SSC14-IX-7

Development of Low-profile Antennas for CubeSats

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ABSTRACT

The advent of transparent antennas on CubeSats originated out of necessity to eradicate the current mechanically dependent monopole antennas that are typically placed on the edges of the satellite to maximize the efficacy of its solar panels. Consequently, as a direct result of their mechanical deployment methods, these antennas are highly prone to failure. Standard patch antennas cannot be used since typical materials would block the solar panels when placed on top. This paper investigates several designs for frequencies at 434 MHz, 2.4 GHz, 1.6 GHz, and 900 MHz to be placed on the faces of a 3 unit (3U) CubeSat. As a result of the combined work over the span of one year, several antennas were manufactured for the 434 MHz, and the 2.4 GHz bands for downlink communication. A silver epoxy conductor was used on quartz substrate for the 2.4 GHz and a copper PIFA antenna on duroid RO6002.

INTRODUCTION AND BACKGROUND

Cube Satellites (CubeSats) are a relatively new type of pico-satellite dating little over a decade since their standardization by the California Polytechnic State University [1]. These satellites come in 10 × 10 × 10 cm modular cubes that can be standalone (1U) or be connected into sets of two or three modules (2U or 3U) with each module weighing approximately 1 [kg]. This standardization allows for manufacturers and research institutions to rapidly develop and launch multiple CubeSats simultaneously with low associated costs compared to their enormous predecessors.

Due to the novelty of these satellites, much of the emphasis was on the payloads and power generation and consumption while the antenna systems used were commercially available off-the-shelf monopoles that were not optimized for a given mission. Consequently, this stimulated the interest in optimizing the antennas by replacing the monopoles with microstrip patch antennas since their performance and reliability are greater. However, patch antennas suffer from being opaque in the visible spectrum and would block the solar panels; thus the need for transparent designs.

The antennas in these projects were designed to fit on the faces of a 3 unit (3U) that are 10 × 10 × 34 cm and also the end faces that are 10 × 10 cm, with operating frequencies of 434 MHz and 2.4 GHz for downlink-ground communications, 1.616 GHz for communication with the Iridium constellation of low-earth-orbiting satellites, and 900 MHz for inter-satellite communication among the CubeSats.

Three design approaches were initially investigated: (1) mesh design (conductor and ground plane), (2) using Indium Tin Oxide due to its transparency, (3) slatted ring. This initial exploration yielded favorable results, with further work going into isolating certain methods to fabricate antennas.

The software of choice for simulating the antennas was ANSYS High Frequency Structure Simulator (HFSS) and the antennas were designed to match to a standard coaxial feeding method at 50 [Ω].

PRELIMINARY DESIGNS

Meshed Design

The foundation for the mesh design spawned from the standard, solid rectangular patch antenna. CAD formulas were employed to obtain approximate dimensions for the lengths of the appropriate resonant frequencies. The material was then sectioned into a grid design where the material was removed leaving only the connecting lines. Figure 1 below is the result of empirically varying the line widths. To preserve the transparency of the entire system, the substrate material also needs to be transparent, thus a 2.25 mm quartz material was used as the substrate. An iterative process was strategically followed that illustrated that the resonant frequency dropped as the grid lines were made thinner and that the resonant frequency was between 8-10% lower than its solid counterpart. It was determined that as the line width decreased, transparency increased, at the expense of efficiency and gain [2].

