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Design and Development of Microstrip Patch Antenna Array for Small Satellite

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Abstract: The paper presents the circular microstrip antenna with an additional small circular patch excited by a single feed for achieving circular polarization (CP) and afterwards 2x2 sequentially rotated array antenna. In order to improve circular polarization bandwidth, sequential rotation techniques using the proposed microstrip antenna were investigated. This paper proposes a left-handed circularly polarized (LHCP) 2×2 array antenna using sequential phase rotation power dividers at 5.8 GHz. This paper primarily focuses on the compact, low-cost design of a circularly polarized antenna to meet the application requirements of next-generation small satellites. The final design has the left-handed circularly polarized with the axial ratio level below 1.5 dB for the whole bandwidth from 5.5 GHz to 6.1 GHz. The proposed antenna is made up of square flame retardant 4 (FR4) substrate. The final design size is of 56 mm x 45 mm, the measured realized gain is more than 7.7 dBi and 3-dB axial ratio bandwidth is 11%. The 10-dB impedance bandwidth of the antenna is better than 10%. Due to compact design, this proposed antenna can be easily mounted on the CubeSat structure as it combines efficient performance with a low profile.

Keywords: Antenna Array, Circular Polarization, 5.8GHz, Cubesat, Small Satellites.

Research Paper

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1. INTRODUCTION

CubeSat program started in 1999 at California Polytechnic State University (Cal Poly) and SSDL (Space Systems Development Laboratory) of Stanford University under the leadership of Robert J. Twiggs [1]. The objective was to address an educational need by designing a feasible satellite mission that could be completed within one to two years, keeping costs low and minimizing mass to reduce launch expenses [2]. Accordingly, CubeSats are most commonly put in orbit by deployers on the International Space Station, or launched as secondary payloads on a launch vehicle. CubeSats are satellites intended for low Earth orbit (LEO) and most commonly involve experiments which can be miniaturized or serve purposes such as Earth observation or amateur radio. CubeSats satellite are not short of technical challenges; they usually require innovative propulsion, attitude control, communication and computation systems [3].

The advancement of CubeSats has made it possible to explore and test new concepts in low-power microelectronics, digital signal processing, and communication protocols, all without the need for multimillion-dollar investments. However, pico-satellites whose mass is less than 1 kg are still to be developed for commercial applications because they are of very limited size resulting in condensed and complex circuitry [4]. At the essential part of CubeSats communication system is the antenna. There are many challenges in that CubeSats antenna design, as it must meet the size and mass restrictions of the CubeSat standard while offering high gain, wide band circular polarization [5]. Among the key characteristics and challenges associated with CubeSat antennas, this research will concentrate on the requirements outlined in Table 1.

For this antenna design, the most important factors are to achieve a good circular polarization with wide bandwidth and to accomplish the stated dimensions of the antenna [6]. And then, the main contribution of this work is the design of single feed excited circularly polarizated antenna array with a very compact size for high-gain at operation frequency 5.8 GHz for CubeSats. The purpose of this work is focused on the antenna design, but not the integration of the antenna to the CubeSat. FEKO Software will be used which is a software for 3-D, full-wave, electromagnetic modeling.

Currently, CubeSats utilize radio bands designated for scientific applications, such as 2450 MHz and 5800 MHz [7]. Consequently, this research focuses on designing an antenna array operating at the 5.8 GHz resonant frequency. The antenna is optimized to meet the strict constraints of CubeSat deployments, ensuring both high performance and compatibility with the compact satellite form factor [8].

This study addresses the challenge of designing a cost-effective, compact circularly polarized microstrip antenna, which involves a three-step process. First step is to design the antenna which can operate in scientific applications in radio band 5.8 GHz, which are available for scientific applications. For second step, circular polarization is achieved by either introducing perturbation segments on the single radiating patch or feeding the antenna can produce equal magnitude and 90 degree out of phase. Thirdly, four element antenna array by using sequentially rotated feeding method is added the single proposed antenna to improve antenna performance of impedance bandwidth, gain, axial ratio bandwidth, directivity. And then, antenna characteristics such as impedance bandwidth, gain, axial ratio bandwidth, directivity are analyzed and carried out to develop the performance of the proposed antenna. Finally, the optimized antenna design is fabricated using Eleven Lab machine at YTU and measured the performance of this fabricated antenna with Vector Network Analyzer.

The content of the paper will be organized as follows: The structure and design principle of the single element antenna and the array antenna with the sequential-phase feeding network is presented in Section 1. In Section 2, results and discussion the research work is described. Finally, some conclusions and future works are given in Section 3.

Table 1: Antenna requirement

Resonant Frequency	5.8 GHz
Realized Gain	>7 dB
Impedance Bandwidth (%)	>10%
3dB Beam width	40˚- 50˚
Polarization	Circular Polarization
Axial ratio Bandwidth (%)	>10%
Dimension	50 x 50 x 6 mm^3 (Very Compact Design)
Material	Low Cost

2. ANTENNA DESIGN METHODOLOGY

2.1 Single Element Antenna

In first stage, the circular patch shape is firstly chosen because of its easy fabrication and analysis. The copper is used as the conducting patch and the ground plane. And then, FR-4 substrate (εr=4.3) is placed between the patch and ground plane as dielectric substrate because it is low cost, available in market.

In single patch antenna contains a single circular microstrip patch antenna with an additional patch is excited by a single feed [9]. An additional patch can induce the phase difference between the orthogonal modes, resulting in circular polarization. By optimizing additional patch, two orthogonal modes with a 90˚phase difference were excited to obtaining the CP radiation at the desired frequency. The circularly polarization occurs when two orthogonal electric field components with equal amplitude and a 90-degree phase difference combine, causing the overall electric field vector to rotate in a circular manner as the wave propagates through space. So, the single patch antenna design consists of two circular patches.one is the main patch and the other is the small additional smaller patch [9]. Based on the transmission line model, the radius of the main patch and additional patch can be approximately determined using Equation 1 to 2 [9].

