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A high gain S-band slot antenna with MSS for CubeSat

Abstract

Cube satellites, aka CubeSats, are a class of tiny satellites that have become popular for space programs. This is because they can be built relatively cheaply using commercial off-the-shelf components. Moreover, CubeSats can communicate with each other, and assemble into swarms to carry out different functions: e.g., wide area measurements and sensing. Swarms of CubeSats also have the effect of increasing the contact period with ground stations allowing for a longer communications window. These capabilities require CubeSats to be equipped with an efficient, high gain, small antenna to facilitate cross-link or inter-satellite communications. Henceforth, this paper presents a high gain coplanar waveguide (CPW)-fed slot antenna for CubeSats. A key feature is the use of a metasurface superstrate structure (MSS) to significantly improve gain and reduce back-lobe emissions. This also has the advantage of minimizing interference to components inside a CubeSat. We have comprehensively evaluated the antenna using the high-frequency simulator structure (HFSS) as well as a carrying out testing on a 3 U (10 x 10 x 30 cm³) CubeSat platform. We have studied the effect of MSS element sets and their position and the effect of a 3-U CubeSat body on the performance of the proposed antenna. The experimental results confirm that our antenna achieves a return loss of 21.5 dB and a fractional impedance bandwidth (BW) of 55.91% with $S_{11} \leq 10$ dB and has a simulated and measured gains of 9.71 and 8.8 dBi respectively at the desired frequency of 2.45 GHz. In contrast, amongst all previous S-band planar antennas that are suitable for CubeSats, the best gain is only 5.96 dB at 2.45 GHz.

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A High Gain S-band Slot Antenna with MSS for CubeSat

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Abstract

Cube satellites, aka CubeSats, are a class of tiny satellites that have become popular for space programs. This is because they can be built relatively cheaply using commercial off-the-shelf components. Moreover, CubeSats can communicate with each other, and assemble into swarms to carry out different functions; e.g., wide area measurements and sensing. Swarms of CubeSats also have the effect of increasing the contact period with ground stations allowing for a longer communications window. These capabilities require CubeSats to be equipped with an efficient, high gain, small antenna to facilitate cross-link or inter-satellite communications. Henceforth, this paper presents a high gain coplanar waveguide (CPW)-fed slot antenna for CubeSats. A key feature is the use of a Metasurface Superstrate Structure (MSS) to significantly improve gain and reduce back-lobe emissions. This also has the advantage of minimizing interference to components inside a CubeSat. We have comprehensively evaluated the antenna using the High Frequency Simulator Structure (HFSS) as well as carrying out testing on a 3U (10 x 10 x 30 cm³) CubeSat platform. We have studied the effect of MSS element sets and their position and the effect of a 3U CubeSat body on the performance of the proposed antenna. The experimental results confirm that our antenna achieves a return loss of 21.5 dB and a fractional impedance bandwidth (BW) of 55.91% with $S_{11} \leq -10$ dB and has a simulated and measured gains of 9.71 and 8.8 dBi respectively at the desired frequency of 2.45 GHz. In contrast, amongst all previous S-band planar antennas that are suitable for CubeSats, the best gain is only 5.96 dB at 2.45 GHz.

Keywords CubeSat, metasurface superstrate, S-band, gain improvement, satellite, slot antenna

1 INTRODUCTION

Cube satellites have opened the door to cost-effective missions that allow universities, small companies or small countries to gain experience in space technology, and to be involved in space exploration and research [1]. CubeSats are small satellites weighing no more than 1 kg and operate in low Earth orbits, e.g., sun-synchronous, at altitudes of 200 to 600 km [2]. All cube satellites have a fixed face size of 10 cm×10 cm with the following depth configurations: 10 cm (1U), 20 cm (2U), and 30 cm (3U). Advantageously, they can be constructed using Commercial Off-The-Shelf (COTS) electronic components [3]. A key feature of CubeSats is their potential to form a collaborative swarm that covers a large geographical area. The resulting swarm allows CubeSats to have a longer contact time with ground stations and enables them to collectively take multiple measurements; consequently, they allow users to conduct comprehensive assessments of a given geographical

region that otherwise would be impossible with a single conventional satellite [4, 5].

