5-2010

Integrated Solar Panel Antennas for Cube Satellites

Mahmoud N. Mahmoud

Utah State University

Follow this and additional works at: https://digitalcommons.usu.edu/etd

Part of the Electrical and Electronics Commons

Recommended Citation

https://digitalcommons.usu.edu/etd/742

This Thesis is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact dylan.burns@usu.edu.
INTEGRATED SOLAR PANEL ANTENNAS FOR CUBE SATELLITES

by

Mahmoud N. Mahmoud

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Electrical Engineering

Approved:

Dr. Reyhan Baktur
Major Professor

Dr. Todd Moon
Committee Member

Dr. Charles M. Swenson
Committee Member

Dr. Byron R. Burnham
Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah
2010
Abstract

Integrated Solar Panel Antennas for Cube Satellites

by

Mahmoud N. Mahmoud, Master of Science
Utah State University, 2010

Major Professor: Dr. Reyhan Baktur
Department: Electrical and Computer Engineering

This thesis work presents an innovative solution for small satellite antennas by integrating slot antennas and solar cells on the same panel to save small satellite surface real estate and to replace deployed wire antennas for certain operational frequencies. The two main advantages of the proposed antenna are: 1) the antenna does not require an expensive deployment mechanism that is required by dipole antennas; 2) the antenna does not occupy as much valuable surface real estate as patch antennas. The antenna design is based on using the spacing between the solar cells to etch slots in these spaces to create radiating elements.

The initial feasibility study shows it is realistic to design cavity-backed slot antennas directly on a solar panel of a cube satellite. Due to the volume of the satellite, it is convenient to design antennas at S band or higher frequencies. Although it is possible to design integrated solar panel antennas in lower frequencies, such research is not the scope of this thesis work.

In order to demonstrate and validate the design method, three fully integrated solar panel antennas were prototyped using Printed Circuit Board (PCB) technology (PCB is a common solar panel material for small satellites). The first prototype is a circularly polarized antenna. The second is a linearly polarized two-element antenna array. The third
prototype is a dual band linearly polarized antenna array. Measured results agree well with simulations performed using Ansoft’s High Frequency Structure Simulator (HFSS).

The thesis also presents a feasibility study of optimization methods and reconfigurable solar panel antenna arrays. The optimization study explores methods to use genetic algorithms to find optimal antenna geometry and location. The reconfigurable study focuses on achieving different antenna patterns by switching on and off the slot elements placed around the solar cells on solar panels of a cube satellite.

It is shown that the proposed integrated solar panel antenna is a robust and cost-effective antenna solution for small satellites. It is also shown that given a solar panel with reasonable size, one can easily achieve multiple antenna patterns and polarization by simple switching.
Acknowledgments

I am heartily thankful to my major professor, Dr. Reyhan Baktur, for first giving me the opportunity to work on this project, which I was very interested in, for supporting me during my stay at Utah State University, and in guiding me always in the right direction. I would also like to thank her for the time and effort in reviewing and giving me feedback about my work. I would also like to acknowledge other members of my committee, Dr. Todd Moon and Dr. Charles M. Swenson, for their time in helping this thesis become a better product.

I am extremely grateful to the Space Dynamics Laboratory for funding this project.

I would also like to thank Robert Burt, Glenn Hatch, and Lynn Chidester from the Space Dynamics Laboratory for helping me to design, prototype the antennas, and measure the solar cells performance.

I would like to acknowledge all my colleagues at Utah State University, especially Tur- sunjan Yasin, Tim Turpin, and Alper Genc, who helped to start my project and give me support through my stay at Utah State University.

Mahmoud N. Mahmoud
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abstract</strong></td>
<td>iii</td>
</tr>
<tr>
<td><strong>Acknowledgments</strong></td>
<td>v</td>
</tr>
<tr>
<td><strong>List of Tables</strong></td>
<td>viii</td>
</tr>
<tr>
<td><strong>List of Figures</strong></td>
<td>ix</td>
</tr>
<tr>
<td><strong>1 Introduction and Initial Feasibility Study</strong></td>
<td>1</td>
</tr>
<tr>
<td>1.1 Antennas for Small Satellites</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Overview of Integrated Solar Panel Antennas</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Basic Design</td>
<td>3</td>
</tr>
<tr>
<td>1.3.1 Feasibility of Integrating Slot Antennas with Solar Panels</td>
<td>3</td>
</tr>
<tr>
<td>1.3.2 Radiation Mechanism of Slot Antenna</td>
<td>3</td>
</tr>
<tr>
<td>1.3.3 System Level Considerations</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Initial Prototypes</td>
<td>4</td>
</tr>
<tr>
<td>1.4.1 Feed Design</td>
<td>4</td>
</tr>
<tr>
<td>1.4.2 Prototype One-Element Cavity-Backed Slot Antenna</td>
<td>12</td>
</tr>
<tr>
<td>1.5 Effect of Solar Cells</td>
<td>13</td>
</tr>
<tr>
<td>1.6 Circular Polarization and Array Configuration</td>
<td>15</td>
</tr>
<tr>
<td>1.6.1 Circular Polarization</td>
<td>15</td>
</tr>
<tr>
<td>1.6.2 Slot Antenna Array</td>
<td>17</td>
</tr>
<tr>
<td><strong>2 Dual Band Cavity-Backed Slot Antennas</strong></td>
<td>24</td>
</tr>
<tr>
<td>2.1 Background</td>
<td>24</td>
</tr>
<tr>
<td>2.2 Dual Band Antenna Analysis</td>
<td>24</td>
</tr>
<tr>
<td>2.3 Prototype and Measurement Results</td>
<td>29</td>
</tr>
<tr>
<td><strong>3 Fully Integrated Solar Panel Antennas for Cube Satellites</strong></td>
<td>33</td>
</tr>
<tr>
<td>3.1 Two-Element Linearly Polarized Antenna</td>
<td>33</td>
</tr>
<tr>
<td>3.2 One-Element Circularly Polarized Antenna</td>
<td>35</td>
</tr>
<tr>
<td>3.3 Dual Band Antenna</td>
<td>36</td>
</tr>
<tr>
<td>3.4 Fabrication and Solar Panel Assembly</td>
<td>36</td>
</tr>
<tr>
<td>3.5 Measurements of Antenna Performance</td>
<td>38</td>
</tr>
<tr>
<td>3.6 Solar Cells Measurements</td>
<td>43</td>
</tr>
<tr>
<td><strong>4 Optimization and Pattern Reconfigurability</strong></td>
<td>49</td>
</tr>
<tr>
<td>4.1 Optimization</td>
<td>49</td>
</tr>
<tr>
<td>4.2 Optimal Side Lobe Suppression</td>
<td>49</td>
</tr>
<tr>
<td>4.3 Optimal Beam Steering</td>
<td>52</td>
</tr>
<tr>
<td>4.4 Optimal Efficiency</td>
<td>52</td>
</tr>
</tbody>
</table>
4.5 Reconfigurablity Study .................................................. 55
4.6 Isotropic, Dipole-Like, and Directive Patterns ................ 57
4.7 Circular Polarization ...................................................... 60