$$R_1 = \frac{130.708}{e_r f_r (GHz)} mm \quad (1)$$

$$R_2 = \frac{54.71}{e_r f_r (GHz)} mm \quad (2)$$

After many simulations approaches, the main patch has a radius 6.5mm to get resonant frequency 5.8GHz. The radius of small additional circle which had been merged to the main circle is 3.3mm and its orientation value to the main patch (6,3.35) for LHCP and (-6, -3.35) for RHCP. There are three main parameters for this proposed antenna such as radius of main and additional patch and location of additional patch. This design is fed by 50Ω microstrip transmission line and it is connected center of the antenna. To design the quarter wave length transformer its impedance has to be determined using Equation (3) [10]. The quarter wave transformer is used to convert 281Ω to 50Ω. A quarter-wave transformer is a transmission line segment that is precisely one-fourth of the wavelength of the signal that it is designed to work with it. The quarter wave length transformer impedance is 117Ω and its calculated width using Equation (4), (5) and (6) is 0.45 mm [11].

$$\text{Quarter Wave Length Transformer} = \sqrt{\text{Patch Impedance} \times z_0} \quad (3)$$

$$W = \begin{cases} \dfrac{8he^{A}}{e^{-2A} - 2}, A > 1 \\ \dfrac{2h}{\pi}\left[B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\ln(B - 1) + 0.39 - \dfrac{0.61}{\varepsilon_r} \right], A < 1 \end{cases} \quad (4)$$

$$A = \left(\frac{z_{in}}{60}\right)\sqrt{\frac{\varepsilon_r + 1}{2}} + \sqrt{\frac{\varepsilon_r - 1}{\varepsilon_r + 1}}\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \quad (5)$$

$$B = \frac{60\pi^{2}}{z_{in}} \quad (6)$$

Where, z_0 is the characteristic impedance of the microstrip line.

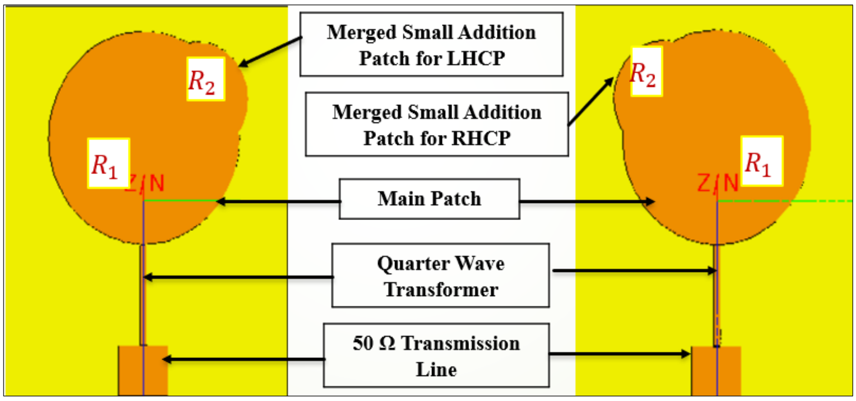

Figure 1: Structure of the Initial Antenna Design (a) LHCP (b) RHCP

Because the resonant frequency and circular polarization frequency band are different, it is used the technique of slotting to make resonant frequency shift. Fig 2a shows the configuration of the microstrip CP patch antenna with one slot. First slot is used for frequency shifting. And then, the second slot were added to the patch for its reflection coefficient performance better. The effect of two slots length and width will improve impedance matching and frequency shifting. There are three main parameters in proposed design that are radius of main patch and small patch, position of small additional patch and length and width of two slots. These three parameters can be affected antenna performance of reflection coefficient and axial ratio and frequency shifting.

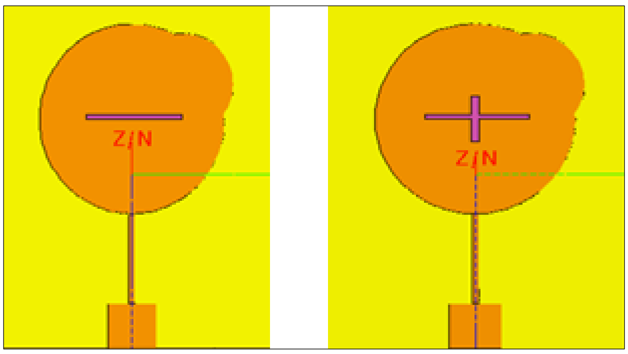

Figure 2: Evolution Process of the Slot Miniaturization Technique: (a) Initial Element with 1 Slot on the Patch, (b) 2 Slots on the Patch

2.2 Antenna Array Design

Feeding networks are crucial components in circularly polarized (CP) antennas, with various types employed to achieve desired performance. Corporate microstrip feed lines are often chosen for their simplicity; however, they tend to introduce higher resistive losses [12]. To achieve good radiation performance, sequential feeding network structure have to use in this proposed four element array antenna. Thus, this sequential feeding network structure is applied in this proposed array antenna.

The proposed sequential feeding network is shown in Figure 3 a. The feeding network consists of four impedance converting segments λ/4 where the length and width of the first segment is l_0 and w_0 (l_0 = 5.7mm and w_0= 3.2mm). This first segment of the feeding network is connected to a 50 Ω coaxial cable while the four outputs are connected to 100 Ω lines. And then, three segments are generated based on a circle of radius R = λ/2π with different impedance values (w_1=5.6 mm, w_2= 3mm, w_3=0.3mm). A multi-segment quarter-wavelength transformer is used to reduce current attenuation along the array feed, thereby enhancing the power coupled to the radiating elements of the array [13]. As shown in Figure 3(b), lowering the input impedance improves current transmission, which leads to an increase in the delivered power. This configuration ensures adequate current distribution across the feeding network, effectively supplying all radiating elements.

