V-band “Bull's eye” antenna for CubeSat applications

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***Abstract*— We simulate and measure the radiation pattern of a V-band “Bull’s eye” antenna for communication between CubeSats. We also propose a modification that allows the beam direction to be arbitrarily chosen over a ±20° range, useful for swarms where CubeSats must communicate with more than one neighbour. The “Bull’s eye” antenna offers high gain in a low profile, which makes it readily integrable into a CubeSat chassis. We study the relationship between the number of indented rings, and overall gain, for emission along the boresight, finding seven rings is optimal. Anechoic chamber pattern measurements show good agreement between measurement and simulation for both E-plane and H-plane. The simulated gain is 19.1dBi at the intended operating frequency of 60GHz, and is better than 16.7dBi over the 5.06GHz bandwidth, with a 19.7dBi peak gain, and the resonant frequency is centered at 60.08GHz with S11 parameter of -55.4dB. We simulate designs with centre-shifted rings, indicating smoothly increasing beam deflection with ring offset, and maximum deflection of 19.8° (16.1°) in E-plane (H-plane) at the maximum shift of one indentation width.**

***Index Terms*—Low-profile antenna, CubeSat antenna, inter-satellite communication, bull's eye, beam deflection.**

I. Introduction

CUBESATS are small satellites that will eventually operate in swarms by using point-to-point or multipoint-to-point communication in order to spread the risks, costs and tasks of the mission (e.g. Edison Demonstration of Smallsat Networks (EDSN), and the European CubeSat Project QB50 [1]). An inter-CubeSat communication system should support high data rates, e.g. uncompressed video, between the nodes of the network. Compact, inexpensive chipsets are emerging for use in the 57-64GHz unlicensed wireless systems band, which would also suit the 59-71GHz inter-satellite band, if they could be paired with a suitable antenna. Unfortunately, standard CubeSats are small (10cm x 10cm x 10-30cm) and even operating at V-band, a high-gain horn antenna takes up to 3cm x 4cm x 7cm, so a low-profile alternative is preferred. A promising candidate, the “Bull’s eye” structure, has been explored in both optics [2,3] and low microwave frequencies [4,5], but not at V-band frequencies when excited by a rectangular waveguide [6].

In this Paper, we present the design, simulation and measurement of a “Bull’s eye” antenna for CubeSat applications. We advance the state-of-the-art by demonstrating fabrication using readily available workshop equipment, directly comparing measured beam pattern with simulation, and quantifying the relationship between number of rings and overall gain. We further show that the main beam can be deflected by progressively offsetting (shifting) the centre of the rings. Until recently directive antennas were not preferred on CubeSat mission but latest commercial Altitude Determination and Control Systems exhibit accurate pointing specifications [7]. Hence, in order to fully exploit the large bandwidth (which comes at a price of lower receiver sensitivity) yet keep an extended communication distance, a directive antenna is seen as a good solution for an inter-CubeSat communication scenario.

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II. Design and Simulation

For our “Bull’s eye” antenna, we chose the frequency of operation to be 60GHz so as to match both the inter-satellite communication band (59-71GHz) and the measurement capabilities of our equipment (<67GHz). Moreover, typical 60GHz unlicensed band chipsets offer 500-1500MHz bandwidth per channel. 60GHz was hence a good trade-off for the center frequency of our antenna.

The dimensions of the antenna are illustrated in Fig. 1, where the side length L_{side} and the thickness h of the plate are respectively 100mm and 3.2mm, with 10mm x 10 mm cut-outs in the four corners to match the CubeSat chassis.

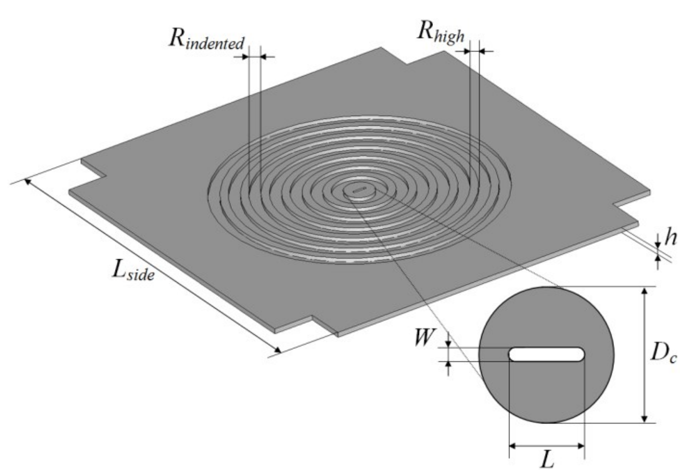


Fig. 1. Dimensions of the “Bull’s eye” antenna

Starting from a scaled version of the antenna presented in [8], the dimensions were adjusted by hand until simulations showed they produced maximum gain within these constraints. Simulations were conducted using CST Microwave Studio's frequency domain solver.

