# Compact Bull's-Eye Antenna in Ridge Gap Waveguide with Circular Polarization at 60 GHz

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***Abstract*— In this work, a Bull's-Eye (BE) antenna with circular polarization (CP) based on ridge gap waveguide (RGW) technology, working in the millimeter-wave band (60 GHz) is numerically and experimentally demonstrated. The structure is coupled through a step transition to a ridge-line that ends in two orthogonal arms of different lengths to generate CP. The wave is coupled to the top plate by a central diamond slot surrounded by the BE structure, which consists of four concentric periodic corrugations around the slot. Simulations and experimental results are in good agreement, with practical bandwidth of 6.8% with respect to center frequency and peak gain of 18.4 dB. The antenna has right-handed CP (RHCP) with polarization discrimination of more than 30 dB.**

**Index Terms—** ***Bull's-eye (BE) antenna, circular polarization (CP), ridge gap waveguide (RGW) technology, millimeter waves.***

## I. Introduction

Leaky wave antenna (LWA) have been study in deep for a long time [1]. Bull's-Eye (BE) antennas [2] are a special part of the larger family of periodic LWA, most of them consist of a metallic plate with a central slot surrounded by concentric corrugations. BE antennas has an interesting characteristic, it usually radiate at broadside direction with a great gain, removing the classical limitations of LWA which is the open-stop band effect that precludes radiation at broadside [3]. Designing the periodic corrugations in such a way that each half of the BE antenna radiates at opposite directions but in angles very close to broadside, giving rise to a single lobe by merging the radiation of both halves.

BE antennas have been considered as a simple alternative to horns and parabolic antennas. Several examples at microwave frequencies give proof of it [4], [5]. However, as the operation frequency is increased towards millimeter-waves, fully metallic designs are preferred to avoid dielectric losses and BE antennas follow the classical implementation of a periodic ring structure around a central slot fed by a standard waveguide attached to the back plate [2]. A high gain BE antenna was designed in [6], using an aluminum plate craved with a sinusoidal profile working at 77 GHz and following it achieve 28.9 dB of gain. Following the classical procedure a large number of corrugations was implemented as consequence a large area and low aperture efficiency was achieved. In [7], this limitations was remove, optimizing the

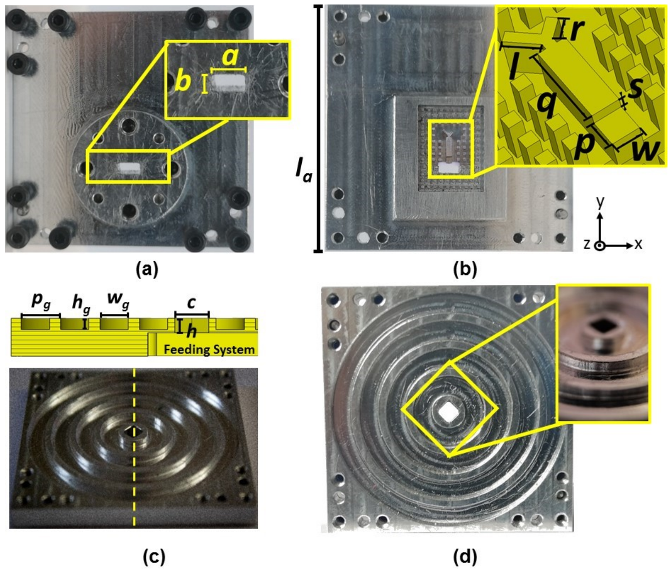


Fig.1 Photographs and schematics showing the fabricated BE antenna. (a) Bottom view of WR-15 waveguide connection. (b) Feeding system. (c) Top view radiation plate. (Inset) Front plane cut (d) Top view of concentric periodic corrugations around the diamond-shaped slot.

resonant modes inside the grooves in such way a gain around 20 dB was obtained with just two corrugations. In this case, the aperture efficiency increase to 32% in a prototype operating at 60 GHz.

In [8] a variant using a low-cost 3-D printing stereolithography technique was designed. As alternative to the traditional manufacture techniques this BE antenna operating at 96 GHz was experimentally study; even with those limitations, a significant gain around 17 dB was achieve.

Most of the BE antennas reported to date have linear polarization due to the good adaptability with a traditional waveguide hollow and usually the source used is a rectangular slot. The first approximation to design a BE antenna able to generate circular polarization (CP) is presented in [9], using a central cross-shaped slot with orthogonal arms of the same length. Certainly, this design can couple a CP wave, it is unable to generate itself CP. Rather, a pair of orthogonal modes in quadrature must be previously generated (for instance, with an orthomode transducer) and coupled afterwards to the cross-shaped slot to radiate a CP wave.