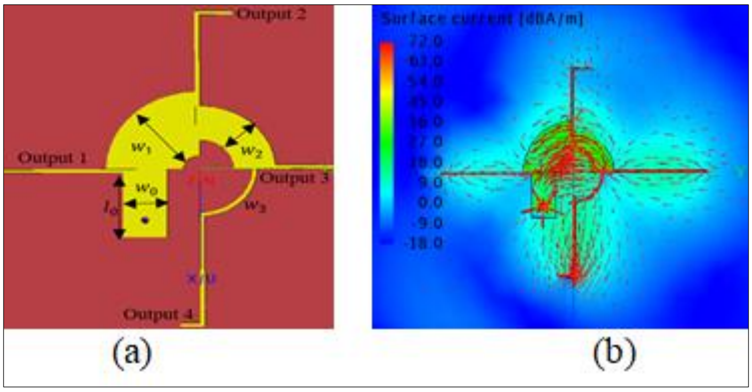

Figure 3: (a) Configuration of the proposed array feed (b) Current flow through the feeding array network

In sequentially rotated array technique consists of multiple of two element and phase feeding between the elements is 0˚, 90˚,180˚,270˚. The configuration of sequential rotation 2 × 2 CP antenna array with SR phase feed is shown in Fig 4. The CP antenna element is a single-fed two slot circular. In practice, the inter-element distance is the key factor that can alter the broadside gain, side lobe level, and cross-polarization discrimination patch, which is sequentially rotated and fed by the proper excitation through the SR feed [14].

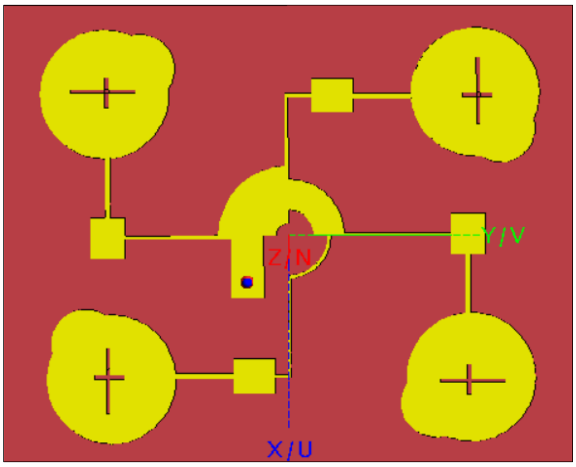

Figure 4: Configuration of 2 × 2 SR CP Array

A commercially available tool, FEKO software is used for simulation purposes. The array is constructed on square flame retardant 4 (FR4). The unit of two type proposed antennas are mm. The design specifications of proposed antennas are shown in Table 2 [15].

Table 2: The design specifications of proposed antennas

Parameters(mm)	Single Element Antenna	Array Antenna
Radius of Main Circle	6.5	6.5
Radius of Small Circle	3.3	3.3
Width of Slot1	0.315	0.315
Length of Slot1	6.48	6.48
Width of Slot2	0.45	0.45
Length of Slot2	3	3
No of Substrate	1	1
Width of Substrate	19	56
Length of Substrate	23	45
Height of Substrate	1.588	1.588
No of Element	1	2 x 2
Feeding Method	Microstrip line feed	Sequentially Rotated (Coaxial Feed)

3. RESULTS AND DISCUSSIONS

3.1 Proposed Single Element Antenna and Measurements

Fig. 5 shows photographs of the prototype 5.8-GHz band LHCP single element antenna. The antenna has been designed on a 1.588 mm thick-single layer FR4 substrate having a relative permittivity of 4.4 with a loss tangent of 0.025. The total size of the antenna is 23 mm× 19 mm× 1.588 mm. It can see the microstrip line is connected directly to the edge of the radiating patch. The impedance matching between the feed line and the radiating patch is achieved through the use of a quarter-wavelength transformer.

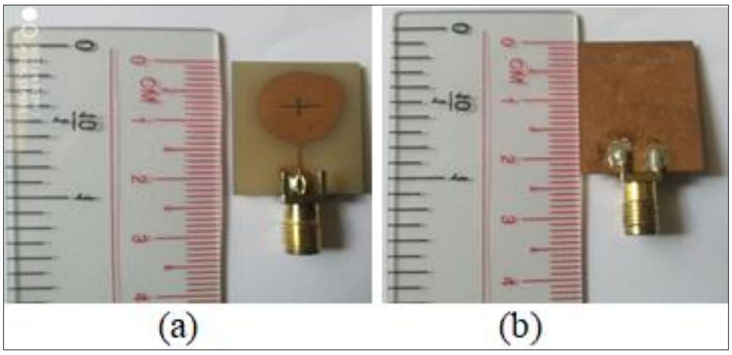

Figure 5: 5.8-GHz Prototype of Single Proposed Antenna (23 mm× 19mm). (a) Top view. (b) Bottom view

The simulated and measured results for the reflection coefficients of the single proposed antenna are compared in Fig. 6. The S11 of the proposed single antenna are measured using VNA master. The behavior of the simulation and measured results are difference because resonant frequency is shifting to low frequency. But this difference is within the acceptable range. The simulated impedance bandwidth is extended from 5.57 to 5.94 GHz (6.4 % with resonant frequency 5.8 GHz). The simulated minimum value of s11 is -32.43 dB at 5.8 GHz and the measured minimum value of s11 is -15.8 dB at 5.8 GHz.

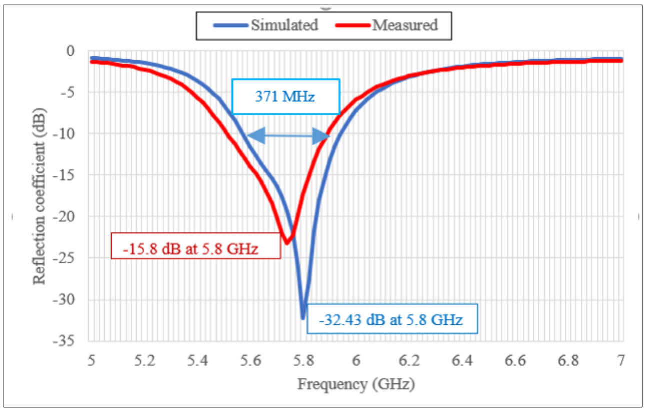

Figure 6: Comparison of Simulated and Measured Results of Reflection Coefficients

The simulated and measured results for VSWR are compared in Fig. 7. VSWR is less than 2, so the impedance is matching between port and patch [16]. According to the result, the measured VSWR value is 1.38 and the simulated value is 1.05. This means that the antenna gets minimum signal reflections, maximize power transfer, and improving antenna performance.

The smith chart plot is also shown in Fig 8 and shows the input impedance of the antenna at frequency 5.8 GHz. According to the result, the impedance of the simulated antenna achieves about 49.8 Ohms and the measured accesses 53.5 ohms at the desired frequency which is match with the characteristic impedance. This impedance varies with the frequency.