5 Conclusion ........................................................................ 62

References ........................................................................... 64
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Advantages and disadvantages of different feeding types.</td>
<td>12</td>
</tr>
<tr>
<td>1.2 Steering angles for different phase delays and spacing.</td>
<td>21</td>
</tr>
<tr>
<td>3.1 Gain of prototyped solar panel antennas.</td>
<td>48</td>
</tr>
<tr>
<td>4.1 Optimized values for the four variables after the end of iterations.</td>
<td>52</td>
</tr>
</tbody>
</table>
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>A typical small satellite used by the Space Dynamics Laboratory.</td>
<td>5</td>
</tr>
<tr>
<td>1.2</td>
<td>Solar cells assembly.</td>
<td>6</td>
</tr>
<tr>
<td>1.3</td>
<td>Slot antenna and its complementary dipole.</td>
<td>6</td>
</tr>
<tr>
<td>1.4</td>
<td>Radiation pattern from a slot antenna.</td>
<td>6</td>
</tr>
<tr>
<td>1.5</td>
<td>Resonance frequency of a 2.4 GHz slot antenna.</td>
<td>7</td>
</tr>
<tr>
<td>1.6</td>
<td>Cavity-backed slot antenna.</td>
<td>7</td>
</tr>
<tr>
<td>1.7</td>
<td>A drawing for the satellite when it is orbiting the earth.</td>
<td>7</td>
</tr>
<tr>
<td>1.8</td>
<td>A probe feed cavity-backed slot antenna.</td>
<td>8</td>
</tr>
<tr>
<td>1.9</td>
<td>S11 parameter of a 5 GHz probe feed slot antenna.</td>
<td>8</td>
</tr>
<tr>
<td>1.10</td>
<td>Radiation from a 5 GHz probe feed antenna.</td>
<td>9</td>
</tr>
<tr>
<td>1.11</td>
<td>(a) Inductive coupling CPW feeding, and (b) capacitive coupling CPW feed.</td>
<td>10</td>
</tr>
<tr>
<td>1.12</td>
<td>S11 parameters of both inductive and capacitive coupling CPW feed.</td>
<td>10</td>
</tr>
<tr>
<td>1.13</td>
<td>Radiation from a capacitive coupling CPW feeding.</td>
<td>10</td>
</tr>
<tr>
<td>1.14</td>
<td>(a) Simple ML feeding, (b) shorted ML feed, and (c) tapered ML feed.</td>
<td>11</td>
</tr>
<tr>
<td>1.15</td>
<td>Comparing S11 parameter between the simple, tapered, and shorted microstrip line feedings.</td>
<td>12</td>
</tr>
<tr>
<td>1.16</td>
<td>A picture of the 5 GHz fabricated antenna.</td>
<td>13</td>
</tr>
<tr>
<td>1.17</td>
<td>Comparing the simulation and the practical S11 parameters for the fabricated antenna.</td>
<td>14</td>
</tr>
<tr>
<td>1.18</td>
<td>The measured radiation pattern for the 5 GHz fabricated antenna.</td>
<td>14</td>
</tr>
<tr>
<td>1.19</td>
<td>The simulated radiation pattern for the 5 GHz antenna.</td>
<td>15</td>
</tr>
<tr>
<td>1.20</td>
<td>Integrating solar cells to antenna.</td>
<td>16</td>
</tr>
</tbody>
</table>
1.21 A picture of the dummy solar cells used.

1.22 The S11 parameter for different solar panels conductivities.

1.23 Circularly polarized cavity-backed slot antenna.

1.24 Feeding network to obtain circular polarization.

1.25 (a) A linearly polarized wave, and (b) a circularly polarized wave.

1.26 The radiation pattern of a circularly polarized cavity-backed slot antenna.

1.27 Two-element LP array.

1.28 The radiation from a 2-element LP array.

1.29 Four-element CP antenna array.

1.30 Feeding network to obtain CP.

1.31 The near-field measurements for the fabricated antenna.

1.32 Picture of the Antenna Under Test (AUT), and picture of the upper and the lower substrate of the fabricated antenna.

1.33 Measured and simulated S-11 parameter for the CP antenna array.

1.34 Measured and simulated radiation patterns for the CP antenna array.

2.1 Illustration of the dual band antenna.

2.2 A picture of the fabricated antenna: (a) lower substrate with feed line, and (b) upper substrate with the etched slots.

2.3 Schematic of the feed locations and the array spacing for the dual band antenna.

2.4 The equivalent circuit of the dual band slot antenna.

2.5 The equivalent model of one slot element while the other slot coupling is taken in to $Z_{couple}$.

2.6 Comparison between the simulated and measured S-11 parameters.

2.7 The measured radiation pattern of the antenna: E and H planes at 5.26 GHz.

2.8 The measured radiation pattern of the antenna: E and H planes at 4.22 GHz.

3.1 The layers of the 2-element antenna array.
3.2 The feed design for the 2-element antenna array. ........................................ 34
3.3 The layers of the circularly polarized antenna. ........................................... 35
3.4 The feed design for the circularly polarized antenna. ................................. 35
3.5 The layer structure for the dual band antenna. ............................................ 37
3.6 The feed design for the dual band antenna. ............................................... 37
3.7 The layer information. .................................................................................. 39
3.8 The solar cells information. ........................................................................ 39
3.9 The solar panel with the circular polarization antenna integrated with it (a) without solar cells, and (b) with solar cells. ........................................... 40
3.10 S-11 parameter for the circular polarized antenna. ..................................... 41
3.11 Radiation pattern for the circular polarized antenna (a) simulation, (b) measurements without solar cells, and (c) measurements with solar cells. ................................. 41
3.12 The solar panel with the linearly polarized antenna integrated with it. ......... 42
3.13 S-11 parameter for the linearly polarized antenna. .................................... 42
3.14 Simulated and measured radiation patterns for the linearly polarized antenna. 43
3.15 The solar panel with the dual band antenna integrated with it (a) without solar cells, and (b) with solar cells. ......................................................... 44
3.16 S-11 parameter for the dual band antenna. ............................................... 44
3.17 Simulated and measured radiation patterns at 2.1 GHz. ............................ 45
3.18 Measured radiation patterns at 2.1 GHz. .................................................. 45
3.19 Radiation patterns for the dual band antenna at the high frequency (a) simulation, (b) measurements without solar cells, and (c) measurements with solar cells. ......................................................... 46
3.20 Simulated and measured radiation patterns at 2.9 GHz. ............................ 46
3.21 Measured radiation patterns at 2.9 GHz. .................................................. 47
3.22 Setup for antennas measurements. ............................................................ 47
3.23 V-I characteristics from solar cells measurements. .................................. 48
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>(a) Linear array, and (b) nonlinear array.</td>
</tr>
<tr>
<td>4.2</td>
<td>The cost function versus the number of iteration.</td>
</tr>
<tr>
<td>4.3</td>
<td>Normalized gain versus theta.</td>
</tr>
<tr>
<td>4.4</td>
<td>Geometry of a 16-element planar array.</td>
</tr>
<tr>
<td>4.5</td>
<td>The cost function versus the number of iterations.</td>
</tr>
<tr>
<td>4.6</td>
<td>The radiation pattern for the array.</td>
</tr>
<tr>
<td>4.7</td>
<td>(a) Efficiency for 8-element array, and (b) efficiency for 16-element array.</td>
</tr>
<tr>
<td>4.8</td>
<td>Solar panel used by a CubeSat.</td>
</tr>
<tr>
<td>4.9</td>
<td>Elements on a panel (a) without coupling effect, and (b) with coupling effect.</td>
</tr>
<tr>
<td>4.10</td>
<td>Radiation from panel with no coupling.</td>
</tr>
<tr>
<td>4.11</td>
<td>Radiation from panel with coupling.</td>
</tr>
<tr>
<td>4.12</td>
<td>Solar panel for isotropic-like pattern antenna.</td>
</tr>
<tr>
<td>4.13</td>
<td>Radiation from isotropic-like pattern antenna.</td>
</tr>
<tr>
<td>4.14</td>
<td>Solar panel for dipole-like pattern antenna.</td>
</tr>
<tr>
<td>4.15</td>
<td>Radiation from dipole-like pattern antenna.</td>
</tr>
<tr>
<td>4.16</td>
<td>Solar panel for directive end-fire pattern antenna.</td>
</tr>
<tr>
<td>4.17</td>
<td>Radiation from directive end-fire pattern antenna.</td>
</tr>
<tr>
<td>4.18</td>
<td>Solar panel for circular polarization antenna.</td>
</tr>
<tr>
<td>4.19</td>
<td>Radiation from circular polarization antenna.</td>
</tr>
<tr>
<td>4.20</td>
<td>Axial ratio from circular polarization antenna.</td>
</tr>
</tbody>
</table>
Chapter 1
Introduction and Initial Feasibility Study

1.1 Antennas for Small Satellites

Satellites are classified according to their weights. Generally, a satellite is called a small satellite if its wet mass (mass including the fuel) is less than 500 kg [1]. Small satellites are important space exploration vehicles and are widely employed in enabling missions that large satellites cannot accomplish, such as gathering data from multiple points with low payloads, or in-orbit inspection of larger satellites.

Small satellite antennas can vary according to the application required [1]. Three different main antennas are needed to establish efficient satellite communications: antennas communicating with ground stations, antennas communicating with other satellites, and Global Positioning System (GPS) antennas. Surrey space center has presented an explicit survey on the existing types of antennas for small satellites [1].