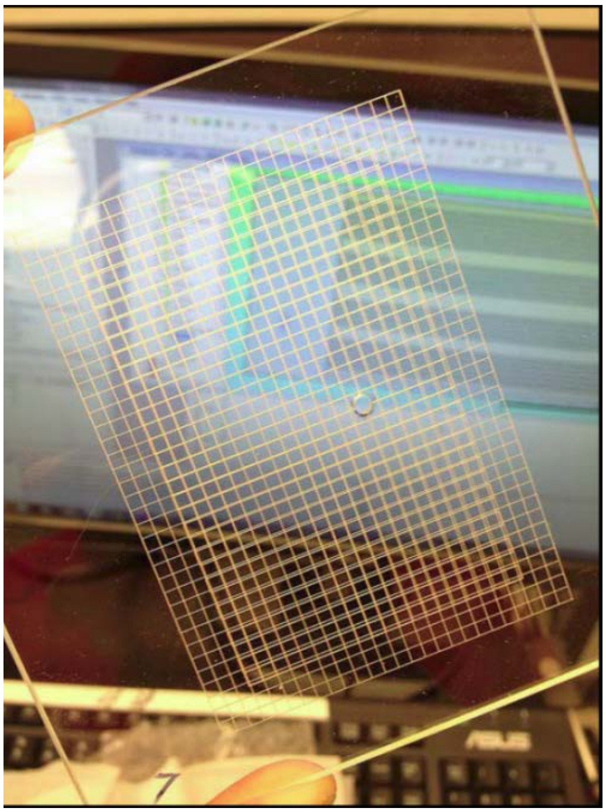

Figure 1. Meshed patch antenna.

ITO Patch Antenna

The design of the ITO patch antenna also shared its roots from the solid copper patch; hence, its dimensions were based off the approximate dimensions of the solid patch. The ITO film thickness, typically on the orders of nanometers, presented another issue since the thickness of copper ranged in the order of microns. These thin films, though highly transparent, came at the expense of efficiency, which was nearly 50%. Design limitations for the ITO antennas were rooted in the fact that vendors only supplied sheets up to 10 × 10 cm, rendering the designs for the 900 MHz and 434 MHz extremely challenging. Furthermore, vendor data were only provided up to 10 MHz, thus introducing a certain level of ambiguity for the 2.4 and 1.616 GHz designs. Figure 2 illustrates a fabricated ITO patch antenna.

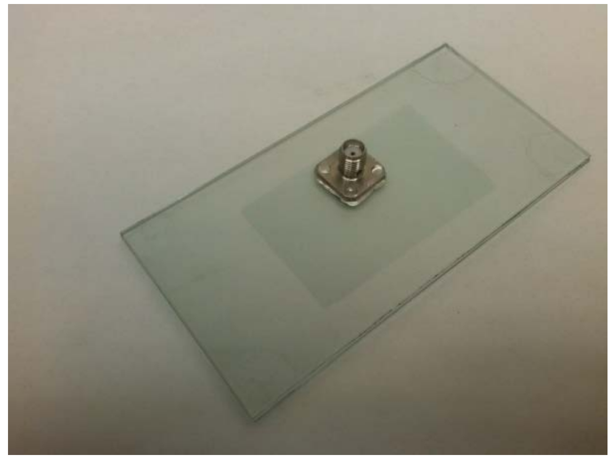

Figure 2. ITO patch antenna.

Slatted Ring Resonator Antenna

This design operates as a direct result of its basic design, having an open area in the center of the ring. This provided an inherent level of transparency by default, thus making it a reasonable choice for lower frequencies. Slats, i.e. metal strips, were added into the open area to control the resonant frequency and input impedance, though transparency was decreased as a result. Figure 3 depicts the slatted ring resonator design.

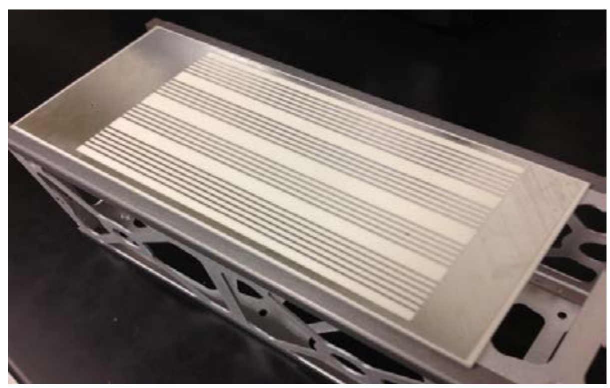

Figure 3. Slatted ring resonator on face of CubeSat.

PRELIMINARY RESULTS

Meshed Results

The silver conductor on a transparent quartz substrate resulted in good resonances that were slightly offset from the design frequency. Modifying the resonant dimensions of the designs to achieve ideal resonance can rectify these discrepancies. The results established the mesh design as an ideal method for transparent antenna designs. Changing the line thicknesses of the design can vary the efficiency and transparency, yielding optimum results.