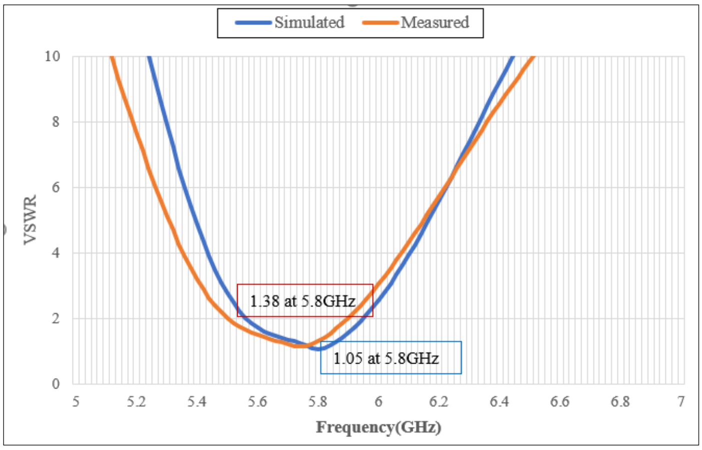

Figure 7: Comparison of Simulated and Measured Results of VSWR

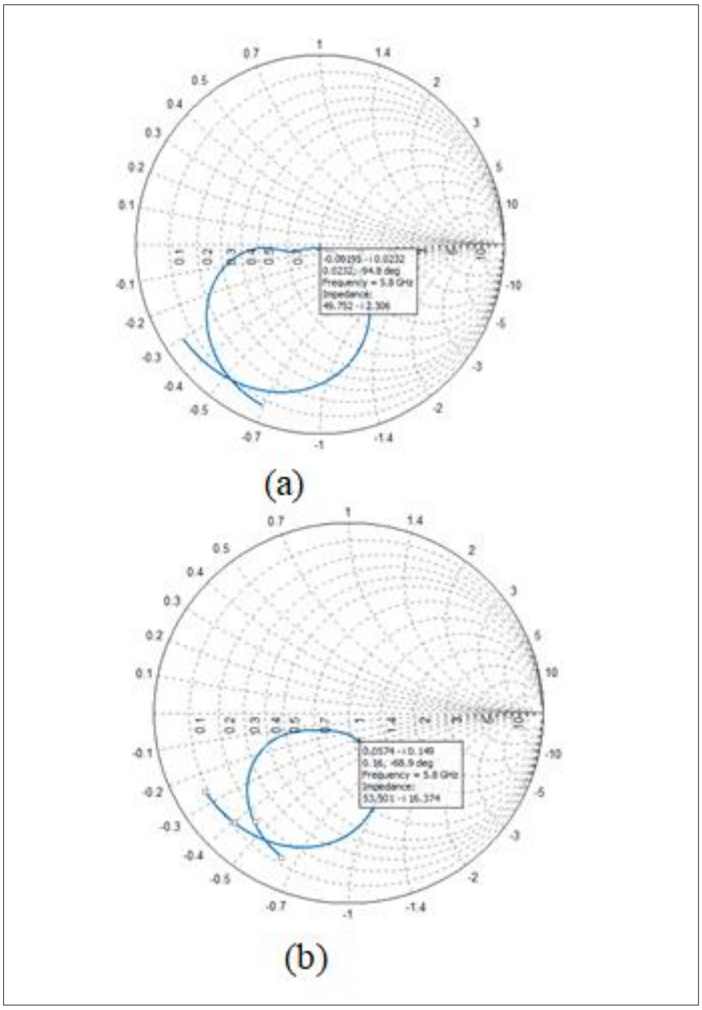

Figure 8: Smith Chart of Proposed Single Element Antenna (a) Simulated (b) Measured

The ideal axial ratio for circular polarization is 1, which is when the ratio between the minor axis and the major axis is 1. This means that the rotation direction of the E following the propagation direction of the wave describes a perfect circle. Achieving this across the entire frequency range is challenging in practice; therefore, circular polarization is considered good when the axial ratio (AR) is 3 or lower, which is also an acceptable value. Figure 8 shows the simulated axial ratio (AR) and realized gain at 5.8GHz of the CP single patch antenna. The minimum values of the simulated AR are 0.3 dB at 5.76 GHz for LHCP. The measured 3-dB AR bandwidth of the LHCP operation is 2.6% (between 5.69 GHz to 5.84GHz and the realized gain is 3.6 dBi at 5.8 GHz.

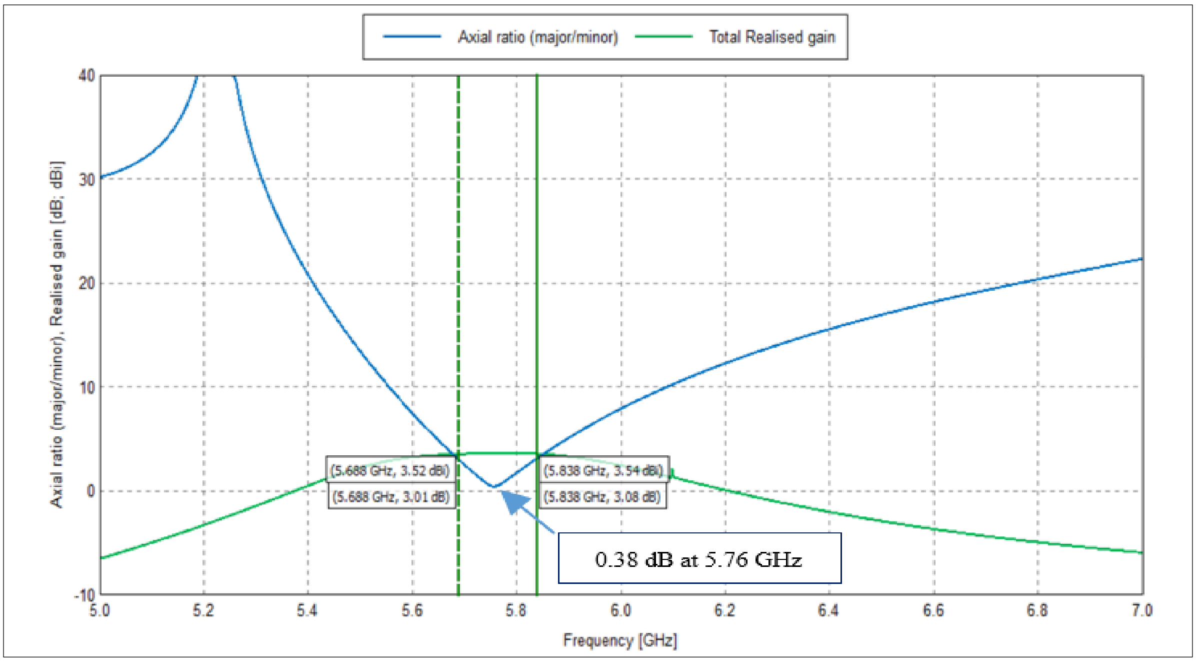

Figure 9: Simulated Results of Axial Ratio and Realized Gain at Frequency 5.8 GHz