The first limitation to generate CP in BE antennas is the feeding system. As alternative and with the objective to design a BE antenna able to generate CP is study the Gap waveguide (GW) technology [10], [11]. GW technology has gained a lot of interest since it is a reliable and competitive alternative for high-frequency communications. Amongst the most important characteristics of GW technology is that it does not need electric contact between the bottom and top plates and tolerances are coarser, keeping at the same time a fully metallic structure to avoid dielectric loss. Furthermore, GW technology is naturally adapted to low-profile planar structures, fitting perfectly with the design guidelines of BE antennas.

TABLE I
DESIGN PARAMETERS

| *Parameter* | *Description* | *Values (mm/λ₀*)* |
|---|---|---|
| $l_a$ | Length of antenna | 40.0 / 7.80 |
| $p$ | Step length | 1.05 / 0.20 |
| $s$ | Step height | 0.38 / 0.07 |
| $w$ | Step width | 1.00 / 0.20 |
| $c$ | Slot diagonal | 3.75 / 0.73 |
| $h_g$ | Corrugation height | 1.28 / 0.25 |
| $p_g$ | Corrugation period | 4.36 / 0.85 |
| $w_g$ | Corrugation width | 3.13 / 0.61 |
| $b$ | WR-15 height | 1.90 / 0.37 |
| $a$ | WR-15 width | 3.18 / 0.62 |
| $r$ | Right arm length | 0.78 / 0.15 |
| $l$ | Left arm length | 1.28 / 0.25 |
| $h$ | Top plate height | 1.62 / 0.32 |

*$\lambda_0$ = 5.1 mm at 58.5 GHz

In [12], we demonstrated a diamond slot antenna able to intrinsically produce CP using GW technology. A mechanism simple and effective to generate circular polarization using one of three variant (Ridge Gap Waveguide) of GW was developed. It was also demonstrated in that paper, that the gain could be increased by incorporating a horn taper and a circular groove around the central slot, reaching a value of 11.12 dB at 67.3 GHz.

However, even in the optimal case, a significant fraction of the top plate area contributed little to the overall antenna gain, as most of the effective radiation was limited to the surroundings of the slot. Therefore, the idea to combine the diamond slot antenna of [12] and BE geometry covering maximally the top metallic plane can merge together three important concepts: generating CP in a simple way, using GW technology and demonstrating a high-gain in a single antenna without the need of using antenna arrays, which require a complex feeding network[13], [14].

In this investigation we design and manufacture a BE antenna with CP in ridge gap waveguide (RGW) technology. The structure fed from the bottom using WR-15 waveguide to RGW transition generate CP by two orthogonal arms with different lengths in the end of ridge line. The top plate, contains four concentric periodic corrugations around the diamond-shape which induce a gain of 18.4 dB at 58.5 GHz with an aperture efficiency of 9%. An excellent polarization purity with an axial ratio (AR) below 1 dB at the central frequency is achieved. The antenna has right-handed CP (RHCP) with polarization discrimination of more than 30 dB.

## II. EASE OF USE

The antennas in this paper were designed and optimized to operate in the V-band of millimeter-waves, specifically from 55 to 70 GHz, using The Transient Solver of the commercial simulator CST Microwave

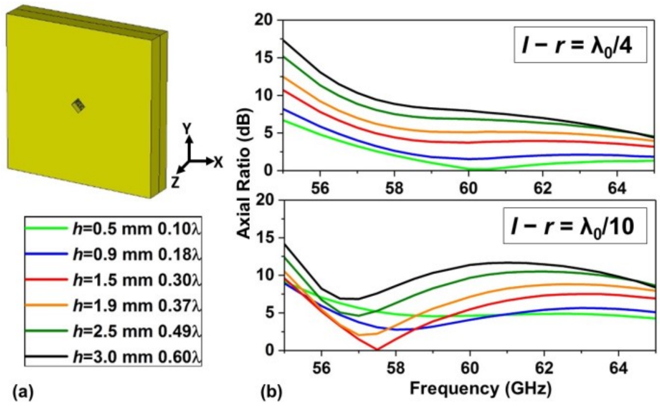


Fig. 2 Parametric study of the AR magnitude as the height of the top metallic plate. (a) The value of $h$ is varied between 0.5 and 3 mm (corrugations have been removed for simplicity). (b) Arms length difference equal to $\lambda_0/4$. and $\lambda_0/10$.