The resulting optimized dimensions are: the diameter of the central circular raised region D_c is 7.12mm. The period of the corrugated structure is 4.53mm, with the width of low rings $R_{indented}$=2.67mm and the width of high rings R_{high}=1.86mm. The depth of the indented rings is 0.91mm.

The antenna is fed by a central sub-wavelength aperture, which is coupled to a WR-15 rectangular waveguide on the back side. The central aperture would ideally have a rectangular cross section the same as the waveguide, but this is difficult to achieve with standard milling tools. The ethos of CubeSats is to reduce the cost of entering space, so we adopted a rounded rectangular shape which could be made using a 0.5mm diameter milling tool. So as to improve the match, the dimensions of the rounded rectangle were optimized under the constraints it had to be 3.2 mm long due to the thickness of the aluminum plate. The sub-wavelength aperture has hence a length L of 3.4mm, a width W of 0.53mm, and rounded edges (0.265mm radius).

The number of indented rings is an important parameter [9]. As shown Table I, the gain reaches almost asymptotically a maximum value that is a consequence of finite surface wave propagation distances, in the presence of the rings, which act as scatters. A simple sub-wavelength aperture has a gain of 6.44dBi, which improves to 18.2dBi if ten indented rings are added, where ten is the maximum number of indented rings a standard 100mm x 100mm face of a CubeSat can contain. The maximum gain is 19.6dBi with eight rings. The gain per additional ring falls below 1dB between six and nine rings, suggesting seven rings as a good compromise between size and performance. Moreover, with a seven-ring structure, more than one antenna can fit per CubeSat side which could eventually lead to separate uplink and downlink channels. For these reasons we chose to characterize a seven-ring structure.

TABLE I
GAIN VERSUS NUMBER OF INDENTED RINGS

Number of indented rings	Gain (dBi)
0	6.44
1	9.29
2	12.4
3	14.9
4	16.8
5	18.6
6	19.1
7	19.1
8	19.6
9	18.9
10	18.2

The simulated S11 parameter and gain are plotted in Fig. 2. The S11 parameter shows a resonant frequency at 60.08GHz with a level of a -55.4dB. The bandwidth at -10dB is 5.06GHz (8.4%), between 57.99 GHz and 63.05GHz. The S11 parameter at 60GHz is -38.0dB. The resonant frequency of the antenna lies within the region of maximum gain.

The gain ranges between 16.7dBi and 19.7dBi within the 5.06GHz of bandwidth (-10dB bandwidth between 57.99GHz and 63.05GHz). At 60GHz, the gain reaches 19.1dBi.

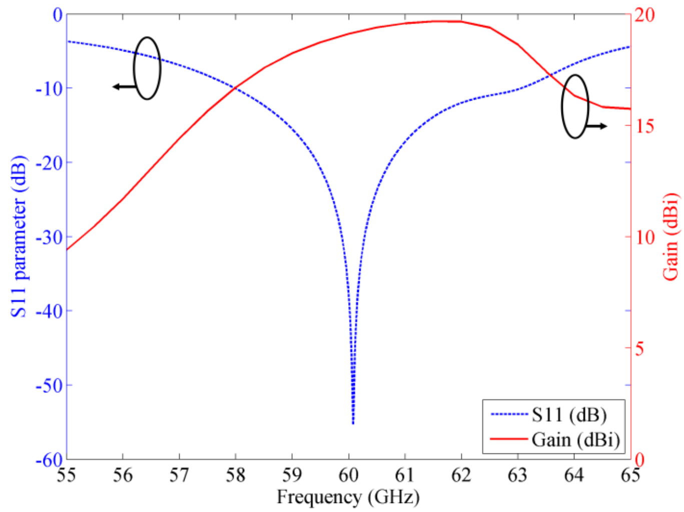


Fig. 2. Simulated S11 parameter (blue) and gain (red) according to the frequency of operation

III. Fabrication and Measurement

In order to evaluate the antenna performance, a "Bull's eye" structure was fabricated in aluminum with seven indented rings, using a 3-axis XYZ SM2000 CNC machine. This type of antenna mounts onto the face of a CubeSat chassis, as shown in Fig. 3.