Figure 10 show axial ratio as a function of Theta. This value can be used to determine the width of the coverage area with circular polarization. From the axial ratio result is less than 3 dB over the entire range (-60˚ to 79˚), axial ratio bandwidth is about 139˚.

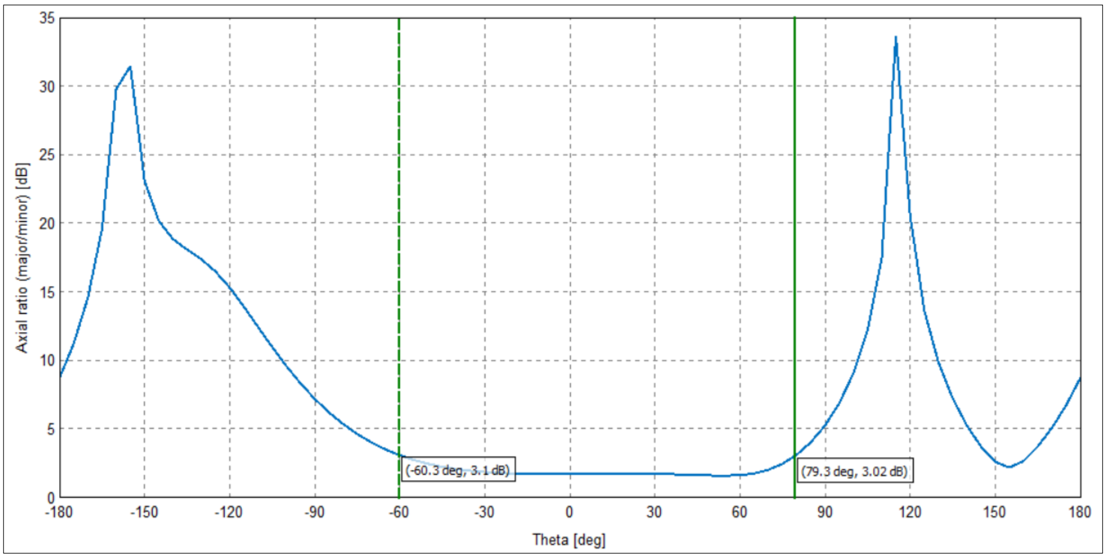

Figure 10: Axial Ratio Beam Width Result at 5.8 GHz

The surface current distribution on an antenna can help determine the type of circular polarization (CP). In show in fig 11 in which the surface current distribution rotates in a clockwise direction when viewed in the direction of propagation, it indicates LHCP [17]. The electric field vector rotates in a left-handed spiral as the wave travels. Analyzing the surface current distribution helps in verifying whether the desired polarization is achieved and allows for tuning the design to optimize the polarization characteristics. If the additional circle position is changed to negative position of the main patch, the type of polarization will be changed to Right hand Circular Polarization (RHCP).

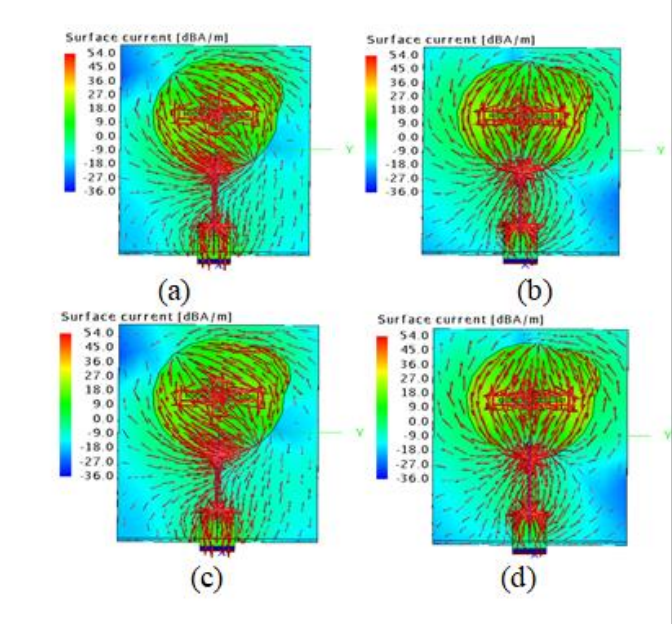

Figure 11: Current distribution of Single Element Antenna (a) at 0 Degree, (b) at 90 Degree, (c) at 180 Degree (d) at 270 degree

The 3D radiation pattern of single patch proposed antenna is presented in Fig 12(a) with the directivity gain is 6 dBi at 5.8 GHz. The polar form radiation pattern with maximum magnitude of gain is presented in Figure 12(b). According to this figure, beam width of the antenna is 94.59 degree in phi = 0 degree and 105.74 degree in phi = 90 degree at 5.8 GHz. The beam width of XZ plane is narrower than YZ plane.

