Integrated Solar-Panel Antenna Array for CubeSats (ISAAC)

Taha Yekan, Reyhan Baktur, Charles Swenson
Utah State University
4120 Old Main Hill, Logan, UT, 84321, USA
taha.shahvirdi@aggiemail.usu.edu

Harry Shaw, Obadiah Kegege
NASA Goddard Space Flight Center
Greenbelt, MD, 20771, USA
harry.c.shaw@nasa.gov

ABSTRACT

Integrated Solar-Panel Antenna Array for CubeSats (ISAAC) is a high gain, efficient, lightweight, conformal X-band antenna array that is integrated with solar panels of a CubeSat. The antenna design is modular and independent from the solar cells, and therefore allows off-the-shelf components. In addition, the antenna elements are of low profile and do not require significant surface real estate. ISAAC will suit a multi-unit (≥ 3U) CubeSat that has sufficient area for solar cells (hence the antennas), or a CubeSat with deployed panels. The paper examines three best antenna candidates: loop, cross dipole, and meshed patch. It is found that while all three can provide sufficient phase range for the reflectarray, loop geometry has the best tradeoff between optical transparency and the antenna gain. The paper also presents the element performance for different array periodicity lengths (lattice distance) such as half wavelength and sub-wavelength. The optimal ISAAC design promises more than 94% optical transparency and higher than 22 dB gain. The targeted application of ISAAC is for Near Earth Network (NEN), however, the design can be conveniently scaled to Space Network (SN) and Deep Space Network (DSN) radios.

I. INTRODUCTION

The importance of integrating antennas with solar cells for small satellite communication is clear and a few studies in element level integration has been presented [1-3]. On the array level, NASA has shown an integration of a high gain array antenna on the opposite side of a deployed solar panel [4]. The goal of this paper is to present an alternative design to ISARA, where a low profile, transparent reflectarray is integrated directly on top of solar cells. The targeted application is for Near Earth Network (NEN), however, the design can be conveniently scaled to other space networks.

This paper examines three types of antenna elements suitable for a reflectarray design that can be integrated on top of solar cells, and presents detailed design methodology, analysis, and comparisons of the three designs. The study also shows the performance of the three element designs for different substrate thickness and lattice sizes. Finally, a feed excitation using a fast prototyping 3D printing method is presented together with a prototyped reflectarray.

II. DESIGN METHODS AND ANALYSIS

The importance of integrating antennas with solar cells for small satellite communication is clear and a few studies in element level integration has been presented.

A. Cross Dipole

Unit cell of the reflectarray is composed of three layers as shown in Fig. 1.a. The bottom layer is copper ground plane. The second layer, which is the substrate for the unit cell element, is AF32 glass with dielectric constant of 4.5 and loss tangent of 0.015. A cross dipole is composed of two orthogonal dipole elements with length of \( \ell \) (Fig. 1.b). The width of cross dipole was chosen to be 0.25 mm. The reflection phase of the element can be changed by adjusting its length. Fig. 2.a shows the reflection phase of the cross dipole element with lattice size of half wavelength (\( \lambda/2 \)) for different values of substrate thickness (\( \ell \)). Also, the symmetric shape of element results in having same electromagnetic response under normal incident wave for TE and TM modes. Fig. 2.b is the reflection magnitude of the unit cell. As seen in Fig. 2.a, when \( \ell \) is small, the provided phase is almost constant, making it unsuitable for reflectarray design. This condition happens when radiation Q is greater than element Q.
The value of $h=1.5$ mm is found to be the critically coupled condition that happens when radiation $Q$ is equal to element $Q$. In this case, the phase response is too sharp and there is nothing reflected back as seen from Fig. 2.b, (near zero reflection at resonant length). When $h$ is greater than 1.5 mm, radiation $Q$ is less than element $Q$ (over coupled) [5]. Then, the phase response is applicable for reflectarray design. Increasing $h$ shows reduction of phase range but smoother phase variations. Considering all of these, $h=2.5$ mm was chosen in this study as a more optimal substrate thickness that provides good trade-off between phase range and feasible phase curve.

Reducing cell periodicity to sub-wavelength can provide special features like reducing loss and broadening the gain bandwidth and can be an effective method to design reflectarray on lossy substrates [6]. As we already know that the solar cells are lossy [7], we studied the cross dipole unit cell for different sub-wavelength lattice sizes as shown in Fig. 3. It is confirmed that working at the sub-wavelength shrinks the phase range and reduces the loss at the same time.

### B. Loop

The same study performed for the cross dipole, was carried out for a loop geometry (Fig. 1.b). The reflection phase of the loop element is obtained by adjusting the loop length while fixing its width as 0.25 mm. The same observation for the cross dipole was seen, where $h=1.5$ mm being critically coupled condition and $h=2.5$ mm being a reasonable substrate thickness to work with. Reflection phase and magnitude of the loop unit cell with different lattice sizes are summarized in Fig. 4.