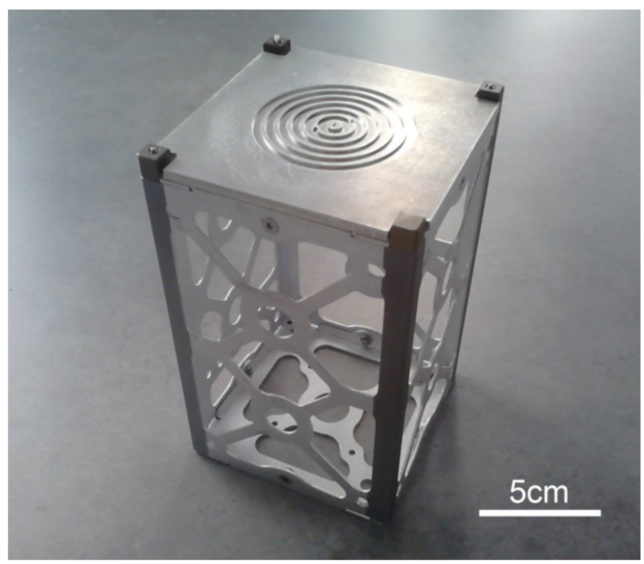


Fig. 3. A 60 GHz 6-indented ring "Bull's Eye" antenna mounted on CubeSat chassis (antenna shown is an earlier iteration with overall similar dimensions, albeit only six indented rings)

We measured the antenna patterns inside a 4.5m x 4.5m x 4.0m anechoic chamber in order to limit interference and parasitic reflections. The influence of the CubeSat chassis and payload is expected to be minimal because they lie behind the antenna where the field strength is negligible. The chassis was removed for the measurement for this reason, and to allow direct comparison with simulation.

The E-plane and H-plane far-field radiation patterns were recorded separately, with the AUT mounted on a rotating stage, taking measurements of the S21 parameter from -100° to 100° every 2° using a linearly polarized 23dBi horn antenna (Custom Microwave, Inc., model HO15R), separated by 110cm (220λ), and an Agilent PNA (E8361A) with 500Hz IF bandwidth and averaging of 10 points per sample. In practice, despite the large aperture, this gives a far-field pattern.