One of the biggest challenges for a small satellite is how to allocate the limited surface real estate. In general, the surface area is occupied by surface mounted solar cells, test instruments for specific mission, and antennas as part of the communication system. Most small satellites use the wire type dipole antenna, and usually there is a deployment mechanism associated with this type of antennas. Before launching the satellite, the dipole antennas are mounted on designated location and are folded on the surface of the satellite. After the satellites are launched and reach their orbits, the dipole antennas then pop open and stick out from the satellite. There are main three disadvantages for dipole antennas. First, the deployment mechanism requires extra mechanical design and is not cost-friendly. Second, in the case that the antenna does not pop open, the entire communication system may fail and the result is losing the whole spacecraft. Third, the antenna properties are limited by the mounting location on the satellite and one cannot always achieve the best
antenna design.

This thesis presents a novel antenna solution for small satellites. The antennas are integrated with the solar panel, and one can flexibly design the desired radiation pattern. Also Circular Polarization (CP) can be easily achieved which is not the case for the dipole antennas. The proposed antenna is conformal with the satellite structure and does not occupy any additional surface area. The antenna design and solar cells are independent, and one can flexibly choose after-market solar cells to assemble a solar panel. This feature is particularly valuable for small satellite applications because it helps reduce the satellite payload with no requirement of custom made solar cells. The proposed antennas are based on slot antennas [2, 3]. Prototype slot antennas with Linear Polarization (LP), CP, and array configuration were designed and fabricated; the measurements agree well with the design data.

1.2 Overview of Integrated Solar Panel Antennas

To resolve the issues in today’s small satellite antenna designs (i.e., limited surface area, limited antenna mounting positions, and deployed mechanism), it is important to integrate antennas with solar cells. Four types of integration methods have been reported. The first type is to place patch type antennas under solar cells [4]. The second type is to create slot antennas and deposit solar cells directly on top of them [5,6]. The third type is to integrate antennas that are transparent to light directly on top of commercial solar cells [7]. The fourth type is to integrate a transparent dielectric resonator antenna on solar cells [8].

All four integrated solar panel antennas suffer from various drawbacks. The transparent dielectric resonant antenna is bulky and is not favorable for space application. The transparent meshed antenna, although promising with very high transparency (higher than 93%), has to be verified under a space environment to validate its functionality. Integrating antennas under the solar cells for small satellite applications was first proposed by the European Space Agency in 2000 [5]. The researchers proposed two different set of antennas: patch antennas [6,9] and slot antennas [9]. In the patch antenna topology, lots of layers were embedded in one design because the solar cells cannot be installed directly
on the patch antenna surface. For the slot antenna topology the European Space Agency overcame the problem of the complicated multilayer structure since the solar cells can be directly attached to the ground plane of the antenna; however, other issues appeared such as the back-radiation occurring from slot antennas due to its nature. The greatest challenge, however, is to integrate the custom made solar cells on the ground plane; a stainless steel ground plane had to be used instead of copper. In doing so, the loss from the stainless steel became a limiting factor for the antenna efficiency.

The antenna design proposed in this thesis is compatible with after-market solar cells. The design philosophy is to place cavity backed slot antennas around solar cells instead of under or above them. In doing so, there are no special requirements on solar cells. The thesis shows that linear polarization, circular polarization, and a dual band structure can be acheived. Three different antennas were designed and fabricated on a real solar panel material used by the Space Dynamics Laboratory [10].

1.3 Basic Design

1.3.1 Feasibility of Integrating Slot Antennas with Solar Panels

Figure 1.1 is an illustration of a Cube Satellite (CubeSat) developed by the Space Dynamics Laboratory. The materiel used to build the eight solar panels of the satellite is Polyimide. The size of a typical one unit (1U) CubeSat is 10 cm×10 cm×10 cm. The solar cells, marked in fig. 1.1, cover most of the CubeSat’s surface. A typical solar panel assembly for small satellites is shown in fig. 1.2. One is able to see that there are gaps between the solar cells; the gaps are labeled by the red arrows. These gaps can be easily utilized to design antennas. We can create radiating slots in these gaps and have these slot antennas replace the current dipole antennas.

1.3.2 Radiation Mechanism of Slot Antenna

According to Babinets principle [11], a slot cut on a Perfect Electric Conductor (PEC) can be treated as a complementary dipole, shown in fig. 1.3. A typical radiation pattern,
as well as the return loss for slot antenna, is shown in figs. 1.4 and 1.5, respectively. It is seen that the slot radiates in both planes (both sides of the PEC).

The slot antenna, shown in fig. 1.3, has to be modified to suit the small satellite application. Usually there is a shielding between the solar panel and the electronics inside the satellite; therefore, the slot is only radiating to one side (one plane). A suitable model for such an application is a cavity-backed slot antenna [3], where a cavity is placed beneath the PEC ground plane. This cavity can be either filled with air or loaded with dielectrics. Figure 1.6 shows an illustration of a typical cavity-backed slot antenna.

1.3.3 System Level Considerations

There are mainly three orientations for a small satellite: it can be pointing to the earth (nadir pointing), it can be pointing to some other location such as the sun, or it can be spinning and keeping a single orientation as shown in fig. 1.7. The choice of antennas for the first two types of satellite orientations is simple, and only one antenna can fulfill the need. For the third type, we need two groups (vertical and horizontal) of slots. Also, as can be seen from fig. 1.7, that in order to steer the beam to the earth when the satellite is on the North Pole (or the South Pole, position B in the figure), we need to have at least an array of two elements to perform beam steering.

1.4 Initial Prototypes

In order to verify the feasibility of choosing a slot antenna as an appropriate antenna for a small satellite, we designed and prototyped a single element slot antenna at 5GHz. The measured results agreed well with the design data, and the geometry of the antenna is reasonable and suitable for the solar panel integration.

1.4.1 Feed Design

How to feed an antenna is a very important design factor and it directly affects antenna properties, system level performance, and realistic prototyping. Among many feeding
Fig. 1.1: A typical small satellite used by the Space Dynamics Laboratory.
Fig. 1.2: Solar cells assembly.

Fig. 1.3: Slot antenna and its complementary dipole.

Fig. 1.4: Radiation pattern from a slot antenna.
Fig. 1.5: Resonance frequency of a 2.4 GHz slot antenna.

Fig. 1.6: Cavity-backed slot antenna.

Fig. 1.7: A drawing for the satellite when it is orbiting the earth.
methods, three are more suitable for slot antennas. The three feeding methods are the simple probe feed [12], Coplanar Waveguide (CPW) feed [13, 14], and Microstrip Line (ML) feed [2, 13]. To decide on the most suitable feeding method, we experimented with all three feeding methods. The slot antenna geometry is as follows: the ground plane is backed by a cavity filled with a substrate, and the relative permittivity of the substrate is 3.5. In all our simulations, Ansoft’s High Frequency Structure Simulator (HFSS) was used to design and study antenna properties.

The probe feeding, as shown in fig. 1.8, offers a very simple geometry, as well as a reasonable antenna bandwidth and pattern, as can be seen from fig. 1.9 (S11) and fig. 1.10 (radiation pattern). One disadvantage of this type of feed is that one has to drill holes on the substrates. This is not desirable when integrating antennas with solar panel as it is not always simple to have number of holes on the panel.

![Fig. 1.8: A probe feed cavity-backed slot antenna.](image1)

![Fig. 1.9: S11 parameter of a 5 GHz probe feed slot antenna.](image2)
Fig. 1.10: Radiation from a 5 GHz probe feed antenna.

CPW feed is another popular feeding choice. There are mainly two ways to feed a slot antenna with the CPW. The first way is called the inductive coupling which is done by splitting the coupling slot into two by the CPW as shown in fig. 1.11(a), and the second is the capacitive coupling shown in fig. 1.11(b). The impedance of the CPW can be determined by the length of the etched slot in the CPW. Generally a CPW feeding needs two substrates; the upper substrate contains the radiating slot and the lower substrate contains the etched feeding slot (fig. 1.11). The S-11 parameters and the radiation pattern are shown in figs. 1.12 and 1.13, respectively. Although CPW feeding has lots of advantages and can be easily matched, we found that it is not flexible for solar panel application because it causes a poor front to back ratio.