The Transient Solver of the commercial simulator CST Microwave Studio® was used to operate in the V-band of millimeter-waves, specifically from 55 to 65 GHz. Photograph of the fabricated prototype is shown in Fig. 1. The material employed the structure is aluminum, due to its good conductivity in the operation band (σAl = 3.72×106 S/m), mechanical robustness and compatibility with standard manufacturing techniques. In addition, the antenna was manufactured using Standard Computer Numerical Control (CNC) milling machine method.

The structure is fed from the bottom by means of a standard WR-15 waveguide to make it compatible with standard measurement systems based on vector network analyzers. Fig. 1(a) shows the WR-15 waveguide ($a \times b$) connection from the bottom. Fig. 1(b) shows the WR-15 to RGW transition used to couple the wave to the RGW. This transition has a very simple design, it consists of a step of height s and length $p$, as shown in the top view of the feeding network in Fig. 1(b), and the values are specified in Table I. In this paper a different transition feeding that used in [12] was implemented, due to this solution is simpler and easier to fabricate; as demonstrated in [15] the transition has an excellent matching with a reflection coefficient below −10 dB and extremely small insertion loss. Fig. 1(c) and inset show the top plate of the antenna with four concentric periodic corrugations of period $p_g$, depth $h_g$ and width $w_g$ filling maximally the metallic plane around the central diamond-shaped slot of diagonal $c$ and a slot cavity height $h$. Below this cavity shaped by the slot and corrugations the feeding system is placed, inset Fig. 1 (c). Finally, Fig. 1(d) and inset show in detail as the four corrugations cover all the top plate of the antenna, approaching this area in the radiation of the system.

In [12] was explained in deep the way to generate CP with this composition, a difference between the two orthogonal arms at the end of the ridge (*r* and *l*) of nearly $\lambda_0/4$ give rise to a phase difference of 90º and therefore to a CP at the output. In this cases is a little different, due to BE antenna has corrugations in the top plate and it supposes an increment of thickness. Therefore, the new cavity created induce a length difference between both arms is 0.5 mm which is only $\lambda_0/10$ ($l = 1.28$ mm and $r = 0.78$ mm). In order to study this disagreement, we did a parametric study varying *h* while keeping a constant difference between arms of $\lambda_0/4$, checking the influence on the AR (note that, without loss of generality, in this study the grooves were removed for simplicity, Fig. 2(a)). The inset of Fig. 2(a) shows the different highs studied and Fig. 2 (b) shows the parametric results for both cases ($\lambda_0/4$ and $\lambda_0/10$). In $\lambda_0/4$ case, for small values of *h* (< 0.9 mm) the structure behaves satisfactorily with low AR (AR < 3 dB) in good agreement with the results of [12], but when *h* increases beyond 0.9 mm the AR degrades rapidly. Using a difference between arms of $\lambda_0/10$ the best AR is achieved with $h = 1.5$ mm ($0.3\ \lambda_0$). These results suggest that the slot height has some non-trivial effect on the phase difference achieved between orthogonal linear components.

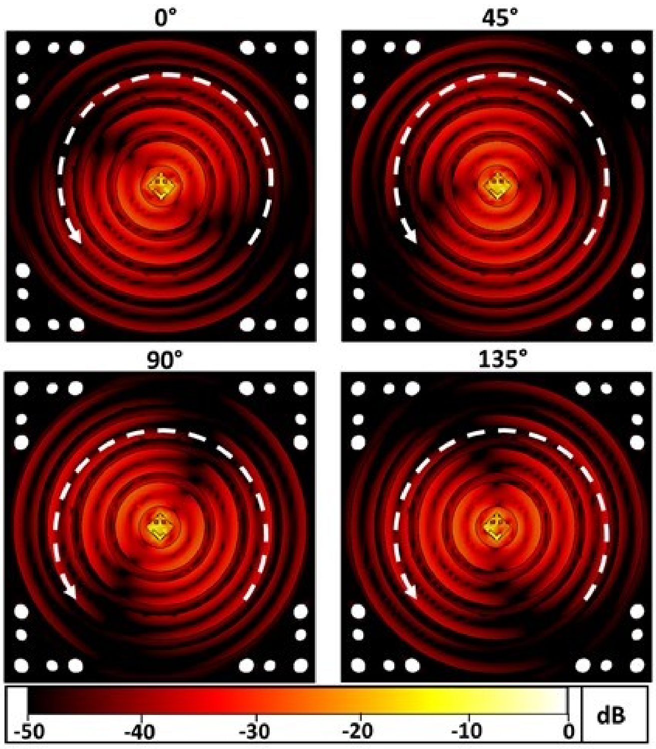


Fig. 3 Upper view of the surface current magnitude on the BE antenna at 58.5 GHz and four different snapshots.