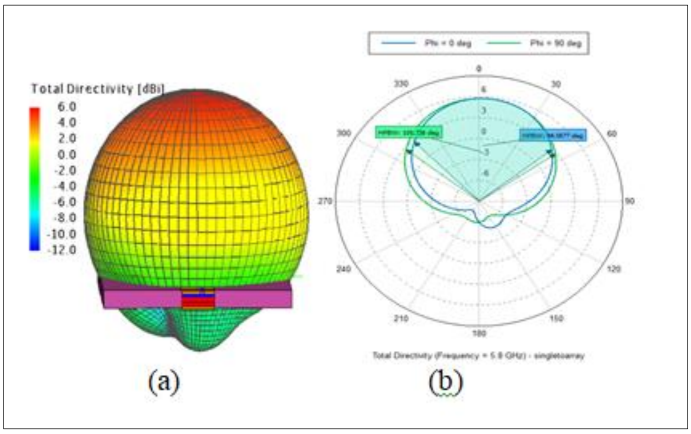

Figure 12: Radiation pattern of Proposed Single Element antenna at 5.8 GHz. (a) 3D View (b) Polar form

As mentioned earlier, the purpose is to achieve a gain of 7 to 12 dBi with wide AR bandwidth. The feeding technique is a crucial aspect of microstrip patch antenna design, as selecting the appropriate method ensures efficient power transfer between the radiating element and the feed structure. Thus, the SP feed can easily be extended to the large CP array for high-gain with wide band axial ratio and wide impedance bandwidth.

3.2 Antenna Array Design

Figure 13 shows a fabricated 5.8-GHz band prototype of the proposed antenna. The size of the antenna is 56 mm × 45 mm. The patch-to-patch separation is 36 mm (0.702λ_0) [18]. The center conductor of the coaxial connector extends through the FR4 and then is soldered to the radiating patch, while the outer conductor is connected to the ground plane.

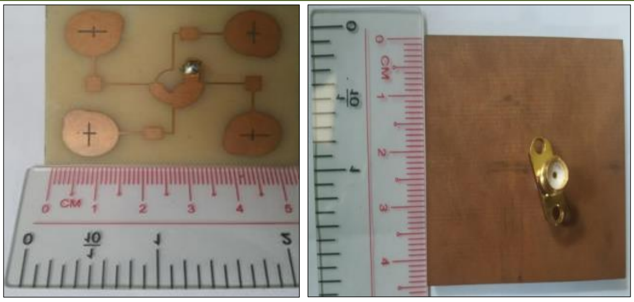

Figure 13: 5.8-GHz Prototype of 2x2 Proposed Antenna Array 56 mm× 45 mm) (a) Top View (b) Bottom View

Figure 14 denotes the measured and simulated reflection coefficient of the circular polarization 2x2 array antenna. Return loss presents to measure how well the antenna match with the transmission line. Blue lines are used to present simulated values whereas red lines represent measured values. According to the result, the measured s11 value is -13.1 dB at 5.8 GHz and the simulated s11 value is -18.08 dB at 5.8 GHz. The impedance bandwidth is 5.54 GHz to 6.62 GHz (10.1%). By the proposed sequentially feeding method, the impedance bandwidth of the array increased from 6.4% to 10.1%.

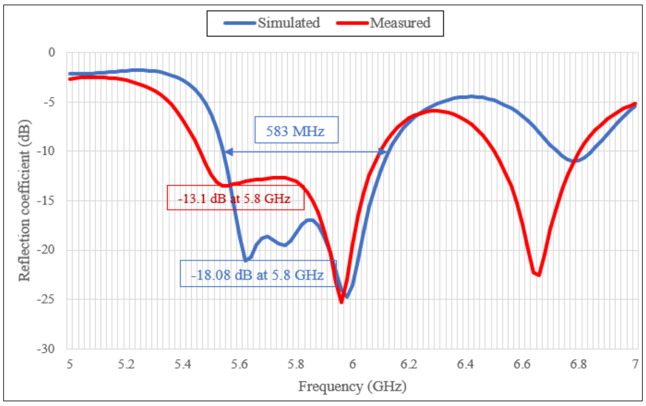

Figure 14: Comparison of Simulated and Measured Results of Reflection Coefficients

The simulated and measured results for VSWR are compared in Figure 15. The simulated value of VSWR is 1.28 at 5.8 GHz and the measured value of VSWR is 1.57 at resonant frequency 5.8 GHz.

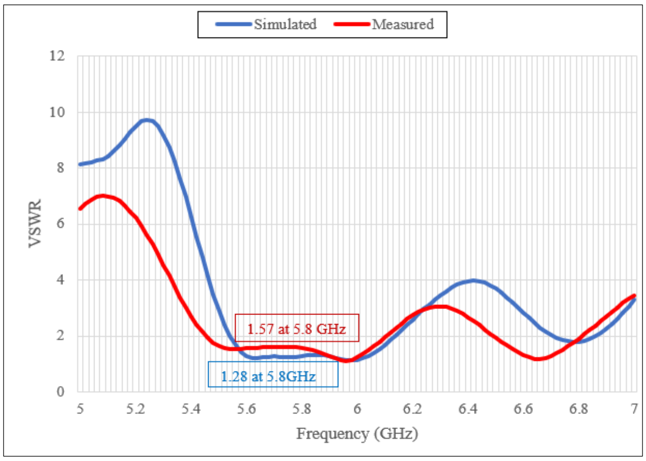

Figure 15: Comparison of Simulated and Measured Results of VSWR

The simulated axial ratio and realized gain of the array are shown in Fig 16. The simulated 3 dB axial ratio bandwidth of the array is 10.3% (5.5 GHz to 6.1 GHz). The minimum axial ratio value is 0.519 dB at 5.829 GHz. And then, in this figure, the realized gain of the antenna is 7.7 dBi.