CubeSats operating in a swarm require reliable cross-link communications. A key challenge is to be able to establish cross-links without a priori position knowledge. An obvious solution is to use omnidirectional antennas, but they are inefficient as they emit radiation that permeates all directions. Also, they have low gains, and hence, they can only afford low data rates and short communication distance. Ideally, CubeSats should employ an antenna with wide coverage while at the same time have high gains in the desired direction. The design challenges are the limited size and low mass of CubeSats. Another challenge is that CubeSats are difficult to reorient and reposition due to the aforementioned limitations (they will require a more complex propulsion system and control mechanisms such as torque wheels which add to the weight), hence an antenna with wide coverage is suitable.

To address the aforementioned challenges, planar antennas are ideal. They are low-cost, have a low profile, light weight, are easily integrated with electronic devices and can achieve high gains. Henceforth, in this paper, we propose a high gain coplanar waveguide (CPW)-fed slot antenna that operates at 2.45 GHz (S-band) and in particular we will demonstrate its performance when mounted on a 3U CubeSat. A key feature is the use of a Metasurface Superstrate Structure (MSS) [6] as a resonant cavity model. This allows our antenna to have high gains because the MSS redirects the back radiation pattern forward [7]. Advantageously, its use allows our antenna to occupy less space than using a reflector as in [8].

Table I compares the proposed CPW-fed slot antenna against competing designs. Observe that the designs of [3] and [9] achieve beam steering using phase shifters and beam forming algorithms respectively. However, this adds extra cost and complexity. The design in [10] is a simple monopole antenna that provides wide directivity without the need for beam steering technique. It, however, has a low total gain. Another drawback of [10] is its deployment mechanism that incurs extra cost and complexity. Also, there is a risk it might not deploy, which contributes to the likelihood of mission failure. In terms of size, the antenna in [11] has the smallest size of 75 mm×75 mm but its main limitation, as pointed out by the authors, is the resulting low gain, i.e., 1.53 dBi, because of its bi-directional radiation [12]. To solve this problem, one common approach is to redirect the back radiation pattern forward by placing a backing metallic reflector that is $\lambda/4$ away from the antenna [8]. Its main drawback, however, is its large profile structure due to the $\lambda/4$ spacing between the reflector and the antenna. Moreover, the authors of [13] propose to place two S-band patch antennas on two faces of the CanX-4 and CanX-5 CubeSats to achieve omni-directional coverage and a data rate of 10 kbps. In another example, the authors of [3] propose to use a square patch antenna array. The antenna array is fed at 0° , 90° , 180° , and 270° to achieve beam steerability using a phase shifter. In contrast, our antenna design achieves a superior simulated and measured gains of 9.71 and 8.8 dBi at 2.45 GHz respectively. This is important as it enables long distance communications. Consequently, fewer CubeSats will be required to operate in a swarm. Moreover, it further reduces the cost related to manufacturing and placing a satellite into orbit. Moreover, as our design uses an MSS to suppress back radiation, there is less interference with components inside a CubeSat. Note that we do not consider other types of antennas because they have a large profile or/and require deployment mechanisms and occupy a large area such as [14].

The rest of the paper is organized as follows: Section II describes the geometry of the proposed CPW-fed slot antenna and its MSS. Section III (A) generalizes the design procedure and studies the influence of lengths and widths of feed section, tuning stub and the position of MSS. Section III (B) compares

the simulated and measured results of Return Loss (R_L), and radiation patterns. The paper concludes with Section V.

2 ANTENNA CONFIGURATION

In this work, we redesign the antenna presented in [15] for the purpose of our CubeSat mission. Namely we modify the two square panels in either corner of the patch and readjust most dimensions and eventually add a focusing metasurface. Then the antenna is tested on an Aluminum CubeSat body. This all results in much higher gain than what was reported in [15] and is suitable for the application for CubeSat communication at our required operating frequency of 2.45 GHz.

