A Dual-Band Circularly Polarized Printed Antenna for Deep Space CubeSat Communication

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ABSTRACT

This paper presents the design of a dual-band printed planar antenna for deep space CubeSat communications. The antenna system will be used with a radio for duplex operation in a CubeSat, which can be used for a lunar mission or any deep space mission. While a high-gain CubeSat planar antenna/array is always desired for a deep space mission, high-performance ground stations are also required for robust communication links. For such a mission, the X-band is the appropriate frequency for the downlink communication, which is very challenging in the case of deep space communication compared to the uplink communication. At this frequency, the antenna size can have small enough dimension to form an array to obtain high-gain directional radiations for the successful communication, including telemetry and data download. NASA's Deep Space Network (DSN) has the largest and most sensitive 70 meter-diameter antenna that can be considered for this type of mission for reliability. DSN has uplink and downlink frequency of operations in 7.1-GHz and 8.4-GHz bands, respectively, which are separated by approximately 1.3 GHz. A straight forward approach is to use two antennas to cover uplink and downlink frequencies. However, CubeSats have huge space constraints to accommodate science instruments and other subsystems and commonly utilize outside faces for solar cells. Therefore, in this paper, we have proposed a planar directional circularly polarized antenna with a single feed that operates at both uplink and downlink DSN frequencies. Simulated 3-dB axial ratio bandwidth of 165 MHz, from 7064 MHz to 7229 MHz for uplink, and that of 183 MHz, from 8325 MHz to 8508 MHz for downlink, are achieved. Also, a wide impedance bandwidth of 23.86% (VSWR < 2) is obtained. From this single probe-fed stacked patch antenna, peak RHCP gain of 9.24 dBic can be achieved.

INTRODUCTION

CubeSat has set its foot in the era of deep space and interplanetary exploration. However, unlike large satellites, CubeSat faces challenges from limited power, mass, and area to install communication components such as antennas. That's why ground station selection is a very important part of communication subsystem design for CubeSat orbiting at deep space. Interplanetary spacecraft missions orbiting in deeps space to observe the solar system or universe get supports from the antenna network of NASA's Deep Space Network (DSN) [1]. The DSN was developed to interface with satellites orbiting at approximately 16,000 km from the earth and beyond [2]. CubeSats orbiting the moon are applicable for deep space communication as the distance to the Moon is about 385,000 km from the earth's center, on average [3]. DSN consisting of three deep-space communication facilities that are located roughly 120 degrees apart from each other around the earth supports both uplink and downlink communication at multiple frequencies [1].

This work aims to design a planar high-gain circularly polarized antenna for deep space communication. We started the design with a detailed link budget analysis considering DSN's 70-meter antenna parameters. A distance of 400,000 km is considered to estimate uplink and downlink link margins. A moderate RF transmits the power of 1 W is considered from the antenna for the worst-case scenario. The link budget study for different scenarios stipulates the requirement of a high-gain directional X-band antenna for a solid deep space communication. From the datasheet of DSN [4], it is known that the allocated frequencies for the deep space X-band uplink communication are 7145 MHz to 7190 MHz, whereas downlink frequencies are 8400 MHz to 8450 MHz. A typical approach is to use two different antennas operating at these two frequencies. Being aware of the space limitation of CubeSat we decided to use only one dual-band antenna which will operate in these two bands. Satellite communications mostly use circularly polarized (CP) antennas because they do not require strict orientation between transmitting and receiving antennas like linearly polarized antennas [5]. Both of the DSN's allocated frequency ranges support right-hand and left-hand circular polarization for satellite communication [4]. We have chosen to develop circularly polarized antennas which will generate radiation with axial ratio < 3dB and VSWR < 2 in those frequency bands.