Among the three types of feeding methods, we found that the microstrip line (ML) feed [2] is the most effective and simple to implement. We used three types of ML feeds (regular ML, shorted ML, and tapered ML) to feed a slot antenna (fig. 1.14). The antenna was designed at a center frequency of 5 GHz; the dimension of the ground plane is 50×50
Fig. 1.11: (a) Inductive coupling CPW feeding, and (b) capacitive coupling CPW feed.

Fig. 1.12: S11 parameters of both inductive and capacitive coupling CPW feed.

Fig. 1.13: Radiation from a capacitive coupling CPW feeding.
mm, and the slot is 18×1.2 mm. The geometry of the antenna and the feed (fig. 1.14) is as follows. Two substrates are used to fabricate the slot antenna and the feed individually. The top plane of the upper substrate is grounded and a radiating slot is etched on the grounded metal coating. The metal coating on the bottom plane of the substrate is etched out. For the lower substrate, a microstrip line is printed on the top plane; the metal coating on the bottom plane is grounded. The two substrates are then assembled together and the four walls are coated with a conductor and are also grounded. Figure 1.15 shows the simulated S11 parameters of the three types of ML feeding and demonstrates that all of them are effective feeding methods. Considering the ease of the fabrication, the simple ML was chosen for prototyping. Finally, the investigated types of feedings are presented in Table 1.1.

Fig. 1.14: (a) Simple ML feeding, (b) shorted ML feed, and (c) tapered ML feed.
Table 1.1: Advantages and disadvantages of different feeding types.

<table>
<thead>
<tr>
<th>Feeding Methods</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe</td>
<td>Small losses, good efficiency</td>
<td>Requires drillings in substrate</td>
</tr>
<tr>
<td>CPW</td>
<td>Wider bandwidth, easily matched</td>
<td>Poor front-to-back ratio</td>
</tr>
<tr>
<td>Simple ML</td>
<td>Easily fabricated</td>
<td>Challenges in matching</td>
</tr>
<tr>
<td>Shorted ML</td>
<td>Better response at whole range</td>
<td>Very hard-to-fabricate</td>
</tr>
<tr>
<td>Tapered ML</td>
<td>Wider bandwidth, easily matched</td>
<td>Challenges in fabrication</td>
</tr>
</tbody>
</table>

1.4.2 Prototype One-Element Cavity-Backed Slot Antenna

To verify the design, we fabricated a single cavity-backed slot antenna. A simple ML feed, as discussed in the previous section, was used. The two substrates used are both Rogers high frequency laminates (RO 4003C) with the relative permittivity, thickness, and loss tangent of 3.5, 0.813 mm, and 0.002, respectively. A conductive epoxy (Creative Materials product number 124-46) was used to coat and ground the four side walls of the assembled substrates (fig. 1.16). The dimension of the ground plane is 50×50 mm, and the slot is 18×1.2 mm.

The resonant frequency of the fabricated antenna was measured with a Vector Network Analyzer (Agilent 8510C) and fig. 1.17 shows measured S11 results in comparison with the simulation. It is seen that the measurements agree reasonably well with the design. The small shift in the center frequency can be due to the accuracy in the fabrication by using a
circuit board milling machine.

The radiation pattern of the antenna was measured with NSI’s near-field antenna range and fig. 1.18 shows the measured radiation pattern. The simulated radiation pattern is presented in fig. 1.19 as a reference, and it can be seen that the shape of the measured pattern matches the simulation in an overall sense. The ripples in the measured pattern are mainly reflections from the room where the antenna range was placed.

1.5 Effect of Solar Cells

The feasibility study in the previous session has shown that a slot antenna is an effective radiator. The next step is to integrate the antenna with the solar panel. The configuration of the integrated solar panel slot antenna is shown in fig. 1.20. There are mainly three layers. The first two layers are feed-line and the antenna, and the last layer is made of solar cells. The solar cells are very thin (about 0.16 mm) semi-conductive layers. Figure 1.21 shows a picture of the dummy solar cells used. As both the dielectric constant and the conductivity of the solar cells cannot be easily found exactly and they may vary among vendors, we treated the solar cell as a silicon layer and varied its conductivity to show that the existence of the solar cells affects the antenna performance.

Fig. 1.16: A picture of the 5 GHz fabricated antenna.
Fig. 1.17: Comparing the simulation and the practical S11 parameters for the fabricated antenna.

Fig. 1.18: The measured radiation pattern for the 5 GHz fabricated antenna.
We placed a silicon layer around a single element slot antenna and varied the conductivity of the silicon. Then we plotted the S11 of the antenna with respect to the conductivity in fig. 1.22. It is seen that the conductivity of the solar cell only shifts the resonant frequency of the antenna and there is no significant shift after the conductivity is raised higher than 5 S/m. This is understandable because as the conductivity increases, the solar cell layer only acts as part of the ground plane and has no large effect on the antenna performance.

1.6 Circular Polarization and Array Configuration

As discussed before, in order to steer the beam to the earth, one needs to consider an array of slots. Also, in most communication systems, CP is favored; therefore, it is important to design slot antennas with a CP capability.

1.6.1 Circular Polarization

A circularly polarized antenna [11] is highly favored in satellite communication for
Fig. 1.20: Integrating solar cells to antenna.

Fig. 1.21: A picture of the dummy solar cells used.
many reasons. While it is not always simple to achieve CP with dipole antennas, the design is straightforward for slot antennas. A CP can be obtained as long as we have two slots perpendicular to each other and phase shift them for 90 degrees. To obtain the 90-degree phase shift, a ML feed was designed as shown in fig. 1.23, where the feed line is adjusted to feed both slots. The line length between the two elements is designed to give a 90-degree phase delay. Figure 1.24 shows a more detailed geometry of the feed-line and the cross-slots. Figure 1.25 shows the differences between linearly polarized and a circularly polarized wave.

There are two criteria to measure a circular polarization. The first is to compare the E-plane and H-plane; they should be very similar. The second one is to check the Axial Ratio (AR), which is a complex number and needs to have a magnitude of 1 and phase of 90 degree. Using the first criteria, it is seen from fig. 1.26 that a reasonable CP is achieved in our design. When checking the AR, we achieved an AR of 1.26, which is acceptable for a CP.

1.6.2 Slot Antenna Array

An array configuration not only allows us to steer the antenna beam to the desired location, but also helps to increase the gain of the antenna. In this section, two types of arrays were implemented. The first type is a two-element LP array to study the beam steering. The second type is a four-element CP cross slot antennas to study the gain.
Fig. 1.23: Circularly polarized cavity-backed slot antenna.

Fig. 1.24: Feeding network to obtain circular polarization.

Fig. 1.25: (a) A linearly polarized wave, and (b) a circularly polarized wave.
enhancement. It should be noted that one can easily steer the beam and enhance the gain at the same time with a CP slot antenna array. We performed these two studies separately to keep the variables simple.

Figure 1.27 shows the geometry of a two-element slot antenna array. The distance between two antennas is noted with \( d \) in millimeters. The phase delay between the two elements is calculated by \( d \) and noted with \( \alpha \). Figure 1.28 shows the radiation pattern for the case when \( d = 15 \) mm and \( \alpha = 100 \) degrees. Table 1.2 shows the maximum steering angle that was obtained for changing the spacing and the phase shift.

Presented in fig. 1.29 is the antenna and feed layout of a 2×2 CP array. The process for designing slots and feed-line is the same as explained in previous sessions. The spacing between elements is uniform and is \( \lambda/2 \) where lambda is the wavelength in free space.

The feed network is shown in detail in fig. 1.30. To facilitate a better matching and an ease in fabrication, two quarter-wave tapered transmission lines are used. The 50-ohm line is then connected to a SMA connector to feed the array. There are two kinds of ML layouts to avoid reflection at the bending in the microstrip line [15]: the swept bend and the mitered bend. In this paper, the swept bend was used. The radius of the bend was set equal to or more than triple the line width.
Fig. 1.27: Two-element LP array.

Fig. 1.28: The radiation from a 2-element LP array.
Table 1.2: Steering angles for different phase delays and spacing.