Up to this point, we have a feeding system working at the operation frequency, a length difference between arms able to generate CP and once the wave is coupled through the slot (of side $\lambda_0/2$ to guarantee good radiation) we can generate CP in the system. Fig. 3 shows the surface current representation on the top plate. The physical mechanism of BE antennas is based on LW excitation and has been extensively described in the past [16]. In the present case, wide grooves were implemented, as they lead to higher gain values as explained in detail in [11], [17]. The grooves support a resonance at the operation frequency (Fig. 3), contributing to the enhancement of gain at broadside. It is also clear that the currents follow a circular shape describing a right-handed CP (RHCP) pattern.

## III. Prepare Your Paper Before Styling

The measurements were performed in an anechoic chamber. A PNA network analyzer E8361C (Agilent Technologies) was used in the frequency range from 55 to 65 GHz and the frequency span was discretized with steps of 50 MHz. The radiation patterns were measured by placing a transmitting horn antenna with linear polarization (Mi-Wave 261) at a distance of 2000 mm (the farfield distance at the operation frequency is 1260 mm) from the antennas under test (AUTs). In each of these positions, the AUT was swept in elevation from −90° to 90° with a step of 0.5°. As the test antenna (Mi-Wave 261) has linear polarization, in each measurement it was rotated in plane at orthogonal positions and from the recorded curves, the CP characteristics of the AUT were obtained.

Fig. 4 shows the main simulation and measurement results. As shown in the solid blue curve of Fig. 4(a), good matching is obtained in all the considered BW with $S_{11} < -10$ dB from 54.3 to 63.7 GHz, which represents a fractional BW of 16.2%, in good agreement with the simulation results (dashed blue curve).

The gain, AR and radiation patterns of the antenna were measured by before method explain, remembering that in AR case, two different measurements were taken at each point by rotating the horn antenna (Mi-Wave 261) in two orthogonal positions. This is required because the test antenna has linear polarization and we need both orthogonal components to retrieve the CP response in the post-processing, which is based on the method described in [18]. Fig 4(a) marron curve shows the AR achieve; taking as a criterion that the wave has CP when the AR is below 3 dB. In this case, we find that the CP BW goes from 57.7 to 61.4 GHz, which represents a fractional BW of 6.3%. The minimum value (0.59 dB) is around 60 GHz.

The measured gain is shown in Fig.4 (a) red solid curve, it was obtained applying the gain transfer method particularized to antennas with arbitrary polarization [18], [19]. The simulation results (red dashed curve) has a good agreement with measured gain (red solid curve), achieving a peak gain of 18.4 dB at 58.5 GHz (which is the frequency of minimum AR) and aperture efficiency of 9%, above the typical value of BE antennas.. Certainly, the gain decays away from the operation frequency, as typically happens in BE antennas. Fig 4(b) shows a summary of the main characteristic of this antenna measured; clearly a practical bandwidth of 6.8% with respect to the center frequency is achieve. In this case, the gain is above of 10 dB in all the practical bandwidth, very good results for applications of the narrow band.