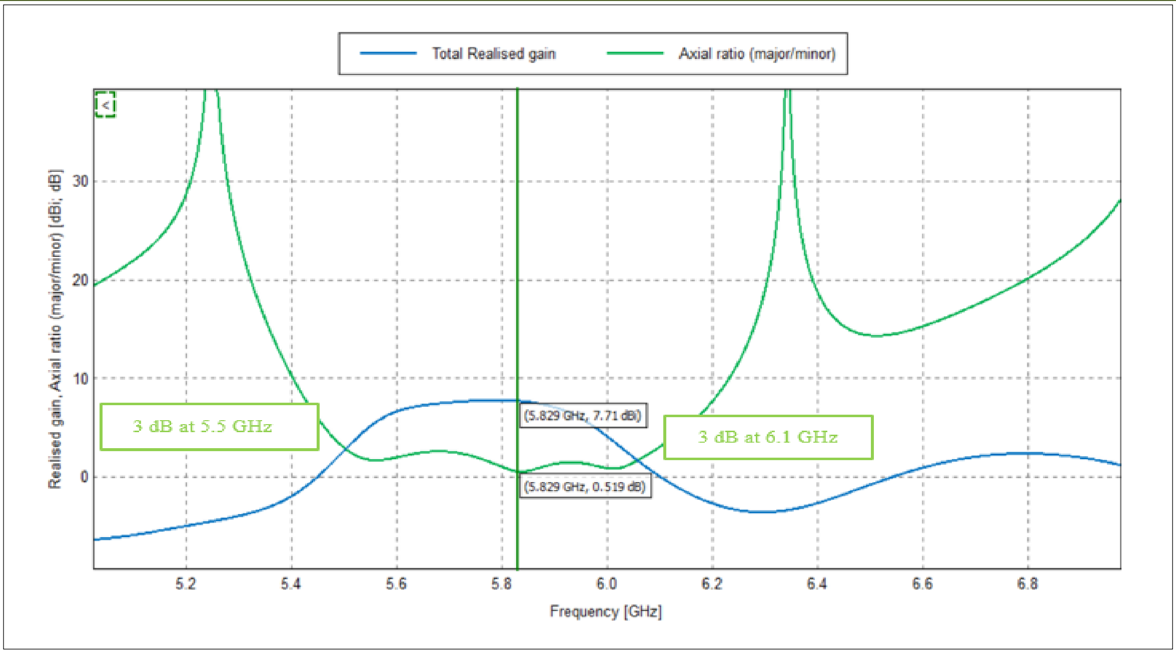

Figure 16: Simulated Results of Axial Ratio and Realized Gain

As shown in Figure 17, the axial ratio beam width is about 119 ° which is axial ratio less than 3 dB. The axial ratio beam width is less than single proposed antenna because it is inversely proportional to the antenna's gain.

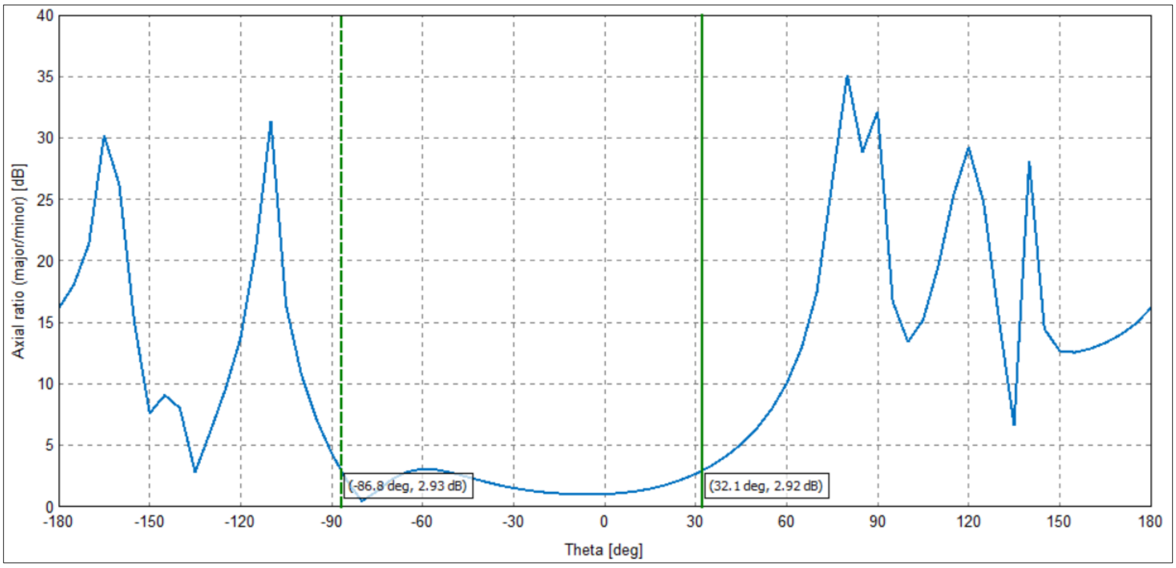

Figure 17: Axial Ratio Beam Width Result at 5.8 GHz varying Theta

The current distribution on the microstrip patch antenna is essential in determining the polarization of the radiated wave, whether it be linear, circular, or elliptical [19]. If the current oscillates in a straight line back and forth along the length of the antenna, resulting in linear polarization. If the current distribution creates a rotating electric field vector as the wave, the wave becomes circularly polarized. The surface current on the patch oscillates in a clockwise direction, making this antenna identifiable as a left-hand circularly polarized antenna.