Fig.1 shows the geometry of the proposed CPW-fed slot antenna. The slot and the feed line are etched on to a square FR4 substrate with a dielectric constant of 4.4 and a substrate thickness of 1.6 mm. This FR4 substrate is commonly used in antennas designed for CubeSats [3]. Small thickness FR4 substrate provides acceptable performance for antennas that operate in the frequency range of 2-10 GHz in a cost effective manner [16, 17]. The antenna is fed by a 50- Ω CPW with a strip line width of $W_f = 3.4$ mm and is separated from the ground plane by two gaps with width $g = 0.45$ mm and $T = 1.65$ mm. In addition, by using the lightening shape of the feedline, Circular Polarization (CP) is achieved. This lightening-shaped feedline is formed by extending the signal strip of the CPW in the -y direction to the lower left corner of the horizontal feed section. This lightening-shaped feed-line has horizontal and slanted (S) feed sections with the same width of $W_s = 3.75$ mm and the slant angle is 45° . The main idea of connecting the slant and horizontal sections at 45° is generating a displacement shift of a quarter cycle between the feeding signal fields to obtain an excitation of two orthogonal modes of the same amplitude and which exhibits a 90° phase difference. This is important as it provides a CP and enhances the Axial Ratio (AR) bandwidth. The horizontal feed section is separated from the lower and left edges of the slot by two gaps of width T and g , respectively. Moreover, tuning stubs are embedded in the feed-line structure to widen the impedance bandwidth by shifting and combining the second operating frequency with the first operating frequency. As shown in Fig. 1 (a), the vertical tuning stub is formed by extending L_n along the CPW's signal line, whereas the horizontal tuning stub is formed by extending the horizontal feed section to the right by $L_t = 7.5$ mm as measured from the right edge of the center signal line of the CPW. Fig. 1 (b), (c) and (d) show an MSS that is comprised of a 7×6 Closed-Square Resonator (CSR) array. It is printed on an inexpensive 0.8 mm thick (h_2) FR-4 material. This MSS has dimensions of 90 mm $\times$ 78 mm and is placed above the slot antenna. The physical parameters of DCSR are as follows: $P = 10$ and $b = 9$ mm. We have selected the square-shaped metasurface elements because it provides better performance [7]. CSR achieves in-phase reflection of the incident waves and provides a uniform current

TABLE I. COMPARISONS BETWEEN ANTENNAS FOR CUBESAT COMMUNICATIONS AND PROPOSED ANTENNA

Reference	Type of Antenna	CubeSat Type	Frequency [GHz] / band	Gain [dBi]	Volume [mm ³]	Beam Steering
<i>Proposed antenna</i>	<i>CPW-fed slot antenna</i>	<i>3U</i>	<i>2.45</i>	<i>9.71</i>	<i>90×90 ×10.5</i>	<i>Not required</i>
[11]	A square slot antenna	1U	2.45	1.53	75×75 ×1.6	Not required
[3]	Phased patch antenna array with 90° hybrid	1U	5.8	5.1	90×90×5	Electronic pointing (using phase shifter)
[13]	Patch antenna	1U	S-band	N/A	N/A	Not required (Omnidirectional)
[9]	Six individual patch antennas. Each is placed on a different face of a CubeSat	3U	2.45	4.8	N/A	Beam-forming algorithm
[10]	Four monopole antennas	2U and 3U	0.437	N/A	N/A	Not required (Omnidirectional)

distribution over unit cells that flow in one direction. This is important as it leads to an increase in the antenna gain and directivity. Moreover, as compared to a 3-D metamaterial structure, the proposed 2-D square-shaped metasurface are easy to construct, cheaper and occupy less space [18]. The considered square shape presents two symmetry axis that will guarantee the same radiation characteristics for the propagation in the two orthogonal directions (parallel to the two-symmetry axis). Consequently, the two components of the field (propagating along the symmetry axis) will go through the same propagation medium, assuring to maintain the initial phase difference and identical radiation that in turn will assure wider polarization bandwidth. Moreover, the proposed MSS structure has no effect on the antenna polarization.

3 RESULTS AND DISCUSSION

This section outlines a parametric study that aims to identify

factors that affect antenna performance; i.e., return loss, impedance bandwidth, gain and radiation pattern. Moreover, in Section III.B we compare simulated and experimental results.

3.1 Parametric Study

We now present various parametric analyses conducted using HFSS [19]. We focus on the best return loss, impedance matching, and gain at the operating frequency of 2.45 GHz. In order to optimize for the best parametric, the Quasi Newton method in HFSS was used. The Quasi Newton method is a computer-aided finite element method-based optimization tool. It works on the basis of finding the minimum or maximum of a cost function by adjusting the variables to meet the constraints. In our case, the decision variable is the antenna dimensions with different ranges (minimum to maximum). The aim is to achieve the best antenna performance, i.e., maximum return loss and gain (design parameter) at operating frequency of 2.45 GHz

(constraint). Therefore, the Quasi-Newton method maximizes the value of return loss (RL) by varying the antenna dimensions, i.e., lengths, width or height, 100 times (iterations) for a given range by minimum and maximum step sizes. Table II lists the optimal parameters of the proposed antenna.