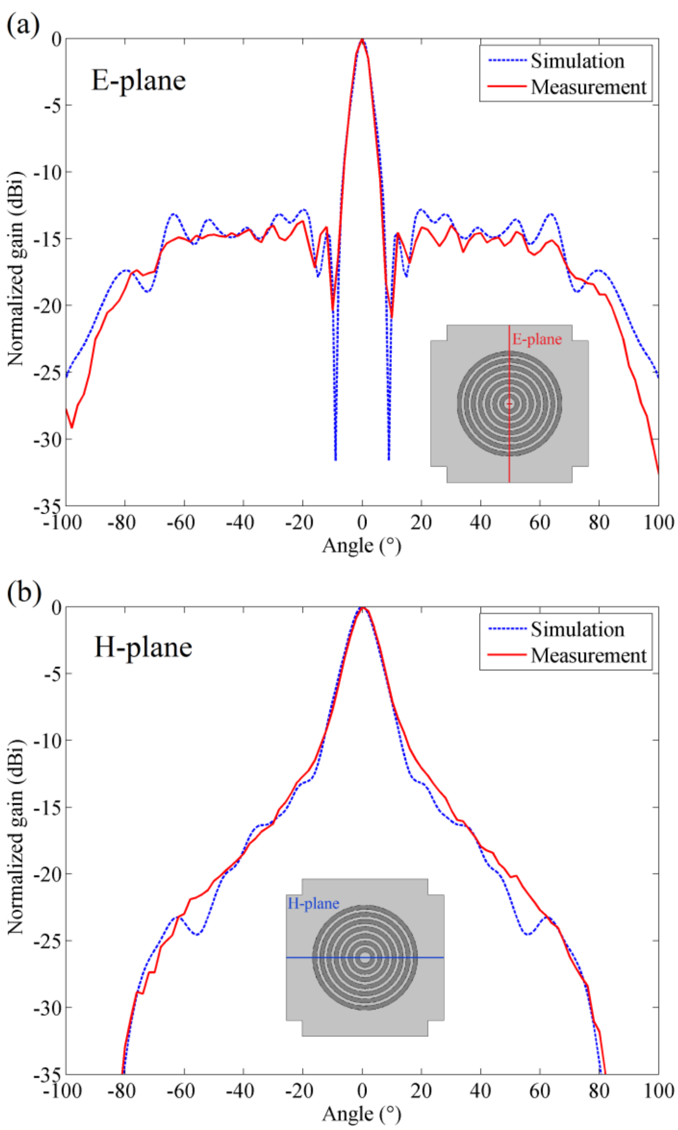


Fig. 4. Measured and simulated, E-plane (a) and H-plane (b), radiation pattern

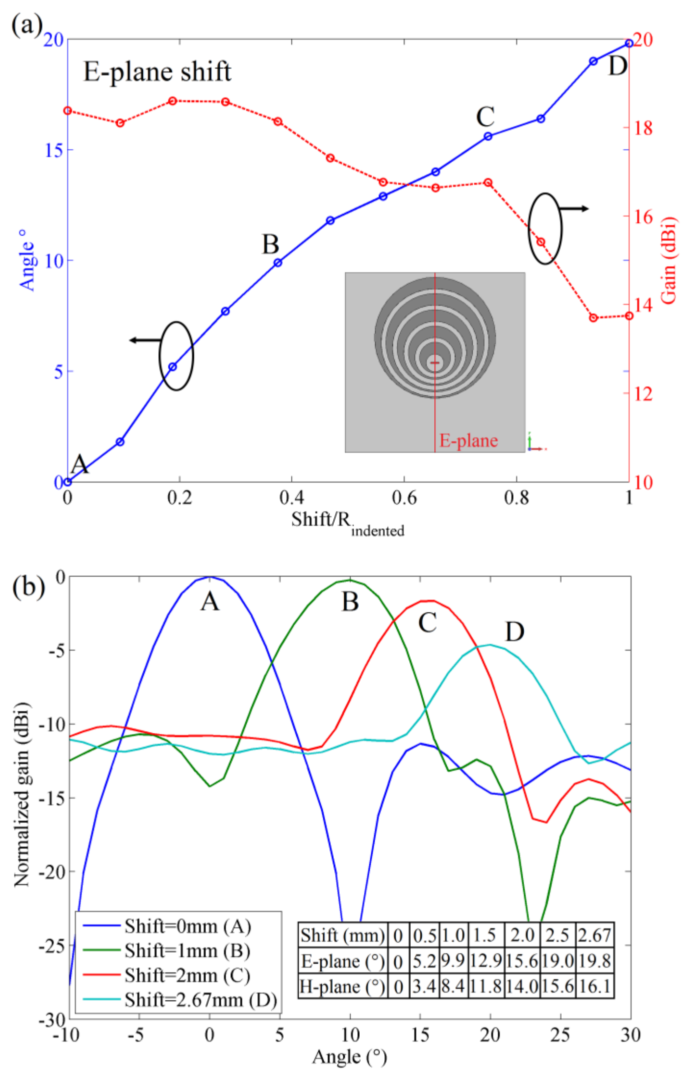
Figure 4 shows good agreement between the simulation and the measurement of the radiation pattern for both the E-plane and the H-plane. From -80° to +80°, the E-plane radiation pattern measurement shows good agreement with error smaller than 2.71dB, and very good agreement for the main beam pattern between -8° and +8° with error smaller than 1.91dB.

At ±64°, the H-plane radiation pattern measurement shows additional lobes at -23dB, which we attribute to the dielectric mounting used to hold the antenna during measurement (which extends further out than CubeSat would). However a very good agreement can be noticed between -30° and +30° with a maximum error of 1.96dB.

These results give us a good confidence with regard to the behaviour of the antenna at the frequency of interest.

IV. Center-shifted rings for beam deflection

By taking advantage of the behavior of the composite diffracted evanescent wave [10], we were able to design and simulate "Bull's eye" antennas with center-shifted rings in order to alter the main beam direction [11]. The angle of the main beam and gain is plotted Fig. 5 (a) and Fig. 6 (a) for E- and H-plane shifts. The parameter Shift is the offset of the first raised ring. Subsequent rings are shifted such that the n^{th} ring is shifted by n x Shift. $R_{indented}$ is the initial width of the low ring (2.67mm). For reduced computing time, we used five indented rings and CST Microwave Studio's transient solver.



Shift (mm)	0	0.5	1.0	1.5	2.0	2.5	2.67
E-plane (°)	0	5.2	9.9	12.9	15.6	19.0	19.8
H-plane (°)	0	3.4	8.4	11.8	14.0	15.6	16.1

Fig. 5. Simulated angle (°) and gain (dBi) of the main beam according to the shift of the centre of the rings along the H-plane (a), and normalized radiation pattern for different values of Shift (0, 1, 2 and 2.67mm) (b); Inset table: E- and H-plane angle according to the Shift parameter

For ring shifting along the E-plane, the beam deflection ranges from 0° to 19.8° and the gain tends to decrease, going from 18.4dBi to 13.8dBi, as shown Fig. 5 (a,b).