### C. Meshed Patch

#### (1) Geometry

Unit cell of the reflectarray is composed of three layers as shown in Fig. 6.a. The bottom layer is copper ground plane. The second layer, which is the substrate for the unit cell element, is Rogers RT5880 with dielectric of
2.2 and loss tangent of 0.0009. In future application, the substrate will be the cover glass of solar cells, but for the current study purpose and for the ease of validation, a common high frequency laminate was chosen. The third layer is the meshed patch antenna element that is printed on top of the substrate, and is composed of horizontal and vertical lines with length of \( L \) and width of \( q \). Fig. 6.b shows a symmetric square 4x4 meshed patch. The transparency can be defined as (1) where \( A_{\text{Patch}} \) is the area of the entire patch and \( A_{\text{Metal}} \) means the area covered by metal.

\[
T_r = \frac{A_{\text{Patch}} - A_{\text{Metal}}}{A_{\text{Patch}}} \tag{1}
\]

The phase of the unit cell can be changed by adjusting \( L \). The meshed unit cell is symmetric with the same number of lines and line width \( q \). It can react the same for normal incident TE and TM modes. It also supports both vertical and horizontal linear polarizations that is an advantage for designing the reflectarray. The design frequency is 10 GHz.

(2) Analysis

2.A: Line width (q) Effect

It is clear that the line width affects the transparency with a thinner \( q \) results in a higher transparency as shown in Table 1. Fig. 7.a and Fig. 7.b represent reflection phase and magnitude of \( \lambda/2 \) unit cell for different values of \( q \). It can be observed that increasing \( q \) shrinks the phase range and decreases the slope of the phase curve. Also, a thicker \( q \) gives higher reflection magnitude, which means most energy is reflected back instead of being trapped inside the substrate. Considering the trade-offs between the optical transparency and the antenna’s performance, we have chosen \( q=0.2 \) mm in this study.

<table>
<thead>
<tr>
<th>( q ) (mm)</th>
<th>L = 6 mm</th>
<th>L = 9 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>87</td>
<td>91</td>
</tr>
<tr>
<td>0.2</td>
<td>75</td>
<td>83</td>
</tr>
<tr>
<td>0.4</td>
<td>54</td>
<td>68</td>
</tr>
</tbody>
</table>

2.B: \( \lambda/2 \) Unit Cell

The study is performed for meshed patch as described in Fig. 6.b and a solid patch with the same size, for a lattice size of \( \lambda/2 \). Fig. 8 shows the reflection phase of meshed patch and solid patch. It is seen from the graph that the meshed patch, similar to the solid patch, can provide required phase range for the reflectarray design. It is also seen that the meshed patch gives greater phase range than the solid patch at the expense of steeper
phase response. The phase range and $|S_{11}|$ at the resonant length are compared in Table 2. The meshed patch shows higher loss than patch antenna. But this level of loss is not a big concern for the array design.

![Figure 8: Phase response of $\lambda/2$ unit cell](image)

Table 2: Properties of $\lambda/2$ Unit Cell Elements

| Element         | Phase Range (deg) | $|S_{11}|$ (dB) |
|-----------------|-------------------|---------------|
| Patch           | 311               | -0.15         |
| Meshed Patch    | 326               | -0.77         |

2.C: Sub-wavelength Unit Cell ($\lambda/4$)

The same study as in 2.B is carried out for the unit cell of $\lambda/4$. The phase response for solid and meshed elements is shown in Fig. 9. It is seen that both elements provide the same phase range required for array design. Properties of the two transparent and non-transparent elements are summarized in Table 3. Comparing Table 2 to Table 3 shows that the sub-wavelength elements promise reduced loss while still providing the same phase range.

III. FEED DESIGN AND ARRAY PROTOTYPE

As we have studied three more optimal transparent elements suitable for ISAAC design, it is seen that the loop geometry offers better trade-offs between array design and transparency, even though the other two are still effective choices. Accordingly, we have chosen a sub-wavelength ($\lambda/4$) loop reflectarray for the final prototype. Before a final integration, the design is prototyped on a FR4 substrate (dielectric constant of 4.2, loss tangent of 0.015, and height of 2.36 mm) as seen in Fig. 10. For the validation purpose, a horn antenna, which is the most common excitation method,
perform validation on ISAAC, which has been planned as the next step.

CONCLUSION

Three types of transparent reflectarray antennas with transparency and aperture efficiency higher than previous publications are presented. The design method and results are presented. It is seen one of the element design offers higher overall performance in terms of optical transparency and antenna efficiency. Such a design is prototyped for a final validation, and a 3D printed horn that will be used for validating the reflectarray is presented. The achieved transparent reflectarray design offers more than 22 dB gain, higher than 94% optical transparency, and more than 40% aperture efficiency. We envision an integration of such an antenna design directly on top of solar panels of 3U or larger CubeSats as a potential replacement of today’s deployed dish antennas.

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REFERENCES