TABLE II. OPTIMAL PARAMETERS OF THE PROPOSED ANTENNA

Parameters	Values (mm)
G	90
L	60
W	60.3
W_n	2.15
W_s	3.75
L_n	12.8
L_t	7.5
h_a	8.1
T	1.65
g	0.45
W_f	3.4
S	55.8

3.1.1 Design Frequency and Initial Parameters

The target operating frequency is $f_t=2.45$ GHz which is

commonly used by the CubeSats community because it is within the 2.4-2.5 GHz unlicensed Industrial, Scientific and Medical (ISM) band [20]. The antenna operating frequency is varied by controlling its size as per $F=f_0/f_t$, where $f_0 = 3.675$ GHz is the obtained resonant frequency of the initial obtained design over the specified dimensions, i.e., $60 \text{ mm} \times 60 \text{ mm}$. As the obtained frequency of the initial design is 3.675 GHz, the antenna size needs to be increased by F to ensure it operates at the desired resonant frequency of f_t with maximum return loss (R_L). In order to determine the best value of F, we used the Quasi Network method [21], which is part of the HFSS package. In our case, the decision variable is the lengths of the antenna's dimensions with a range of 0.653 (minimum) to 1.959 mm (maximum). The aim is to achieve a maximum return loss (design parameter) at operating frequency of 2.45 GHz (constraint). Therefore, the Quasi-Newton method maximizes the value of return loss by varying the antenna lengths 100 times (iterations) from 0.653 to 1.959 mm by minimum and maximum step sizes of 0.013 and 0.13 mm respectively.

(a)

(c)

(b)

(d)

Fig. 1 Configuration of CPW-fed slot antenna with MSS (a) the proposed CPW-fed slot antenna, (b) MSS, (c) a cross section view, and (d) the model in HFSS

The results show that the antenna size must be increased by a factor of 1.5 to achieve a maximum return loss of 21.5 dB at an operating frequency of 2.45 GHz.

3.1.2 Effect of W_n and L_t

Fig. 2 (a) illustrates the return loss with the following widths (W_n): 1.8, 2.15 and 3.15 mm. Other parameters are fixed. We see that the width W_n of the tuning stub has an effect on impedance matching, operating frequency and impedance bandwidth. When the width W_n increases, e.g., exceeds 2.15 mm, the return loss decreases and the impedance bandwidth (BW) improves; we observe that BW increases proportionally with W_n . Also, the operating frequency is slightly increased when W_n increases and vice-versa. The best value of W_n is 2.15 mm, which gives good impedance matching with the input impedance of about 49 ohms and hence low reflected power at the target resonant frequency of 2.45 GHz. This is because of the excitation of the magnetic currents at operation frequency of 2.45 GHz with $W_n = 2.15$.

Fig. 2 (b) shows the simulated return loss of the proposed CPW-fed slot antenna for the following L_t lengths: 6.5, 7.5 and 8.5 mm. We see that L_t also has a significant effect on the operating frequency and return loss. As the length of the horizontal feed section increases (L_t), the return loss and the operating frequency decrease. The highest return loss is achieved at $L_t=6.5$ mm. However, the operating frequency shifts to 2.55 GHz. The most suitable L_t value is 7.5 mm. This value shifts the operating frequency from 2.55 to 2.45 GHz with a return loss of 27.5 dB and bandwidth of 730 MHz (1.9 – 2.63 GHz).

3.1.3 Effect of L_n

With the width of the tuning stub fixed at $W_n = 2.15$ mm and the length of the horizontal feed section set to $L_t = 7.50$ mm, we then study the following L_n values: 11.80, 12.80 and 13.80 mm. Referring to Fig. 3, the length L_n has a significant effect on the return loss and the impedance bandwidth. As the value of L_n increases, the return loss decreases. This means more power is reflected instead of being radiated into space. Moreover, the BW decreases proportionally with L_n . The highest return loss is achieved at $L_n=11.8$ mm. However, the operating frequency is not at the required operating frequency of 2.45 GHz. The most suitable length is $L_n=12.80$ mm as it provides high return loss ($R_L = 27$ dB), and wide bandwidth of 750 MHz at the required operating frequency of 2.45 GHz.