ANTENNA GEOMETRY AND DESCRIPTION

The proposed antenna is a singly-fed circularly polarized – electromagnetically coupled patch (SFCP-EMCP) antenna, similar to the one presented in [6]. It comprises of three metal layers and two dielectric layers. The driven patch is on a ground plane, separated by a dielectric substrate: Rogers RT6010 material with relative permittivity, $\varepsilon_r = 10.2$, and thickness, $h_1 = 0.635$ mm. This is the first dielectric layer. This dielectric material is ideal for operation in X-band as it has a low dissipation factor and a stable permittivity against atmospheric changes in space [7]. The driven patch is excited by a 50-Ω SMA probe at a point 2.75 mm away from the center of the patch. The second dielectric layer is an air gap of 2.3 mm which separates the parasitic patch that is electromagnetically coupled to the driven patch. The use of air dielectric as layer separation has the advantage of fine-tuning the axial ratio and impedance matching over foam dielectric [6]. The top metal layer is an inverted parasitic patch on a dielectric substrate, which does not have any direct electrical connection. We have used RT5880 for this layer with a relative permittivity of 2.2 and thickness, $h_2 = 1.57$ mm. The ground plane actually determines the actual size of the antenna, which is preferably smaller than the smallest face of a CubeSat: 10 cm. If a bigger face is available, then a larger ground plane can be used. A smaller ground plane affects the CP performance greatly. However, acceptable performance is obtained with a square ground plane size of 18 mm from this antenna for a 3U CubeSat. The circular polarization is achieved using negative perturbation on both the driven and parasitic patches in the form of diagonal corner cuts. This is a popular technique to generate CP from planar printed patch antennas when a single feed is used [8, 9]. Single probe-fed CP patch antenna has narrow axial ratio bandwidth. Wide axial ratio bandwidth can be achieved easily if dual orthogonal feeds are used. However, dual feeds require larger space on the substrate to accommodate the feed network. Since a large bandwidth in the dual bands is not required in this case, a single probe feeding is considered for the feed. The perturbations, driven and parasitic patch dimensions, and the air gap are judicially selected to optimize antenna performance. The optimized antenna parameters are given in Table 1. Figure 1 shows the detailed antenna geometry where all parameters are labeled.

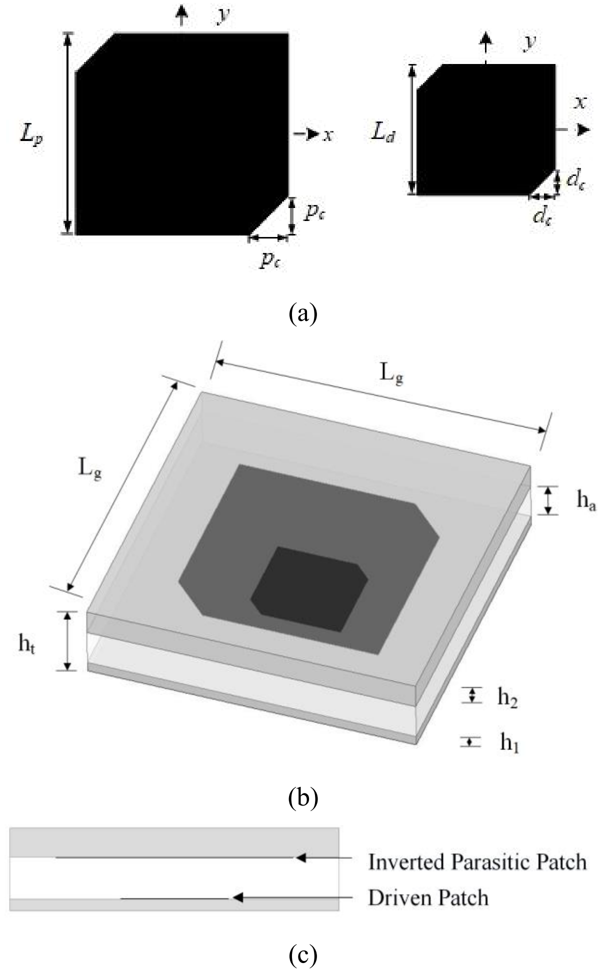


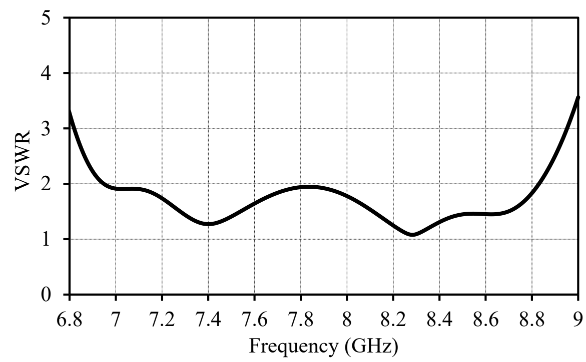
Figure 1: (a) Geometry of the Parasitic and the Driven Patches with Negative Perturbations, (b) 3D View, and (c) Side View of the Proposed Antenna