ITO Results

The efficiency of the ITO design proved to be 20% less than the corresponding solid copper design at an operating frequency of 1.616 GHz. The conductivity of ITO is lower than copper and its skin depth is also much less than that of copper, thus producing more losses. This design also provides less degrees of freedom since the manufacturers dictate specifications such as its conductivity and thicknesses. However, the transparency can exceed 75%. ITO designs yield high transparencies, but their losses are attributed to the films being thin.

Slatted Ring Resonator Results

The 434 MHz was the frequency of choice for this design due to its size of 8.3 × 19.5 cm. This design yielded a transparency of 40% but the return loss (S_{11}) only reached a level of -9 dB at the resonance. It was thus realized that a transparent antenna at such low frequencies was highly problematic.

IMPROVED DESIGNS/RESULTS

2.4 GHz Design

Using the previous results, it was realized that the mesh design would be ideal to pursue and refine to achieve the desired results. The 2.4 GHz operating frequency was designated as the primary operating frequency for ground communications and as such, was concentrated on for achieving improved results. Patch antennas inherently exhibit a broadside, linearly polarized (LP) antenna pattern. [3]. Consequently, a linearly polarized antenna will be designed for testing purposes to ensure that the both materials, the silver conductor and the quartz, will endure the extreme thermal changes and the vibrations experienced throughout the launch process. A circularly polarized (CP) design will also be designed as a final product. Figure 4 illustrates the LP design.

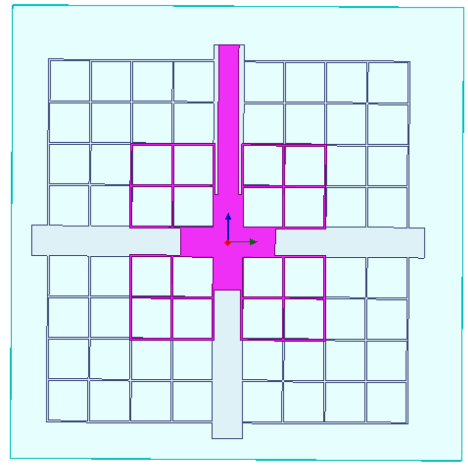

Figure 4. Linearly Polarized 2.4 GHz design.

Both the patch and the ground plane preserved the initial mesh proposal, but were slightly modified to achieve the proper resonance frequency and matched input impedance. The size of this antenna is a 4.34 cm square on a meshed square ground plane measuring 8.01 cm, fed from a transmission line. Though not exactly a true grid as in Fig. 1, these alterations produced better matching and bandwidth performance. Figures 5 and 6 show the return loss plot and the input impedance versus frequency.

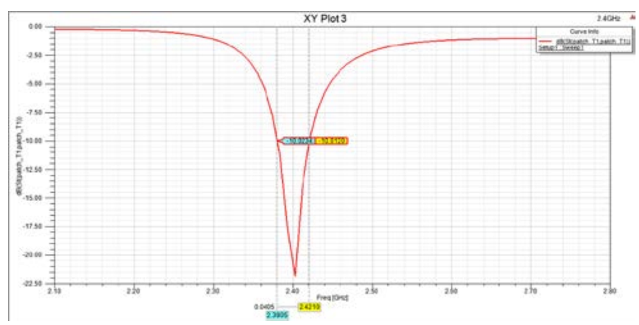

Figure 5. S_{11} vs. frequency plot for the antenna in Figure 4.

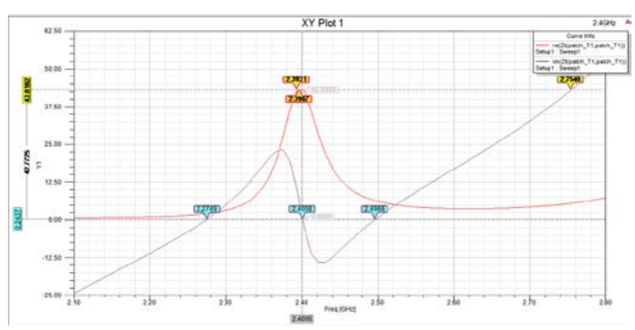

Figure 6. Input impedance vs. frequency for the antenna in Figure 4.