<table>
<thead>
<tr>
<th>Alpha</th>
<th>Spacing</th>
<th>Maximum Theta</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>100</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>165</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>225</td>
<td>37.5</td>
<td>30</td>
</tr>
</tbody>
</table>

The four-element CP array antenna was fabricated using a milling machine as described before on a substrate (RO 4003C). The substrate has a permittivity of 3.5, height of 1.54mm, and a loss tangent of 0.002. Figure 1.31 is the measurement set up with the near-field antenna range. Figure 1.32 is the Antenna Under Test (AUT). The measured S11 parameter and the radiation pattern are shown in figs. 1.33 and 1.34. It can be seen that the measurement agrees fairly well with the design. It is also observed that the E and H-plane patterns are reasonably close to each other, showing that a reasonable CP is achieved.
Fig. 1.30: Feeding network to obtain CP.

Fig. 1.31: The near-field measurements for the fabricated antenna.

Fig. 1.32: Picture of the Antenna Under Test (AUT), and picture of the upper and the lower substrate of the fabricated antenna.
Fig. 1.33: Measured and simulated S-11 parameter for the CP antenna array.

Fig. 1.34: Measured and simulated radiation patterns for the CP antenna array.
Chapter 2
Dual Band Cavity-Backed Slot Antennas

2.1 Background

The design basics of cavity-backed slot antennas have been presented in Chapter 1. This chapter presents a very simple design where one can achieve a dual band antenna by utilizing coupling between two adjacent slots. When there are more than one slot element, the natural next step is to study the coupling between elements. It has been found that cavity-backed slot antennas have small mutual coupling [16]. Further studies have been reported to compute the coupling with more accuracy using numerical techniques [17] and analytical methods [18].

While there is an abundance of supportive literature on cavity-backed slot antennas and their coupling, most studies focus on the slot elements in parallel alignments. When the slots are placed in series, the spacing between the elements is usually large enough (e.g., half wavelength) for one to ignore the resonance due to coupling. When two serial slot antennas were placed close to each other, we found that one can achieve two resonances, and this suggests a dual band antenna design. The design principle is simple and can be conveniently implemented using printed circuit board techniques. This chapter presents the design method, analysis using an equivalent circuit modal for the antenna and a prototyped dual band antenna. The measured results agree well with the simulations; the results validate the dual band antenna design that can be potentially implemented on solar panels as communication links or sensor nodes.

2.2 Dual Band Antenna Analysis

The configuration of the proposed dual band cavity-backed slot antenna is as shown in fig. 2.1. The antenna and the feeding lines are composed of two circuit board substrates (fig.
Two slots are etched on the top layer, which is a copper layer, of the first substrate as radiating elements (fig. 2.2(a)). The feeding lines are printed on the top layer of the second substrate (fig. 2.2(b)). The bottom layer of the second substrate is the ground plane. The two substrates are then assembled together with an antenna layer residing on top of the substrate layer; the antenna elements are vertical to the feed lines (fig. 2.1). It should be noted that one does not have to choose the same substrates to etch antenna and to print feed lines. By adjusting the position and length of the feed line the slot antenna can be matched. After assembling the two substrates, the four side walls of the substrates and the top plane (i.e., slot antenna and the metal plane) were shorted to the ground plane with either conductive pastes or conductive tapes. When prototyping the antenna, it was necessary for us to cut a rectangular notch on the top substrate in order to solder a SubMiniature version A (SMA) connector (fig. 2.2). The existence of the notch affects the resonance frequency and impedance matching, and we have included it in the full wave simulation.

We found that when the two elements are placed close, a new resonance appear due to the strong coupling between the two slots. The explanation for the second resonance is that the coupling between the two slots acts as if there is an equivalent slot antenna that is longer than the individual slot; at the same time, it is shorter than the total length of the two slot elements.

![Fig. 2.1: Illustration of the dual band antenna.](image)
In order to analyze the mechanism of the dual band resonance and provide some insight for designing effective antennas for both frequencies, we established an approximate circuit model to study the input impedance of the slot antenna. The important parameters of the slot geometry are marked in fig. 2.3; both $L_{e1}$ and $L_{e2}$ are critical for matching the impedance of the two slots, and $d$ has been seen to affect the impedance of the equivalent slot.

The approximate model is presented in fig. 2.4, and it is derived by modifying Syahkals circuit model for a single slot antenna fed by a microstrip line [19]. Each slot is modeled as two short-circuited slot lines parallel with a radiation conductance $G_r$ that represents the radiated power from the slot [19]. The parameters $L_{e1}$ and $L_{e2}$ (fig. 2.3) correspond to the length of the two short-circuited slot lines, and are marked in fig. 2.4 for ease of reading. The characteristic impedance of the slot line is $Z_{cs}$. $L_1$, and $L_2$ are inductance of microstrip feed line and slot line, respectively. The mutual inductance $M_1$ represents the coupling between the microstrip line and slot line.
The mutual inductance $M_2$ represents the coupling between two serial slots. Because of the coupling, there appears an equivalent slot that radiates at a frequency lower than the two slots. The circuit model for the equivalent slot is presented in fig. 2.5. The length of the equivalent slot is $L_{eq}$, and is expected to be between $(L_{e1}+L_{e2})$ and $2(L_{e1}+L_{e2})$. The coupling between the two slots reflects as added impedance $Z_{couple}$ to the equivalent slot line (fig. 2.5). It is straightforward to expect that changing the spacing $d$ (fig. 2.3) between the two slots will change $M_2$, and accordingly change $Z_{couple}$, where $Z_{couple}$ is the dominant factor for the input impedance of the equivalent slot because the other factors (characteristic impedance $Z_{cs}$, radiation conductance $G_{er}$, and the length $L_{eqtot}$ of the equivalent slot line) do not vary much with respect to $d$. Therefore, after matching the impedance of the two slots, one can adjust the spacing between the two slots to achieve a reasonable return loss for the equivalent slot antenna.

Two methods can be employed to validate the model shown in fig. 2.3. One can determine the values of $Z_{cs}$, $L_1$, $L_2$, $M_1$, and $M_2$ following Syahkal [19]. Then one can compute the input impedance of the equivalent slot before comparing the computed S11 value of the equivalent slot at the input port (i.e., the SMA connector) with experiments. Alternatively, using the model as the guideline, one can perform parametric studies using simulation software and then validate the design with measurements. We chose the second approach in this paper for there are several well-tested antenna design software.
Ansoft’s HFSS is used to perform the simulations for two serial slot antennas on substrates with different thickness and relative permittivity, and different ground plane size. It is found that after matching two identical serial slots to a resonant frequency $f_1$, a secondary resonance $f_2$ ($f_2 \leq f_1$) appears when the spacing between the two slots is less than 0.19 wavelength. This resonance is generally weak with an S11 higher than -3dB and we need to continue to move the two slots closer to achieve a reasonable S11 at $f_2$. It is observed that changing the spacing only changes the level of the resonance, and does not have much effect on $f_2$. It is also observed that the spacing affects the resonance at $f_1$, and one has to adjust the matching microstrip lines to achieve a good S11 at $f_1$. As with the case for $f_2$, the spacing between two slots does not affect the location of $f_1$. These observations are consistent for different substrates and ground plane sizes, and they are also consistent with the model in figs. 2.4 and 2.5. When the dimension of the slots is fixed, the input impedance of the equivalent slot is mainly determined by $Z_{\text{couple}}$ (fig. 2.5) which is affected by the mutual inductance $M_2$ (fig. 2.4). It is also seen from fig. 2.4 that $M_2$ affects the input impedances of two serial slots, and therefore the spacing between them will affect S11.
value at \( f_1 \). The ratio of \( f_1/f_2 \) is found to be close to 1.25, the fluctuation is less than 5% for different substrates and ground plane. In another word, the ratio between the length of the equivalent slot and one of the serial slots is about 1.25.

### 2.3 Prototype and Measurement Results

Using the approximate model and observations from HFSS studies in sec. 2.2 as guild lines, we designed and fabricated a dual band slot antenna prototype. The substrates used are Rogers high frequency laminates RO 4003c (thickness= 0.831 mm, permittivity= 3.38) and the two slots are designed and matched to operate at 5.26 GHz. The equivalent slot operates at 4.22 GHz. The spacing between the two slots and the position of the microstrip feed line are adjust to be \( d= 0.5 \) mm and \( L_{e1}= 1.5 \) mm to achieve good S11 values at both frequencies. The antennas and the feeding microstrip lines were fabricated using a Lighted Program Function Keyboard (LPKF) circuit board milling machine, and the ground plane or the size of the substrate was chosen to be 100 mm \( \times \) 100 mm. The two slots on the upper plane have the same width of 1 mm and the same length of 25 mm. After assembling the two substrates, the four size walls were shorted with conductive copper tapes.