Table 1: Design Parameters of the Stacked Patch Antenna with Negative Perturbations For CubeSats

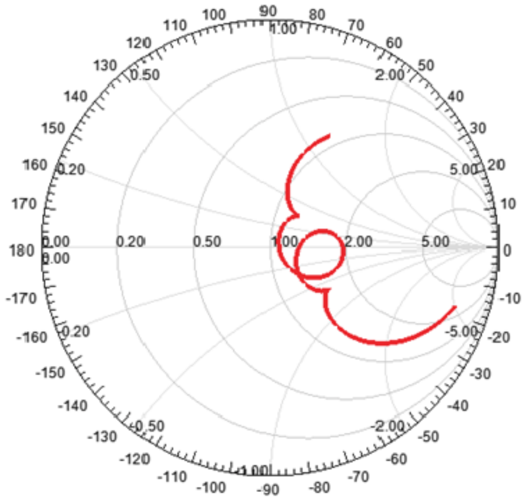
Driven Patch Size, L_d	5.9 mm × 5.9 mm
Driven Patch Corner Cut, d_c	1.05 mm
Parasitic Patch, L_p	13 mm × 13 mm
Parasitic Patch Corner Cut, p_c	2.3 mm
Air Gap, h_a	2.3 mm
Total Antenna Thickness, h_t	4.6 mm
Ground Plane, L_g	18 mm × 18 mm

RESULTS AND DISCUSSIONS

For a ground plane size of 18 mm × 18 mm, a wideband VSWR < 2 bandwidth of 1.88 GHz or 23.86% (from 6948 MHz to 8830MHz) is achieved from this antenna. The VSWR plot is showed in Figure 2(a). The simulated



(a)



(b)

Figure 2: (a) VSWR Versus Frequency, and (b) Impedance Versus Frequency Plots of the Proposed Antenna

results are obtained using the Finite Element Method (FEM) based software, Ansys HFSS 2019. Multiple loops form on the impedance response of this antenna, presented in Figure 2(b), indicates the wideband performance from this antenna.

The Axial ratio versus frequency plot of the antenna is shown in Figure 3. The aim is to keep the lowest AR values at the center frequencies of those two NASA allocated uplink and downlink bands. Two minima in the AR versus frequency plot due to two resonators indicate the dual-band CP nature of this antenna. The driven patch operates in the uplink frequency band whereas the parasitic patch operates in the downlink band. AR ~ 3 dB bandwidth of this dual-band antenna is 7064 MHz to 7229 MHz and 8325 MHz to 8508 MHz for the uplink and downlink respectively, which match nicely with DSN frequencies. The variation in the axial ratio with the

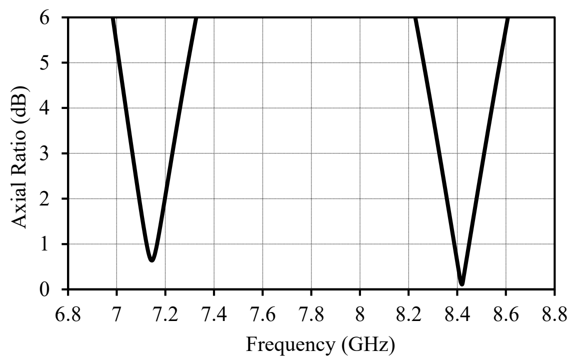
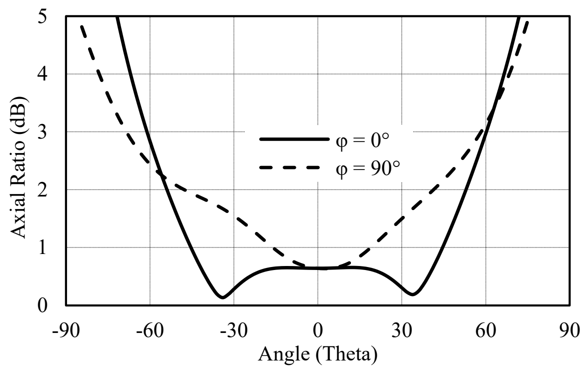
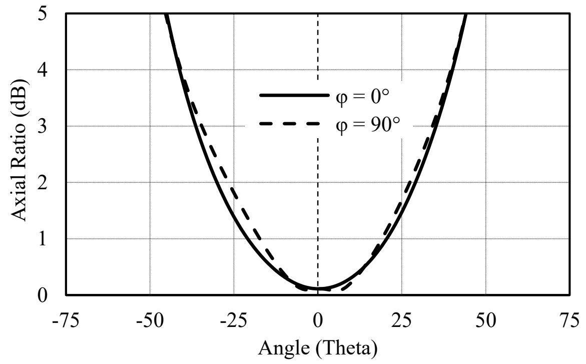