It is seen from the figures that a 50 [Ω] match at 2.4 GHz was achieved and the bandwidth for this design is 1.2%. The industrial, scientific, and medical (ISM) radio standard for this frequency band is 4.08% [4]. The CP design can be seen in Figure 7.

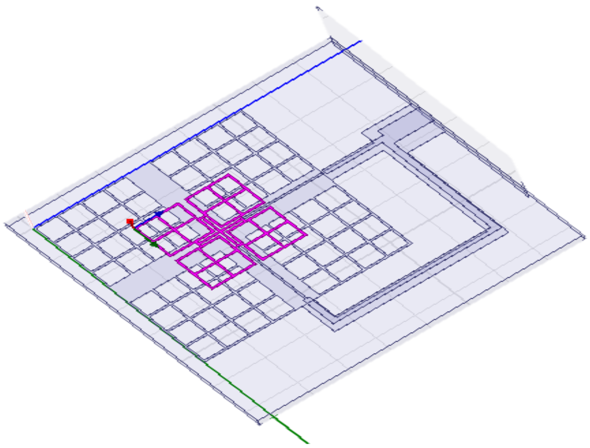

Figure 7. Circularly polarized 2.4 GHz design.

This design also uses the transmission feed network to achieve a match to the 50 [Ω] coax line. Two 100 [Ω] lines in parallel were then connected and matched to the edge impedance of the mesh patch. An axial ratio of 1.4 was achieved, though an axial ratio of 1.0 would be ideal. Using a scaling factor, this design can be resized to resonate at other frequencies, such as 1.616 GHz.

434 MHz Design

A conventional 434 MHz microstrip antenna is by nature a large antenna. Corollary to its size, this design would not fit on the faces of a CubeSat, which explains the difficulty in design even with the slatted ring resonator. Consequently, the transparent approach for this frequency was abandoned. A new approach was pursued, in which a microstrip antenna will be placed underneath the solar panels, so that the antenna does not need to be transparent. As a result of its size, however, a solid patch would still not meet the size constraints; thus, shorting vias were introduced on one edge of the patch to effectively reduce the resonant length by half, creating a PIFA-like microstrip antenna. The coaxial input was placed near the center of patch to match the input impedance of the antenna. The bandwidth requirement based on the ISM standards is 0.59%, leading to another challenging design feature. Therefore, a notch was introduced into the patch to increase the bandwidth. Figure 8 illustrates the PIFA design of the 434 MHz design with the C-notch.

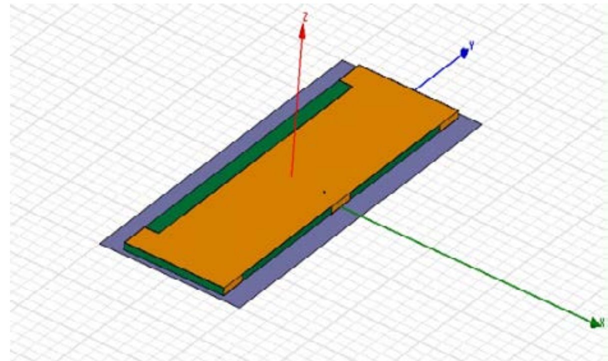

Figure 8. PIFA with a C-notch, designed for 434 MHz.

The original bandwidth for this PIFA design without the notch was 0.3%, with a substrate (Rogers duroid RO6002 ε_r = 2.94) thickness of 1.5 mm. The thickness was doubled, to the next standard size of 120 mils, and the notch dimensions were empirically optimized to yield an end bandwidth of 0.7%, exceeding the ISM minimum requirements. This design measures 7.1 × 29 cm, nearly overlaying one of the entire long faces of the CubeSat. Figures 9 and 10 illustrate the return loss plot and the impedance match.