The simulation and measured results of frequency responses are plotted in fig. 2.6. The S-parameters were measured using a vector network analyzer (Agilent 8510C). It is seen that the agreement between simulation and measurements is good for both frequencies. The slight shift in the frequency is likely due to three possibilities: 1) the fabrication accuracy when milling the two slots, 2) cutting the rectangular notch for soldering the SMA connector (fig. 2.1), and 3) the possibility of having some air between two substrates when they were assembled.

The normalized radiation patterns for both bands were measured using a far-field range in an anechoic chamber. The simulated E-plane, H-plane patterns for 5.2 GHz antennas were plotted in fig. 2.7(a). The measured co- and cross-polarization patterns at 5.2 GHz were plotted in fig. 2.7(b). It can be seen that the agreement between E-plane patterns is good and the cross-polarization level is overall less than -20dB. The measurement facility is not optimal for measuring H-plane patterns, and it is reasonable to expect some distortion on the
Fig. 2.5: The equivalent model of one slot element while the other slot coupling is taken in to $Z_{\text{couple}}$.

Fig. 2.6: Comparison between the simulated and measured S-11 parameters.
H-plane pattern from the measurement. Having this factor in consideration, the agreement in overall shape in H-plane patterns is reasonably good. The radiation patterns for the band at 4.22 are plotted in fig. 2.8. Agreements between simulations and measurements are good and the cross polarization level is overall less than -20dB. The gain of the dual band antenna was measured using a NSI 2000 near field scanner, and was found to be 2.5dB and 3.4 dB for lower and upper bands. The result is reasonable considering the dielectric loss in two layers of substrates.

Fig. 2.7: The measured radiation pattern of the antenna: E and H planes at 5.26 GHz.
Fig. 2.8: The measured radiation pattern of the antenna: E and H planes at 4.22 GHz.
Chapter 3

Fully Integrated Solar Panel Antennas for Cube Satellites

In this chapter, three fully integrated solar panel antennas were designed and fabricated on a real solar panel material commonly used in space applications. Three prototypes were fabricated to present antennas of linear polarization, circular polarization, and dual band operation. The measured results were compared with simulations for both the frequency response and the radiation patterns, and good agreements have been achieved. Finally, solar cells were integrated on the antenna panels, and the measured efficiency of the solar cells in the presence of antennas were outstanding.

3.1 Two-Element Linearly Polarized Antenna

In this section we designed linear array antennas consisting of two series elements. The structure of our design was as follows: we used two substrates, the lower substrate for the feeding network and the upper for the slot antennas etching. The substrate was made from Polyimide, a material which is commonly used for space applications. Finally, a layer of solar cells was integrated with antennas on the top layer as shown in fig. 3.1. The simulation of the antenna was performed using Ansoft’s HFSS. For the feed layer (shown in fig. 3.2) a 50-ohm microstrip line was etched to be connected to the SMA connecters, this line is then divided using a tee junction into two different lines each having a characteristic impedance of 100-ohm. Each line is feeding a separate element. The parameter (d) was used to match the microstrip line to the slot antenna. The antenna layer is simply two slots etched in a metallic ground plane. The slots were half wave length each, with a spacing of 0.6 wavelength. This value was chosen because it is typically less than a wave length to avoid grating lobes and not small to decrease the coupling effect. The solar cells were modeled as very thin silicon layers with certain conductivity.
Fig. 3.1: The layers of the 2-element antenna array.

Fig. 3.2: The feed design for the 2-element antenna array.
3.2 One-Element Circularly Polarized Antenna

Circular polarization [11] is preferred in satellite communication as explained in Chapter 1. In the case of linear polarization, one has to synchronize the ground receiver antenna with the satellite antenna and this requires extra complication for the ground station. For the case of circular polarization, on the other hand, there is no need for such synchronization, and the direct result is the reduced cost. The design is composed of three layers as explained in the previous section (fig. 3.3). The parameter d (fig. 3.4) was used to match the antenna.

![Fig. 3.3: The layers of the circularly polarized antenna.](image1)

![Fig. 3.4: The feed design for the circularly polarized antenna.](image2)
3.3 Dual Band Antenna

For the dual band antenna array, the slot locations were chosen to be at the edges of the solar panels, rather than the center, for two reasons. The first reason is to achieve a more omni-directional pattern which is frequently required in space applications. The second reason is due to the realistic electric connection and the size of solar cells. Figure 3.5 shows the layer information of the solar-antenna panel. The feed network is more complicated in this case. Figure 3.6 shows the feed design in more details. A 50-ohm probe was placed at the center of the panel which can be connected to an SMA connector for excitation. The probe is connected to a 50-ohm microstrip line, each end of the line is then increased to 25-ohm line by a $\lambda/2$ tapered transformer. The 25-ohm line is divided in to two equal 50-ohm lines; therefore we have a total of four 50-ohm lines. Each of these four lines is then divided into two 100-ohm lines, so that in the end we have eight equal 100-ohm lines to feed eight slot antennas (fig. 3.6).

Dual band performance in space applications is important because it first saves money since one antenna will be performing the job of two. It also saves additional surface area, which is an important factor especially for small satellites. The design basis of the dual band slot antenna has been explained in Chapter 2, and can be realized by adjusting the parameter $s$ shown in fig. 3.6. The design of the final antenna array is as follows: there are eight antenna elements that radiate at a given resonant frequency, and two adjacent elements in the center coupled to each other, to create a lower resonance as the second band.

3.4 Fabrication and Solar Panel Assembly

It is worthwhile to explain the choice of solar/antenna panel material. Commonly used planar antenna materials like FR4 and high frequency laminates would not handle either the temperature or the pressure in outer space. For example, FR4 material has an expansion coefficient in the x-y plane (width and length, not the thickness) of 16 ppm (particle per million). This expansion coefficient in the case of a 2.4 GHz antenna design may cause a shift of 0.2 GHz in the main frequency. Polyimide is a better candidate because it has a
Fig. 3.5: The layer structure for the dual band antenna.

Fig. 3.6: The feed design for the dual band antenna.
very low expansion coefficient (almost one quarter the FR4), and has been mechanically tested and proved to handle the pressure and temperature fluctuation in the outer space. The trade off, however, is the loss of the Polyimide at GHz frequencies. The typical efficiency for slot antennas on a high frequency laminates ranges from 60 to 80%, but for Polyimide the efficiency of the proposed antennas is ranging from 40 to 60%. Considering the overall performance and the link budget, Polyimide is still one of the best choices at this time.

When prototyping the proposed antennas with PCB technology, a mask is prepared for each layer and the nonmetallic parts were etched out from the layer. Figure 3.7 shows the layers organization. A three-layer board was designed; the black color represents the copper metallic parts, while the white color represents the nonmetallic parts. We have a lower ground plane and an upper ground plane. They were connected using vias which were separated from each other by a $\lambda/4$ spacing. The middle layer is the feed network layer. The dimensions of both slots in the upper layer and the microstrip line in the middle layer are chosen according to the design procedures discussed in sec. 3.2. All the slot antennas have a length of 28 mm that corresponds to a length of $\lambda/2$ at 2.5 GHz. Three feed designs following the principles described in Chapters 1 and 2 were etched in the middle layer. The linear antenna array and CP antenna have ground planes of 155 by 96 mm and the dual band antenna had a ground plane size of 190 by 96 mm.

After the antennas were fabricated, 28.3% ultra triple junction solar cells were assembled in series, as shown in fig. 3.8. Each solar cell provides an output voltage of 2.5 volt and current of 450 mA. The solar cells were all connected in series to provide an output voltage of 10 volts to power the electronics inside a cube satellite. The solar cells were attached using an adhesive material (part no. CV10-135 from NuSil Technology LLC). The assembly process was performed in a vacuum chamber to ensure that the solar cells were perfectly connected to the panel.

### 3.5 Measurements of Antenna Performance

Figure 3.9 shows a picture of the fabricated circularly polarized antenna with and without the solar cells. The antenna was designed at 2.64 GHz. Figure 3.10 shows the
Fig. 3.7: The layer information.