3.1.4 Effect of metasurface starting positions

Fig. 4 shows (a) the simulated return loss (R_L) and (b) the simulated 2D gain for the following MSS positions: 0, 6, and 12 mm from the bottom CPW feed at an MSS height of 8.1 mm. Other parameters are fixed. The MSS positions

Fig. 2 Simulated return loss against frequency for various (a) W_n , and (b) L_t values

Fig. 3 Simulated return loss against frequency for various values of L_n

have a significant effect on the return loss. We can see that the return loss (R_L) decreases and the gain decreases when the MSS starting position is close to the feed line, e.g., 0 and 6 mm. There is almost no change to the resonant frequency of 2.45 GHz. Therefore, the starting position of 12 mm from the CPW feed in the -x direction yields the best results. This is because it gives the highest return loss (good impedance matching), e.g., 36.5 dB, and highest gain, e.g., 5.20 dBi, at the required operating frequency of 2.45 GHz.

3.1.5 Effect of metasurface array element sets

As shown in Fig. 5 the array element sets of the MSS have a significant effect on the return loss and hence, impedance matching. As the number of elements increases, the operating frequency approaches the operating frequency of

2.45 GHz and return loss increases. We have tested different array element sets. We found that the most important sets that have a significant effect on return loss are 7×2 , 7×4 and 7×6 . Thus, we only focus on these sets from here onwards. Fig. 5 shows that a 7×6 array element set is ideal because it achieves the highest return loss; i.e., 36.5 dB at an operating frequency of 2.45 GHz.

Fig. 4 The effect of the starting edge of the MSS position on (a) the Return Loss RL, and (b) antenna gain

Fig. 5 The influence of MSS element sets over the return loss of the proposed antenna

3.1.6 Effect of metasurface height

We now study the effect of the MSS height on the impedance matching by varying the MSS height from 4.1 to 10.1 mm; see Fig. 6. heights of $h_a = 4.1$ and 6.1 mm result in smaller return loss as compared to $h_a = 8.1$ and 10.1 mm. In the case of $h_a = 8.1$ mm, the obtained impedance bandwidth (VSWR ≤ 2) is wide, i.e., 130 MHz (2383 – 2513 MHz), and the return loss is very high, i.e., 36.8 dB.

This means large bandwidth, low reflected power and good impedance matching. This is because at $h_a = 8.1$ mm, a good coupling between the MSS and the slot antenna is achieved with only a single resonant mode excited at the operating frequency of 2.45 GHz.

Fig. 6 The MSS height, i.e., h_a , as a function of (a) the return loss and (b) VSWR of the proposed antenna.

3.1.7 Effect of the MSS

We now study the effect of the MSS on antenna gain. We fix the width of the tuning stub at $W_n = 2.15$ mm, the length of the horizontal feed section at $L_t = 7.50$ mm, the length of the tuning stub at $L_n = 12.8$ mm, the MSS array set has 7×6 elements and we set the MSS height, i.e., h_a , to 8.1 mm. Fig. 7 shows the total gain of the CPW-fed slot antenna with and without the use of the MSS. We can see that the use of the MSS dramatically increases the antenna's gain from 2.52 to 5.67 dBi. Moreover, the amount of back lobe radiation has been further reduced from -9.9 to -8.7 dBi. We conclude that the MSS has a significant effect on the antenna gain; we observe decreases in the back-lobe pattern. The reason for this is that when the antenna is tuned to the resonant frequency of the MSS, the radiated electrical field is spread over a larger radiating aperture enhancing its gain. The use of the MSS provides more radiating slots as compared to only one radiating slot for an antenna without

an MSS. Moreover, the metasurface picks up the radiated power of the antenna, and then re-radiates. This improves the boresight radiation and reduces the back radiation. We also see that there is a small tilt in the radiation pattern of the proposed antenna. This is because the proposed antenna has an asymmetric structure. Also, the transmission through the MSS which occurs with a linear phase variation along the MSS leads to a steering in the antenna pattern.

Fig. 7 The total gain of our CPW-fed slot antenna (a) without MSS, and (b) with the MSS

3.1.8 Effect of CubeSat body

We place the proposed antenna on a 3U CubeSat as shown in Fig. 8 and Fig. 17 (b). Note, the antenna can have different placement configurations on a 3U CubeSat. Specifically, for satellite to ground station communications, placing it on only one CubeSat face is sufficient [14]; magnetic torqueing can be used to ensure it is always pointed at a ground station. For inter-satellite (cross-link) communications, placing an individual antenna on each face of a 3U CubeSat will be required [22].