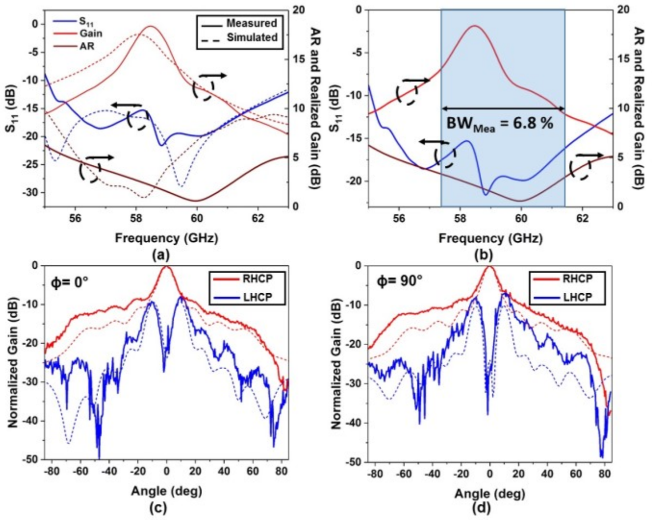


Fig. 4. Simulated (dashed curves) and experimental (solid curves) results of the BE antenna. (a) Reflection coefficient magnitude (blue curve), axial ratio (marron curve).and realized gain at broadside (φ = 0° and θ = 0°). (b) Main characteristics of BE antenna measured with a practical bandwidth of 6.8%. Co-polarized and cross-polarized radiation pattern at 58.1 GHz, (c) φ = 0°, (x-z plane) (d) φ = 90°, (y-z plane). The reference coordinate axes are the same in all figures and are shown in the Fig. 1(b).

TABLE II
COMPARISON BETWEEN DIFFERENT MILLIMETER-WAVE ANTENNAS

| Ref | Size (mm/λ) | Number of Elements | Fractional BW (Total BW)* | Fractional BW (Total BW)+ | Peak Gain-(GBW) # |
|---|---|---|---|---|---|
| [12] | 80 × 63 (16 × 13) | 16 × 16 | 14% (57 - 66) | 5.0% (59-62) | 32.3 (96.9) |
| [20] | 2.4 × 2.4 (0.5 × 0.5) | 4 × 4 | 14.1 % (56 – 65) | 21.1% (55-68) | 19.5 (253.5) |
| [14] | 30 × 30 (6.0 × 6.0) | 1 × 1 | 14.64 % (60.3-69.6) | 17.32% (60-71) | 11.12 (122.3) |
| BE | 40 × 40 (7.8 × 7.8) | 1 × 1 | 16.16 % (54.3 – 63.7) | 6.3% (57.7 - 61.4) | 18.4 (68.0) |

* Defined as S11 < −10 dB. Total BW is in GHz
+Defined as AR < 3 dB. Total BW is in GHz
# Peak Gain is in dB. For the gain-bandwidth product (GBW) calculation, the BW is defined as AR < 3 dB

Finally, Fig. 4(c) and (d) show the co-polarized and cross-polarized radiation patterns at 58.1 GHz, analyzed in two different planes: Fig. 4(c) φ = 0° (x-z plane); and Fig. 4(d) φ = 90° (y-z plane). The experimental results show an excellent polarization isolation of more than 30 dB at broadside, a main lobe of beamwidth equal to 11º and a small side lobe level of −9.7 dB in both cutting planes, in good agreement with the simulation results. These results improve our previous diamond-horn-groove (DHG) antenna discussed in [19] thanks to the addition of the BE structure, which optimizes the radiation on the top plane.

Table II present a brief comparison between our design and other CP antennas reported in the literature that operate at millimeter waves [12], [14], [20]. Analyzing it we can see that our BE antenna in general, has a good radiation characteristic, competitive value of gain (18.4 dB) and 6% AR bandwidth. Note that this gain is similar to that achieved by antenna arrays, which are comparatively more complex that our BE antenna based on a single radiating element and a simple feeding network. In addition, it is usual in BE antennas, the operation bandwidth (6%; we take here the AR BW as it is the interesting one for applications) is narrow, impacting directly in the gain-bandwidth product (GBW), although there are other examples in the Table in which it is even narrower. Therefore, from this quantitative comparison we can validate that the designed BE antenna can be a good alternative for moderate gain and narrowband applications at 60 GHz.

## IV. CONCLUSIONS

To sum up, in this paper we have designed and manufactured a BE antenna with CP operating at 60 GHz based on RGW technology. We have demonstrated that a combination of two arms of different lengths in the feeding system and the BE technology study, allows the generation of CP in a simple way achieving a high gain value. The simulated and experimental results are in good agreement, demonstrating good radiation characteristics with a compact and low profile structure. A high gain of around 18.4 dB at 58.5 GHz, with an aperture efficiency of 9% is obtained with a design of just (40 mm × 40 mm). A good CP purity with an AR of 0.59 dB at 60 GHz is demonstrated. More than 30 dB of cross-polarization isolation is observed in the measured radiation patters, with a main lobe beamwidth equal to 11º and small side lobe level of −9.7 dB. The resulting antenna is small and very compact with excellent radiation characteristics. This is the first BE antenna based on RGW technology, able to generate CP by itself and be used in narrowband applications at millimeter-waves.

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