Figure 3: Simulated Axial Ratio Versus Frequency Plot of the Proposed CP Antenna



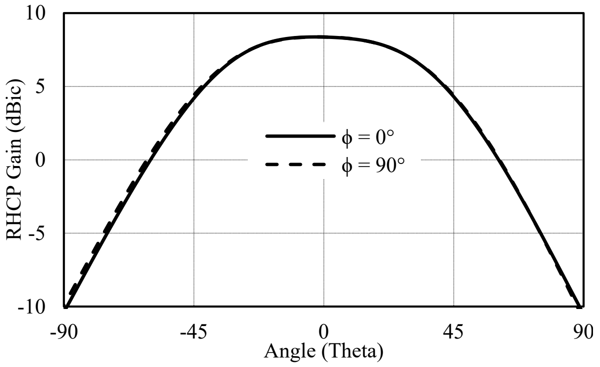
(a)



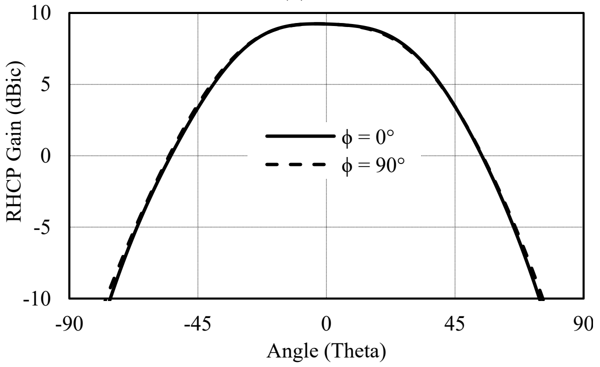
(b)

Figure 4: Axial Ratio Versus Elevation Angle Plots in ϕ = 0° and 90° Planes at (a) 7146 MHz, and (b) 8420 MHz

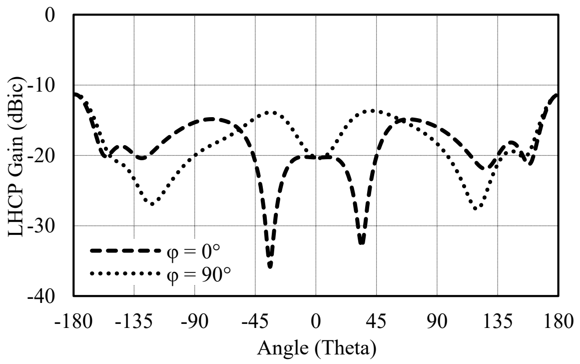
elevation angle at these two frequencies are also plotted in Figure 4. The antenna exhibits wide 3-dB axial ratio beamwidths, which are 121°, -61° to 60° off the boresight in the ϕ = 0° plane, and 126°, -68° to +58° off the boresight in the ϕ = 90° plane at 7146 MHz. At 8420 MHz, the 3-dB axial ratio beamwidth is 71°, -36° to 35°



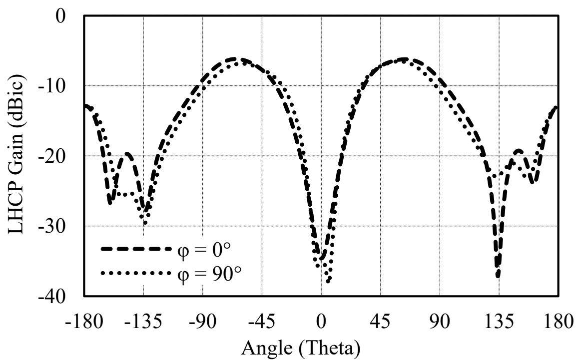
(a)



(b)



(c)



(d)

Figure 5: Gain Patterns at Two Principal Planes, (a) RHCP at 7146 MHz, (b) RHCP at 8420 MHz, (c) LHCP at 7146 MHz, and (d) LHCP at 8420 MHz