To avoid direct contact between the backside (dielectric) of the antenna and the satellite body, we kept a distance (air gap) of 8.5 mm between the antenna and the satellite body. Consequently, the satellite body will act as a reflector that leads to higher gains. This air gap distance between the CubeSat and the proposed antenna is obtained using the Quasi-Newton method. Quasi-Newton method maximize the value of the antenna gain by varying the air gap 100

times (iterations) from 0.5 to 20 mm by minimum and maximum step sizes of 0.013 and 0.13 mm respectively. The results show that the air gap distance of 8.5 achieves the highest gain of 9.7 dBi at the required resonant frequency of 2.45 GHz.

We see that the 3U CubeSat body has no effect on the operating frequency. However, the return loss decreased from 36.8 to 21.5 dB; see Fig. 9(a). Moreover, the total antenna gain increased from 5.67 to 9.71 dBi; see Fig. 9 (b). This is because the Aluminum surface of the CubeSat acts as a reflector and reflects some of the back-lobe radiation forward. Fig. 10 shows the simulated radiation pattern on the yz-plane. We see that our antenna achieves a maximum gain with a 20° elevation tilt and Half Power Beamwidth (HPBW) of 33° at 2.45 GHz. We can see that the radiation is in the direction almost normal to the substrate (z-axis).

Fig. 8 A CPW-fed slot antenna on a 3U CubeSat

As shown in Fig. 11 (a) and (b), the proposed antenna is placed in two different positions, e.g., positions 1 (the left corner) and position 2 (middle) to study the effect of the antenna position on a 3U CubeSat. Fig. 12 shows the return loss of the antenna at two different positions on CubeSat's surface, i.e., middle and corner positions. In the middle position, the proposed antenna operates at three bands, i.e., 1.76, 2 and 2.38 GHz; see Fig. 13. However, our proposed antenna is designed to achieve a single operating frequency of 2.45 GHz. Therefore, positioning the antenna at the corner is more appropriate.

(a)

(b)

Fig. 9. Simulated results of proposed antenna on the CubeSat's body (a) return loss and (b) total gain at 2.45 GHz.

Fig. 10 Simulated radiation pattern of the proposed antenna on a CubeSat's body at 2.45 GHz

Fig. 13 shows the 3D total gains of the proposed antenna at (a) corner position and (b) middle position. We note that the total gain has not been significantly affected by changing the location of the antenna on the surface. This is because when using a lumped terminal for the excitation model, the field distribution model is stabilized and is not significantly affected by changing the antenna position

using the same surface size. The total gain of the proposed antenna at the corner position is higher than the middle position by 1.23 dB.

(a)

(b)

Fig. 11 Proposed antenna at two positions (a) corner and (b) middle

Fig. 12 the effect of antenna position on return loss

Fig. 14 depicts the simulated axial ratio of the proposed antenna located on the 3U CubeSat. We see that the antenna achieves a circular polarization with 3 dB axial ratio bandwidth of 130 MHz, ranging from 2.34 to 2.47 GHz. This corresponds to a 5.4% relative bandwidth with respect to the center frequency of $f=2.41$ GHz. The obtained axial ratio of the antenna is 0.44 at 2.41 GHz. CP is important for establishing cross-link communications. Moreover, to

perceive the CP that is generated by the designed antenna, we examined the distribution of the magnetic current.

Fig. 13 The simulated total gains of proposed antenna at surface's positions (a) corner and (b) middle

Fig 15 illustrates the variation of the electric fields at 2.45 GHz for different time instant, i.e., $\omega t = 0^\circ, 90^\circ, 180^\circ$ and 270° . For 0° and 180° , the predominant magnetic current is parallel to the x axis while for 90° and 270° , it is parallel to the y axis and horizontal feed section. The electric field distribution at $0^\circ, 90^\circ$ is opposite to that at 180° and 270° respectively. This electrical field distribution implies a quadrature phase between the x and y directions. We note that when the magnetic current rotates, the proposed antenna generates Right-Hand Circular Polarization (RHCP) in $+Z$ direction and Left-Hand Circular Polarization (LHCP) in the $-Z$ direction. Moreover, Fig. 16 shows the normalized RHCP and LHCP patterns of the proposed antenna at the operating frequency of 2.45 GHz.