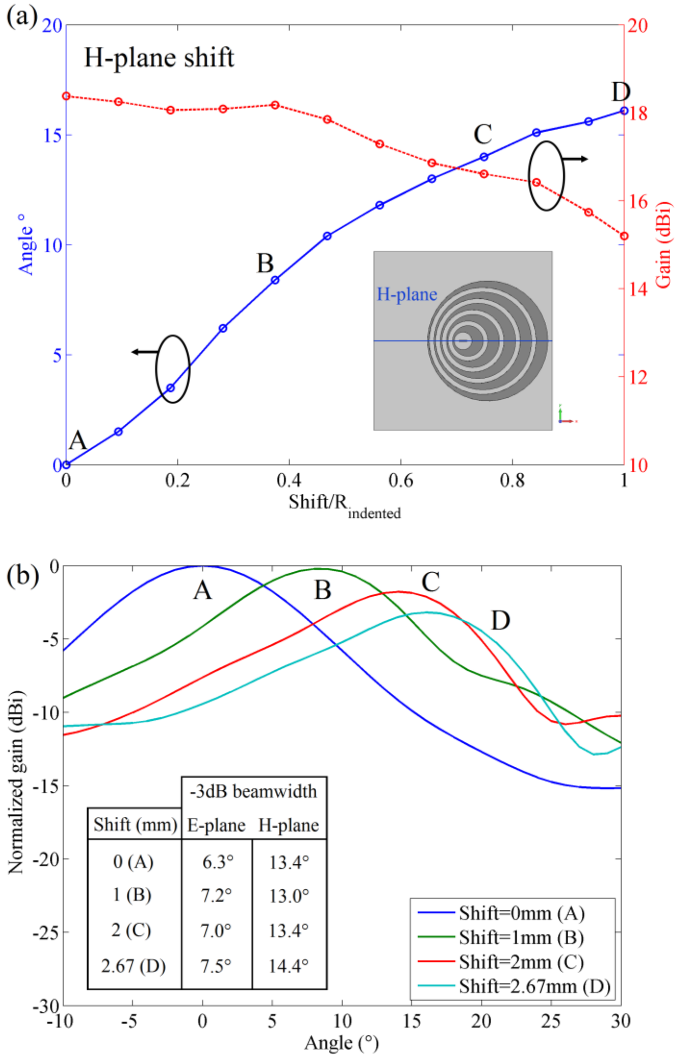


Fig. 6. Simulated angle (°) and gain (dBi) of the main beam according to the shift of the centre of the rings along the E-plane (a), and normalized radiation patterns for different values of Shift (0, 1, 2 and 2.67mm) (b); Inset table: 3dB beamwidths for E- and H-plane patterns shown in Fig. 5 (b) and Fig. 6 (b)

For ring shifting along the H-plane, the beam deflection ranges from 0° to 16.1° and the gain decreases smoothly from 18.4dBi to 15.2dBi. All deflected beam patterns remain qualitatively the same, with only four shown for clarity. Specifically, the 3dB beamwidths remain within 1.2° (1.0°) of the 6.3° (13.4°) beamwidth for the unshifted E-plane (H-plane), as listed for selected patterns in inset table in Fig. 6 (b).

These results show the first beam deflection at microwave frequency using a "Bull's eye" antenna and highlight the flexibility of this antenna.

V. Conclusion

We designed, fabricated and characterized a low-profile antenna suitable for V-band communication between CubeSats, and simulated a novel approach to altering the direction of the main beam. The antenna is 3.2mm thick and, thus, can conveniently integrate onto the outside of the CubeSat. We used a rounded edge feedthrough to permit fabrication by a milling machine.

We studied the effect of adding additional rings to a sub-wavelength aperture structure, finding that seven indented rings was a good compromise between gain and area (total diameter of 66.82mm). In terms of gain, there are diminishing returns for adding more than seven indented rings. Our E-plane (H-plane) measurements agreed to better than 2.71dB (4.68dB) over ±60°, and the gain was better than 16.7dBi over the 5.06GHz bandwidth.

We proposed and simulated a modification (shifted rings) which allows arbitrary choice of main beam direction from 0°-19.8° (0°-16.1°) for E-plane (H-plane). The 3dB bandwidth of the pattern was similar at all deflection angles, 6.3-7.5^{o} (13.0-14.4^{o}) for E-plane (H-plane). Our approach offers more flexibility in CubeSat swarm design by allowing communication between CubeSats that are not directly facing each other along the normal to their chassis faces.

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