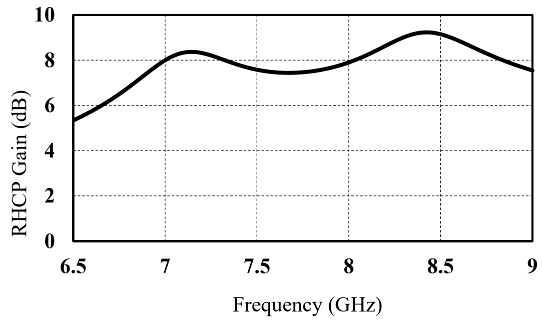


Figure 6: Simulated RHCP Gain Versus Frequency. Peak gains are achieved at 7146 MHz and 8420 MHz

in the ϕ = 0° plane, and 68°, from - 34° to + 34° in the ϕ = 90° plane. The beamwidths at uplink frequencies are significantly larger than that with a single-layer CP patch antenna, where the axial ratio degrades drastically just off the boresight. From the simulation results, it is observed that a maximum RHCP gain of 9.24 dBic can be achieved at 8420 MHz whereas the maximum RHCP gain is 8.37 dBic at 7146 MHz. Both Right-hand and left-hand CP gain plots are shown in Figure 5. LHCP gains are significantly lower than RHCP gains.

DESIGN TECHNIQUE

Simultaneously, obtaining the lowest dual-band axial ratio values at the targeted frequencies and achieving acceptable impedance matching is quite a challenging task for this design. We started the design following the algorithm presented in [6], where transmission line feeding is used. In CubeSat applications, the line feeding network will require more antenna real estate on any CubeSat face. In order to obtain a compact antenna, we chose probe feeding and the lowest possible ground plane size. Along with patch dimensions, the air gap, ground plane, and feeding point affect the impedance matching significantly. It is observed that for a lower air gap, the VSWR increases, although bandwidth increases significantly. On the other hand, the VSWR decrease with a higher air gap within a limit decreasing the impedance bandwidths. Moreover, variations in the air gap significantly affect axial ratio values. In the case of different ground plane sizes, for a larger ground plane, the impedance matching degrades. The axial ratio remains almost the same if the ground plane size is not significantly small. Figure 7 shows the variations in the reflection coefficient of the antenna for different ground plane sizes.

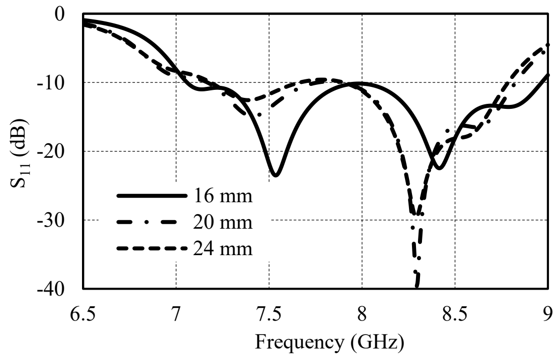


Figure 7: S_{11} Versus Frequency for Different Ground Plane Sizes

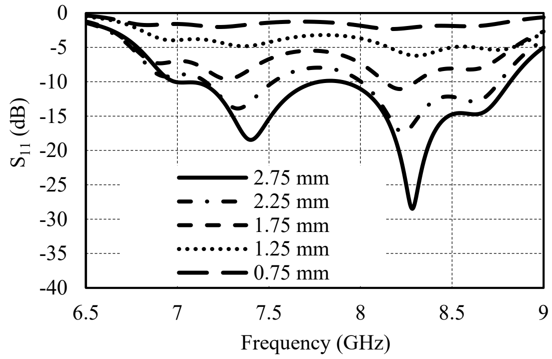


Figure 8: S_{11} Versus Frequency for Different Probe Feed Locations (All Distances are Calculated from the Center Point of the Driven Patch)

Figure 8 shows the variation in S_{11} for various feed locations. The feed point to match to 50 Ω for this design is found to be near the edge of the driven patch when $S_{11} < -10$ dB for a wide frequency range. If the feed point is near the center, the reflection coefficient response of this antenna is poor.

CONCLUSIONS

The design of a dual-band circularly polarized printed antenna is presented in this paper. The primary aim of this design is for use in deep space CubeSat communication. For deep space, high onboard antenna gain is desired. The stacked configuration provides a considerably high gain from this antenna. If more gain is required, an array can be developed considering this as the array element.

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