3.2 Experimental Verification

In order to verify the simulated results, we have fabricated the CPW-fed slot antenna with an MSS array set of 7×6 elements; see Fig. 17 (a) and (b) for a photograph. Our experiments consider the case with and without a 3U CubeSat model. We measure the antenna's characteristics using Keysight's M9370A vector network analyzer (VNA). We attach the antenna to port one of the VNA using a ridged interconnect featuring male SMA connectors on

Fig. 14 Simulated axial ratio of proposed antenna

Fig. 15 Electric field distributions of the proposed antenna at different phase instants (a) $\omega t=0^\circ$, (b) 90° , (c) 180° and (d) 270°

Fig. 16 Simulated radiation patterns of proposed antenna at 2.45 GHz

both ends. The test setup was calibrated with a Rohde & Schwarz ZV-Z270 50Ω calibration kit and a characterized female SMA to male N-connector adapter. The system is de-embedded to the reference plane of the SMA connector

on the antenna. We set the VNA to sweep from 1.5 to 3.5 GHz using a resolution bandwidth of 100 kHz and an output power of -5 dBm.

The simulated and measured return losses (R_L) with and without the 3U CubeSat model are depicted in Fig. 18; all are in agreement with the simulation results from HFSS as they have the same shape and same resonance frequency at their highest R_L . Compared to the simulated return loss of the proposed antenna on the CubeSat's body, the measured and simulated (individual) return losses of the proposed antenna without the CubeSat's body have higher R_L . Moreover, both simulation (solid line and long dashed line) and measured (dashed line) results of R_L indicate that the CPW-fed slot antenna is well matched at the desired operating frequency; e.g., 2.45 GHz with $R_L > 10$ dB. The simulated and measured fractional impedance bandwidths of the CPW-fed slot antennas with CubeSat are 740 MHz (1900 – 2640 MHz) and 1370MHz (1600 – 2970 MHz) respectively. These discrepancies between the measured and simulated results are caused by the limited accuracy of the etching process used and the antenna testing set up. Fig. 19 shows the simulated and measured input impedances of the proposed antenna in the frequency bands 1.900 – 2.630 and 1.819 – 2.787 GHz respectively. The simulated and measured input impedance at 2.45 GHz is 43.97Ω and 48.59Ω , respectively.

Fig. 17 A photograph of the fabricated prototype CPW-fed slot antenna: (a) geometry, and (b) its installation on a 3U CubeSat model face

Fig. 18 Simulated and measured return losses (R_L) of the proposed antenna

Fig. 19 Simulated and measured input impedance of the proposed antenna

Fig. 20 compares the simulated and measured patterns on the plane parallel to the satellite axis and contain the antenna itself. The plane includes the direction of the maximum radiation, as discussed earlier in section A. The radiation pattern is quite similar with a small rotation in the pointing angle. This can be due to the mounting of the antenna during measurement, see the inset of Fig. 20, as the center of the rotation is different with respect to the phase center of the antenna.

Fig. 21 shows the measured and simulated gains versus varying frequencies of the proposed antenna with the CubeSat. We see that there is a reasonable agreement through the entire band. The peak gains of simulated and measured gains are 9.71 and 8.8 dBi at 2.45 GHz respectively. The minor discrepancy can be mostly attributed to the fabrication error and measurement uncertainties.

Fig. 20 Simulated and measured radiation pattern of the proposed antenna on a CubeSat's body at 2.45 GHz (inset: Antenna under measurement)

Fig. 21 Simulated (continuous line) and measured (dashed line) gain of the proposed antenna with CubeSat

4 CONCLUSION

We have presented the design and the realization of a high gain CPW-fed slot antenna for CubeSat communications. We also obtained the optimal parameters of the proposed antenna and the optimal element sets of the MSS using parametric analysis. We have designed and built an MSS to significantly increase the gain from 2.52 to 5.67 dBi. This gain further improved to 9.71 (simulated) and 8.8 dBi (measured) when the CPW-fed slot antenna is placed on the Aluminum cube satellite's surface. Simulation and measured results show that the proposed antenna has a return loss that is well below 10 dB at the operational frequency of 2.45 GHz and achieves an impedance bandwidth of 1370 MHz.

