall, D. Becker, J. Britton, H.-M. Cho, A. Fox, G. C. Hilton, J. Hubmayr, D. Li, J. Mcmahon, M. D. Niemack, K. D. Irwin, J. Van Lanen, and K. W. Yoon, "An 84 pixel all-silicon corrugated feedhorn for CMB measurements," *J. Low Temp. Phys.*, vol. 167, nos. 3–4, pp. 522–527, May 2012.

[9] D. Hotte, Y. Duroc, S. Tedjini, and R. Siragusa, "Directive and high-efficiency slotted waveguide antenna array for V-band made by wire electrical discharge machining," *Electron. Lett.*, vol. 51, no. 5, pp. 380–382, Mar. 2015.

[10] A. Vosoogh, P.-S. Kildal, and V. Vassilev, "A multi-layer gap waveguide array antenna suitable for manufactured by die-sink EDM," in *Proc. 10th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2016, pp. 1–4.

[11] X. Cheng, Y. Yao, J. Hirokawa, T. Tomura, T. Yu, J. Yu, and X. Chen, "Analysis and design of a wideband endfire circularly polarized septum antenna," *IEEE Trans. Antennas Propag.*, vol. 66, no. 11, pp. 5783–5793, Nov. 2018.

[12] C. Lee, G. Chattopadhyay, E. Decrossas, A. Peralta, I. Mehdi, C. A. Leal-Sevillano, M. A. Del Pino, and N. Llombart, ''Terahertz antenna arrays with silicon micromachined-based microlens antenna and corrugated horns,'' in *Proc. Int. Workshop Antenna Technol. (iWAT)*, Mar. 2015, pp. 70–73.
[13] S. Bhardwaj and J. L. Volakis, ''Hexagonal waveguide based circularly polarized horn antennas for Sub-mm-Wave/Terahertz band,'' *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3366–3374, Jul. 2018.
[14] C. A. Balanis, *Modern Antenna Handbook*. Hoboken, NJ, USA: Wiley, 2011.
[15] C. Sommer and S. Sommer, *Complete EDM Handbook*. Houston, TX, USA: Advance Publishing, 2017.
[16] J. Singh, R. Singh, and R. Kumar, ''Review on effects of process parameters in wire cut EDM and wire electrode development,'' *Int. J. Innov. Res. Sci., Eng. Technol.*, vol. 2, pp. 701–706, Apr. 2016.
[17] Y. Liu, H. Lu, Y. Wu, M. Cui, B. Li, P. Zhao, and X. Lv, ''Millimeter-wave and terahertz waveguide-fed circularly polarized antipodal curvedly tapered slot antennas,'' *IEEE Trans. Antennas Propag.*, vol. 64, no. 5, pp. 1607–1614, May 2016.
[18] P. Zhao, Y. Liu, H. Lu, Y. Wu, and X. Lv, ''Experimental realization of terahertz waveguide-fed circularly polarized Double-Fan-Shaped slot antenna,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2066–2069, 2017.
[19] G. B. Wu, Y.-S. Zeng, K. F. Chan, S.-W. Qu, and C. H. Chan, ''High-gain circularly polarized lens antenna for terahertz applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 5, pp. 921–925, May 2019.

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