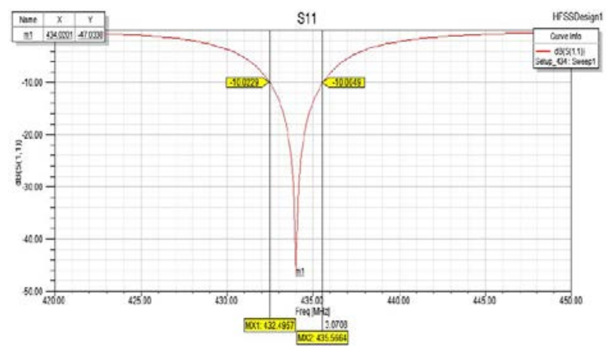

Figure 9. S_{11} vs. frequency plot for the antenna in Fig. 8.

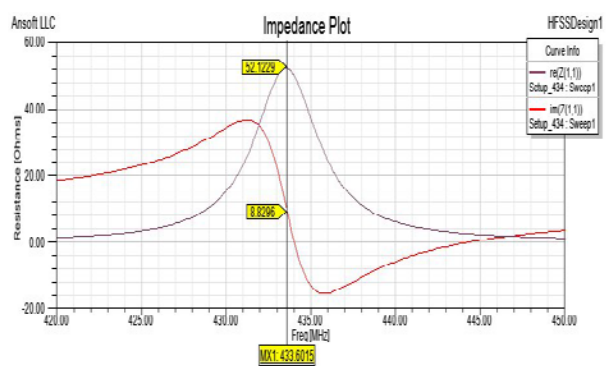

Figure 10. Input impedance vs. frequency plot for the antenna in Fig. 8.

It is clear from the figures that the impedance is matched and the resonance frequency occurs at 434 MHz with an S_{11} of -47 dB. Figure 11 below is an image of actual antennas that will be sent for testing purposes.

Figure 11. 434 MHz antennas. The left two show the PIFA designs with a notch, while the one on the right has no notch.

ITO Design

The ITO conductor was abandoned after determining the quality (Q) factor of patches made with it, and extracting from this the losses attributed to the thin film. The quality factor can be expressed by

$$Q = \left(\frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sp}} + \frac{1}{Q_{sw}} \right)^{-1},$$

where Q_c = quality factor due to conductor loss; Q_d = quality factor due to dielectric loss; Q_{sp} = quality factor due to space wave radiation; Q_{sw} = quality factor due to surface wave excitation. The model used for analysis was a resonant cavity model with an ideal ground plane, dielectric, and perfect magnetic boundaries (PMC) on the perimeter of the patch. Thus, from this perspective, radiation is the only loss. The quality factor was extracted in HFSS, using the eigenmode solver feature, and found to be much lower than that for the meshed design. Therefore, the use of ITO for transparent antennas for CubeSat applications was abandoned in the favor of the meshed design.

CONCLUSIONS AND FUTURE WORK

Transparent antennas were initially explored using a mesh design, ITO (transparent metal), and a slatted ring resonator design for various frequencies of operation. The mesh design proved highly effective while preserving transparency. The ITO design had a reasonable performance, but with a lower efficiency than for the mesh design, for the same level of transparency. The slatted ring antenna, designed for the lower band at 434 MHz, achieved operation at the desired frequency but with a fairly poor transparency. The mesh design was developed to operate at 2.4 GHz, but it can then be scaled to other frequencies.

A non-transparent 434 MHz design was developed that was a variation of a microstrip PIFA, introducing a notch to increase its bandwidth. For this antenna the solar panels would get placed above the antenna instead of below it as they would for the transparent designs. This antenna demonstrated satisfactory performance in the simulations.

Testing of the fabricated antennas for the 434 MHz band will be scheduled and the results obtained will be compared to those in the simulations for accuracy and to make necessary adjustments. The 2.4 GHz linearly-polarized design will be fabricated and sent for testing as well.

Once the results are obtained for the linearly-polarized design, the proper adjustments will be made on the circularly-polarized version of the design, which will then be sent for testing as well. Equally important for all designs, is to explore the bandwidth enhancement on each design to allow for manufacturing tolerances and thermal expansion due to the temperature extremes encountered in space. The radiation patterns and input impedance properties of the antennas mounted on actual CubeSat frames will also be obtained.

References

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