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REFERENCES

- [1] M. Swartwout (2013) The first one hundred cubesats: A statistical look. *Journal of Small Satellites* 2:213-233
- [2] C. Underwood, V. Lappas, A. D. S. Curiel, M. Unwin, A. Baker, and M. Sweeting (2004) Science Mission Scenarios Using "PALMSAT" Pico-Satellite Technology. In: *Proceedings of 18th annual AIAA/USU conference on small satellites*, 2004, pp 1-11
- [3] R. M. Rodriguez-Osorio and E. F. Ramirez (2012) A Hands-On Education Project: Antenna Design for Inter-CubeSat Communications. *IEEE Antennas and Propagation Magazine* 54:211-224
- [4] C. Pincioli, M. Birattari, TE. uci, M. Dorigo, M. d.R. Zapatero, T. Vinko, and D. Izzo (2008) Self-Organizing and Scalable Shape Formation for a Swarm of Pico Satellites. In: *adaptive hardware and systems NASA/ESA conference*, IEEE, pp 57-61
- [5] C. A. Rouff, M. G. Hinchey, J. Pena, and A. Ruiz-Cortes (2007) Using Formal Methods and Agent-Oriented Software Engineering for Modeling NASA Swarm-Based Systems. In: *2007 swarm intelligence symposium (SIS) conference*, IEEE, pp 348-355
- [6] R. W. Ziolkowski (2003) Design, fabrication, and testing of double negative metamaterials. *IEEE Transactions on Antennas and Propagation* 51:1516-1529
- [7] S. Chaimool, K. L. Chung, and P. Akkaraekthalin, (2010) Bandwidth and gain enhancement of microstrip patch antennas using reflective metasurface. *IEICE transactions on communications* 93:2496-2503
- [8] Y. Yoshimura (1972) A Microstripline Slot Antenna (Short Papers). *IEEE Transactions on Microwave Theory and Techniques* 20:760-762

- [9] A. Budianu, T. J. W. Castro, A. Meijerink, and M. J. Bentum (2013) Inter-satellite links for cubesats. In: *Proceedings Aerospace conference*, IEEE, pp 1-10
- [10] *An international network of 50 CubeSats Project [online] available: <https://www.qb50.eu/>.*
- [11] F. Em . Tubbal, R. Raad, K.-W. Chin, and B. Butters (2014) S-band shorted patch antenna for inter pico satellite communications. In *Proceedings of 8th international conference on telecommunications, systems and services and applications (TSSA)*, IEEE, pp. 1-4
- [12] C. Rakluea, S. Chaimool, P. Rakluea, and P. Akkaraekthalin (2011) Unidirectional CPW-fed slot antenna using metasurface. In: *Proceedings of 8th international conference on electrical engineering, electronics, computer, telecommunications and information technology (ECTI-CON)*, pp 184-187
- [13] N. Orr, J. Eyer, B. Larouche, and R. Zee (2007) Precision formation flight: the CanX-4 and CanX-5 dual nanosatellite mission. In *Proceedings of 21st Annual AIAA/USU conference on small satellites*, pp. 1-10
- [14] F. EM. Tubbal, R. Raad, and K-W. Chin (2015) A survey and study of planar antennas for pico-satellites. *IEEE Access* 3:2590-2612
- [15] J. Y. Sze, C. I. G. Hsu, Z. W. Chen, and C. C. Chang (2010) Broadband CPW-Fed Circularly Polarized Square Slot Antenna With Lightening-Shaped Feedline and Inverted-L Grounded Strips. *IEEE Transactions on Antennas and Propagation* 58:973-977
- [16] E. L. Holzman (2006) Wideband measurement of the dielectric constant of an FR4 substrate using a parallel-coupled microstrip resonator. *IEEE transactions on microwave theory and techniques* 54:3127-3130
- [17] A. A. Qureshi, M. U. Afzal, T. Tauqeer, and M. Tarar, (2011) Performance Analysis of FR-4 Substrate for High Frequency Microstrip Antennas. In: *Proceedings of microwave conference*, pp 1-4
- [18] T-K. Wu. *Frequency Selective Surfaces: Wiley online library*, 1995.
- [19] *High Frequency Structure Simulator (HFSS) [online] available: <http://www.ansys.com/>.*
- [20] F. EM. Tubbal, R. Raad, and K-W. Chin (2016) A Wideband F-shaped Patch Antenna for S-band CubeSats Communications. In: *Proceedings of 10th International Conference on Signal Processing and Communication Systems (ICSPCS)*, IEEE, pp 1-4
- [21] R. Fletcher, *Practical methods of optimization (2nd ed.)*. New York: John Wiley & Sons. ISBN 978-0-471-91547-8.
- [22] F. Em . Tubbal, ER. Raad, K-W. Chin, and M. Madni (2015) Low profile aperture coupled microstrip antenna for inter cubesat communications. In *Proceedings of 4th International CubeSat workshop*, pp 1-2