Fig. 3.8: The solar cells information.
measured and the simulated S-11 parameter. One can notice they agree fairly well except for a small shift between the measured and simulated results. A 0.05 GHz shift in the center frequency is about 1.8% error and is acceptable considering fabrication and assembly process. One interesting thing was noted that the matching is enhanced after integrating the solar cells by 4dB. The measured radiation patterns were performed with a far field range in an anechoic chamber at University of Utah. Figure 3.11 shows the radiation pattern before and after integrating solar cells. One can notice that the E-plane pattern did not change much after integrating the solar cells. The measurement facility at University of Utah is primarily for E-plane measurements and the results of H-plane measurements were not as accurate for us to reach a conclusion at this time. It is also noted that there were 20 dB difference between the co-pol and the cross-pol levels, which is outstanding.

![Fig. 3.9: The solar panel with the circular polarization antenna integrated with it (a) without solar cells, and (b) with solar cells.](image)
Fig. 3.10: S-11 parameter for the circular polarized antenna.

Fig. 3.11: Radiation pattern for the circular polarized antenna (a) simulation, (b) measurements without solar cells, and (c) measurements with solar cells.
For the linearly polarized antenna, the prototype had no solar cells integrated due to the cost of high efficiency solar cells. Figure 3.12 shows a picture of the fabricated antenna. The frequency response is shown in fig. 3.13. One can notice good agreements in the resonance frequency between the measurements and the simulation. Although the matching does not seem outstanding, it is expected that it will improve once the solar cells are integrated as in fig. 3.9. The radiation patterns for both simulation and measurements results are shown in fig. 3.14, and the agreements are reasonably good.

Fig. 3.12: The solar panel with the linearly polarized antenna integrated with it.

Fig. 3.13: S-11 parameter for the linearly polarized antenna.
Fig. 3.14: Simulated and measured radiation patterns for the linearly polarized antenna.

For the dual band antenna array (fig. 3.15), the measured and the simulated S-11 parameter were plotted in fig. 3.16. It was again noted that after integrating the solar cells, there was an improvement in the matching level. Figures 3.17 and 3.18 show the radiation patterns of the antenna at the lower frequency, while the radiation patterns at the high frequency is shown in figs. 3.19, 3.20, and 3.21. It is seen that measured radiation patterns agree with the simulation reasonably well, especially in the front side of the antenna. This is expected because the backside radiation cannot be captured well in most measurement facilities. Figure 3.22 shows a picture of the measurements setup. One can notice the metallic rod where the antenna under test is mounted on. This metallic rod can contribute to back scattering. Therefore, it is more reasonable not to measure the backside of the radiation pattern when using a near field antenna range. All the measured gains, simulated directivities and efficiencies are summarized in Table 3.1.

3.6 Solar Cells Measurements

The measurements on solar cell functionality is as follows. The measurements were performed at the Space Dynamics Laboratory. On a sunny clear day, the solar panel was taken outside. The solar cells connections at the back of the antenna were connected to an electrical variable resistor and the current was being measured for different voltage corresponding from the variable resistance. Figure 3.23 shows the power and the current measurement versus the voltage. One can notice that there is no current induced after 10 volts, which is expected because the maximum voltage output from the solar cells (connected
Fig. 3.15: The solar panel with the dual band antenna integrated with it (a) without solar cells, and (b) with solar cells.

Fig. 3.16: S-11 parameter for the dual band antenna.
Fig. 3.17: Simulated and measured radiation patterns at 2.1 GHz.

Fig. 3.18: Measured radiation patterns at 2.1 GHz.
Fig. 3.19: Radiation patterns for the dual band antenna at the high frequency (a) simulation, (b) measurements without solar cells, and (c) measurements with solar cells.

Fig. 3.20: Simulated and measured radiation patterns at 2.9 GHz.
Fig. 3.21: Measured radiation patterns at 2.9 GHz.

Fig. 3.22: Setup for antennas measurements.
Table 3.1: Gain of prototyped solar panel antennas.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Directivity (dB)</th>
<th>Efficiency</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP</td>
<td>7</td>
<td>0.54</td>
<td>2.5</td>
</tr>
<tr>
<td>LP</td>
<td>6.5</td>
<td>0.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Dual band</td>
<td>8.5</td>
<td>0.52</td>
<td>3.4</td>
</tr>
</tbody>
</table>

in serial) is no more than 10 volts. Also, the current produced is very consistent through the range of the voltage which proves that the solar cells function stably. The maximum power obtained was measured to be 3.6 watts. The power reaching the solar cells from the sun on the day of test was measured using a thermal sensor, and the solar power is found to be 12.15 watts. By taking the ratio of maximum power obtained by solar cells to the solar power reaching the cells, the efficiency of the solar cells was estimated to be close to 28.5%, which is the same efficiency of the solar cells without antennas. This proves that the antenna does not affect the solar cells performance.

Fig. 3.23: V-I characteristics from solar cells measurements.
Chapter 4

Optimization and Pattern Reconfigurablity

This chapter discusses initial study on optimization of the slot antennas that can be further developed and improved in future research. The chapter also presents feasibility study on reconfigurable solar panel antennas, so that one antenna can perform the role of three or more antennas. As a future work, one can continue to improve and prototype optimized reconfigurable antenna for small satellite applications.

4.1 Optimization

When the size of the solar panel permits an array of slots instead of only one or two slots, then it is not only desirable but also feasible to locate these slots in positions that can provide the most optimal antenna performance. The objective in this session is to present methods to optimize antenna performance in array configuration. The first study is to find the antenna layout that gives the optimal pattern with the suppressed side lobes. The second study is to optimally steer the antenna main beam. The third study is to optimize the antenna efficiency [20–22].

4.2 Optimal Side Lobe Suppression

The solar panel under consideration has a dimension of 20 cm×10 cm; this solar panel can easily allow multiple slots integrated on it (fig. 4.1). In general, the process of optimization is to adjust the inputs of a system (in this case, the antenna design parameters) and then find the maximum (or minimum) output. The process of finding the optimal output is called the cost function or objective function. HFSS has three optimization methods, and they are all experimented in this paper. These methods are Quasi Newton (QN) method (gradient methods), the Linear Programming method (simplex search method), and the
Genetic algorithms (GA). In the study where the side lobe suppression is the objective, the cost function is naturally chosen to be the lowest side lobes in the radiation pattern. For a planar array, the antenna elements can have equal or unequal spacing, and these two types of layout are called linear and nonlinear configuration, as illustrated in fig. 4.1(a) and (b).

The field pattern of a planner antenna array is the multiplication of the array factor and the element pattern (field pattern of the antenna element that constructs the array) as follows.

\[
[F_t] = [AF_x][AF_y]F_e,
\]

where \([F_t]\) is the total field pattern of antenna array, \([AF_x]\) is the array factor of the arrays on x axis (fig. 4.1(a)), \([AF_y]\) is the array factor of the arrays on y axis (fig. 4.1(a)), and \(F_e\) is the element pattern.

![Fig. 4.1: (a) Linear array, and (b) nonlinear array.](image-url)
There are eight elements in this study, as shown in fig. 4.1, four elements are on the x axis, and two are on y axis. Therefore, from Balanis [12], the array factors $[AF_x]$ and $[AF_y]$ can be written as follows.

$$[AF_x] = \cos[0.5(Kd_x \cos\theta) + \beta_x],$$

(4.2)

where $k=2n/\lambda$, $d_x=$ separation between the elements , $\beta_x = \text{phase difference between elements}$, and $\lambda = \text{wavelength}$.

$$AF_y = \frac{1}{N} \times \frac{\sin(N/2\psi)}{\sin(a/2\psi)},$$

(4.3)

where $\psi = (Kd_y \cos\theta) + \beta_y$, $N=4$, $d_y=$ separation between the elements , and $\beta_y = \text{phase difference between elements}$.

Considering eqs. (4.2) and (4.3), one can easily find that there are four variables ($d_x$, $\beta_x$, $d_y$, $\beta_y$) in eq. (4.1). To search for the optimum pattern, we set $[F_t]$ as the cost function and experimented with all three optimization methods. Table 4.1 shows the optimized values for the four variables in each case. Figure 4.2 shows the normalized gain versus theta for both the HFSS and the Matlab code, one can notice the results are very similar except for some small side lobes in the simulation results. Figure 4.3 shows the cost function versus the number of iterations for the optimization methods used.