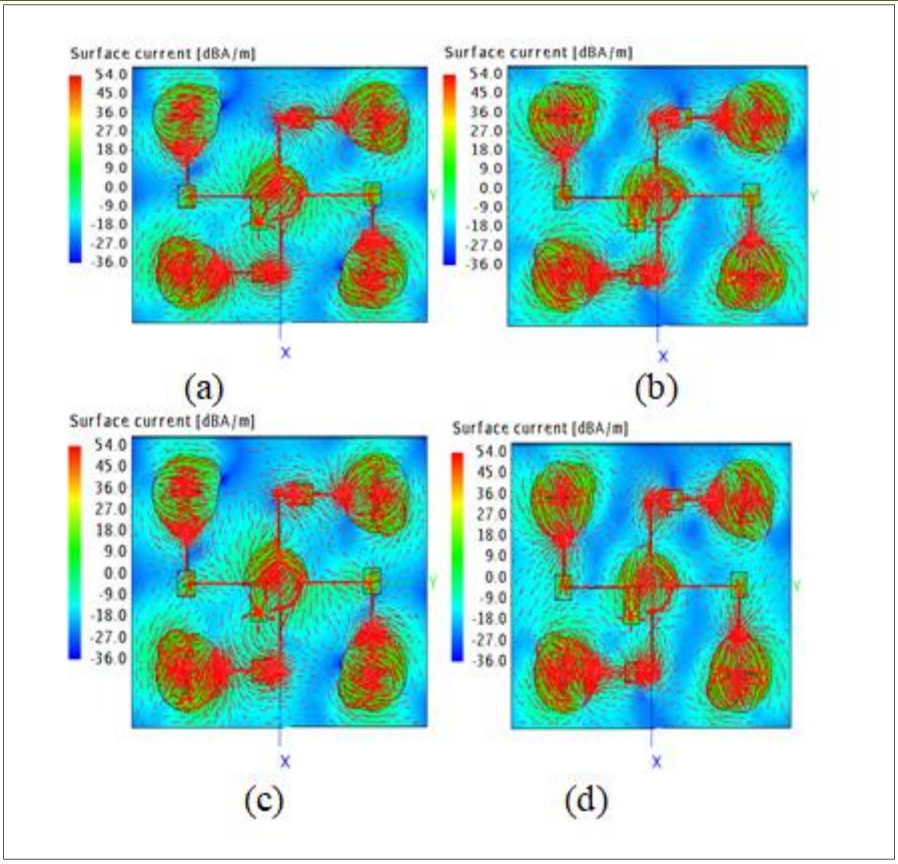

Figure 18: Current distribution of Antenna (a) at 0 Degree, (b) at 90 Degree, (c) at 180 Degree, and (d) at 270 Degree

The radiation pattern is one of the most essentially parameters in the radiation part of the antenna. The radiation pattern with maximum directivity of gain is presented in Fig 19 (a), the maximum gain can be found 12 dBi with beam width 54 degree in phi=0 degree and 43 degrees in phi = 90 degree the maximum gain can also be found the same gain in XZ plane and YZ plane at 5.8 GHz. The radiation pattern polar form of proposed antenna is shown in Figure 19 (b).

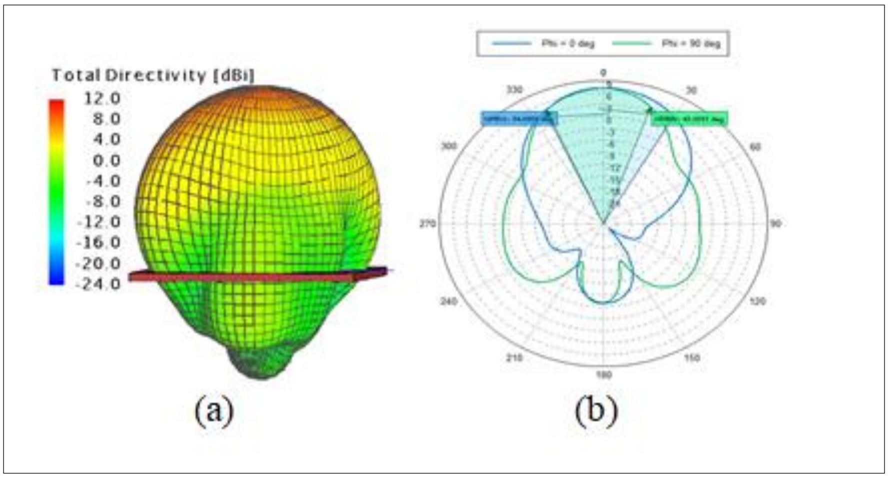

Figure 19: Radiation pattern of Proposed Array Antenna at 5.8 GHz. (a) 3D Radiation pattern, (b) Polar form

The primary aim of this study was to design a C-band antenna for a CubeSat satellite, addressing key challenges involved in the process. The principal requirements to be accomplished were high gain 7.7 dB, compact size, low cost, a beam width of 40◦ – 50◦ in all the frequency range and circular polarization of the antenna. Table 2 compares the performance summary of single patch and array design.

Table 3: Comparison of single element antenna and 2x2 element antenna array

Parameter	Single Design	Array Design
Impedance Bandwidth (%)	6.4 %	10.1 %
Axial Ratio Bandwidth	2.6 %	10.3 %
3dB Beamwidth (˚)	94.59˚at XZ	54˚at XZ
Axial Ratio Beamwidth (˚)	105.74˚at YZ	43 at YZ
Realized Gain	139˚	119˚
Directivity	3.6 dBi	7.7 dBi

Table 4 presents a performance comparison between the proposed antenna and previously published antenna designs for CubeSat applications.

Table 4: Comparison of the proposed array antenna with previously reported antennas

Ref	[19]	[20]	[21]	[22]	Proposed
Frequency [GHz]	5.8	5.1	5.8	3.5	5.8
Size [mm2]	90 x 90	83 X 69	74X 74	100 x 100	56 x 45
No. of elements	9	2	4	16	4
No. of substrate	2	1	1	1	1
Impedance BW [%]	1.28%	10.20%	3.2%	2.2%	10.1%
Axial ratio BW [%]	Not Provided	Not provided	-	-	10.3%
Realized Gain	6.9	5.9	13	8.03 dBi	7.7 dBi
polarization	CP	CP	LP	LP	CP
Material	Rogers RT 6010 and FR4	Glass Substrate	RT/duroid®6002 s	Rogers TMM10	FR4
Applications	Cubesat	Cubesat	Cubesat	Cubesat	Cubesat

It can be seen that the antennas reported in [19, 20], have a smaller gain than the proposed antenna. The antenna in [21, 22], has a higher gain than the proposed antenna but its size is larger and using expensive material. In terms of IBW and ARBW, antennas in [19-22], are narrower than that of the proposed antenna.

4. CONCLUSION

In this study, a single feed compact circular polarization antenna array was designed for CubeSats. A single element antenna with microstrip line feed and a sequentially antenna array with coaxial feed using sequentially rotated method for wide impedance bandwidth and axial ratio bandwidth are presented. A comparison between single element of proposed antenna with a four elements sequential rotated array show that axial ratio bandwidth and input impedance bandwidth of antenna array improved to 7.7 % and 3.7%, respectively. And then, the realized and directivity gain were improved 3.6 dBi to 7.7 dBi and 6dBi to 12 dBi when it is passed to the array antenna. The circular polarization performance of the proposed design depends strong upon the position of small additional patch. The proposed antenna design can be adjusted for other desired frequencies by modifying the radius parameters of the main and additional patches. A potential future development to extend this study is the integration of the proposed antenna with a CubeSat. And then, a 4 × 4 CP antenna array that is based on the compact 2 × 2 array fed by a multistage SR feeding network can be further enhanced.

Competing Interests: The authors declare no competing interests.

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