From fig. 4.3, it is seen that the simplex search method took the least number of iterations. The GA method converges after about 20 more iterations than the simplex search method, and the QN method did not converge. The reason for the failure in QN can be due to the noise generated by the meshing process in HFSS, and the QN method works well only with low noise, unlike the simplex search method and GA that are not affected with the noise.

Generally, GA are robust and stochastic optimizers modeled on the principle of natural selection and evolution. GA is effective in solving complex problems with many variables or multi-objective function. When applying GA in our study to suppress side lobes, the GA
Table 4.1: Optimized values for the four variables after the end of iterations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Q.N</th>
<th>L.P</th>
<th>G.A</th>
</tr>
</thead>
<tbody>
<tr>
<td>dx</td>
<td>42.1 mm</td>
<td>36.2 mm</td>
<td>36.6 mm</td>
</tr>
<tr>
<td>dy</td>
<td>44.6 mm</td>
<td>34.8 mm</td>
<td>34.4 mm</td>
</tr>
<tr>
<td>x</td>
<td>1.2</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>y</td>
<td>0.8</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

is started with placing four random values for the chromosome \((d_x, \beta_x, d_y, \beta_y)\). A uniform cross-over type and a mutation with a Gaussian distribution were selected. The constraints were only to keep the slot within the substrate. For details about GA, the reader is referred to Samii’s Book [21].

### 4.3 Optimal Beam Steering

In this study, a total of 16 slot antennas are placed on a larger panel \((20 \text{ cm} \times 20 \text{ cm})\) (fig. 4.4). The variables to be optimized are the same as in sec. 4.2 (i.e., the position of the antenna elements on the panel). The cost function is chosen to steer the main beam and to suppress the side lobes. GA is used to perform the optimization and results are shown in fig. 4.5. It can be seen from fig. 4.6 that when minimizing the side lobes, the main beam can be steered up to 35 degrees, which satisfies most communication requirements.

### 4.4 Optimal Efficiency

This study is aimed to optimize the efficiency of the antenna array. The size of the panel and the variables to be optimized are the same as in the previous section. The relation between the antenna gain and the efficiency is given by:

\[
\text{Gain} = \text{efficiency} \times \text{directivity}. \tag{4.4}
\]

The cost function in this case is set to be such that it maximizes the efficiency of the antenna array. The efficiency of an 8-element antenna array and a 16-element array were optimized and the results are shown fig. 4.7(a) and (b). As expected, increasing the number
Fig. 4.2: The cost function versus the number of iteration.

Fig. 4.3: Normalized gain versus theta.

Fig. 4.4: Geometry of a 16-element planar array.
Fig. 4.5: The cost function versus the number of iterations.

Fig. 4.6: The radiation pattern for the array.
of elements results in higher efficiency.

4.5 Reconfigurability Study

In this study we used a solar panel (10 cm×30 cm) of the satellite presented in Chapter 1 (fig 1.1) to allocate multiple slot antennas to obtain reconfigurable patterns. Eighteen possible slot antenna locations were considered as shown in fig. 4.8. Three basic patterns were targeted to achieve: the isotropic, dipole, and directive patterns. These patterns were obtained by simply activating and phasing slot elements.

It is important to take in consideration the coupling effect between the slot antenna elements. Some elements will not be activated during certain configurations, but this does not mean they do not radiate or disturb the primary pattern. In the first study, two different antennas were simulated for a simple four-element slot array. One set contains only four active slots, and the other set has non-activated slots next to the four primary slot antennas. Radiation patterns from the two set of antennas were compared to understand the effect of the coupling on our primary pattern.

![Fig. 4.7: (a) Efficiency for 8-element array, and (b) efficiency for 16-element array.](image-url)
Figure 4.9 shows a picture of the two panels with and without the unactivated elements. The 3-D patterns are plotted in figs. 4.10 and 4.11. One can notice a difference between the two patterns which proves coupling has an important role and cannot be neglected. From figs. 4.10 and 4.11, it is seen that we can easily use this coupling to our advantage to help improve the radiation patterns, especially in the case of achieving an isotropic pattern.

Following the study of the coupling effect, three different radiation patterns were obtained by activating and phasing different slot elements. A circular polarization was achieved on the same panel.

![Solar panel used by a CubeSat.](image1)

![Elements on a panel (a) without coupling effect, and (b) with coupling effect.](image2)
4.6 Isotropic, Dipole-Like, and Directive Patterns

An isotropic pattern is widely adapted for space applications. An isotropic-like pattern was obtained by activating the outer eight elements (1 to 4 and 9 to 12) on the solar panel, as shown in fig. 4.12. No phase shifting between the elements was considered. When those elements were activated together with the effect of coupling, a radiation pattern was obtained, as shown in fig. 4.13. Small nulls were noted in the pattern, but the overall radiation is an acceptable isotropic-like pattern.
The twelve elements (1 to 12) shown in fig. 4.14 were activated in this case to get a dipole-like pattern. No phase shifting was applied between these elements. The radiation pattern in this configuration is shown in fig. 4.15, and it is seen that the pattern resembles a dipole antenna.

The last pattern we were interested in was a directive end-fire pattern. The advantages of this pattern are the high gain and directive characteristics that can be beneficial for applications where high gain and security considerations are needed. The same twelve elements activated in the dipole-like pattern antenna were used, but this time with phase shifting applied (fig. 4.16). The phase shifting was applied only in the x direction making the array directive in this direction (fig. 4.16). A phase shift of 45 degrees was applied to achieve a directive pattern shown in fig. 4.17.
Fig. 4.15: Radiation from dipole-like pattern antenna.

Fig. 4.16: Solar panel for directive end-fire pattern antenna.

Fig. 4.17: Radiation from directive end-fire pattern antenna.
4.7 Circular Polarization

By activating the four elements (6, 7, 16, and 17) in the center and phase shifting them by 90 degrees as shown in fig. 4.18, a circular polarization was obtained. The radiation patterns of this antenna are shown in fig. 4.19. The axial ratio, which is a measurement of circular polarizations is shown in fig. 4.20. An axial ratio of 0.5 dB was obtained, this value is sufficient to show a very good circular polarization.

Fig. 4.18: Solar panel for circular polarization antenna.

Fig. 4.19: Radiation from circular polarization antenna.
Fig. 4.20: Axial ratio from circular polarization antenna.
Chapter 5

Conclusion

The thesis presents an alternative antenna geometry for small satellites, particularly CubeSats. The proposed antenna topology is based on the cavity-backed slot antenna. The feeding methods for the antenna are discussed in details. The antenna geometries that produce linear polarization, circular polarization, and dual band properties are presented. The antennas were integrated with solar panels to provide a conformal and cost-friendly design. In order to perform the integration, we studied the effect of the solar panel material on the antenna performance by modeling the solar cells as silicon material with varied conductivity. It is found that the solar cells do not affect the antenna performance on the large scale and it is feasible to integrate slot antennas with solar panels to form a novel antenna solution.

To validate the design principles of the proposed antennas, three prototype fully integrated solar panel antennas were designed, fabricated, and tested. The substrate material was Polyimide. Both the antenna and the solar cells measurements were demonstrated and yield excellent results. The advantages of this topology are extremely significant since it will enable antennas to be integrated with any solar cells arrangement on the solar panels of most satellites. There will be no need for neither custom solar cells nor an antenna solution that requires mechanical operation.

As a feasibility study, the optimization for slot antennas in array configuration were performed. It is found that when the size of the solar panel permits integration of multiple slot antennas, one can optimize antenna radiation pattern to have the minimum side lobe, optimize the steering angle of the main beam to achieve the highest communication efficiency, and to optimize the total gain of the antenna system.
Finally, the possibilities of obtaining pattern reconfigurable antennas were demonstrated. It was shown that different radiation patterns can be obtained on the same panel by simply turning on and off certain antennas on the panel. Isotropic-like, dipole-like, and a directive end-fire patterns were obtained on a board having 18 switching elements. A circularly polarized antenna was also demonstrated on the same panel.

The advantages of integrated solar panel antennas are significant since these antennas can be integrated with any after-market solar cells, and there is no need for either custom-made solar cells or an antenna solution that requires mechanical operation. For future study, one can continue to finalize and prototype optimized reconfigurable solar panel antennas for small satellites. It is also desirable to test fly prototype antennas to obtain real satellite mission.
References


