Optically Transparent Multifunctional Patch Antennas Integrated with Solar Cells for Small Satellites

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Abstract- Small satellites currently suffer from limited surface real estate, imposing challenging constraints on the design of antenna system. Optically transparent meshed patch antennas proposed in this paper enable convenient and direct integration of antennas and solar cells of small satellites. These antennas have many attractive advantages over other antenna types. Two meshed patch antennas were prototyped and measured to verify the feasibility of achieving high optical transparency (>90%) and of integration with solar cells. Furthermore, the design flexibility offered by meshed patch antennas is addressed in details. Designs are presented of solar cell integrated meshed patch antennas and their array configurations characterized by multifunctionality of harmonics tuning, circular polarization, omnidirectional pattern, high directivity or improved bandwidth. These attractive features of the proposed transparent meshed patches are very promising for small satellite applications.

I. INTRODUCTION

Small satellites (with a mass below 500 kg) are cost-effective and can be launched to the orbit in a more economic way. Because of these advantages, which traditional satellites do not possess, they are widely employed in many space missions such as telecommunications, earth observations, and a wide variety of scientific research. However, the small size of a small satellite also limits the surface area for solar arrays and hence imposes constraints on the amount of available energy. Consequently, design of antenna system for small satellites, especially for cube satellites or even smaller ones, remains one of the biggest challenges.

As part of their communication systems to handle command control, data download, and communications relay, antennas are very important components of satellites. Wire antennas such as crossed dipoles are the most popular antenna type in small satellite applications due to the ease of cross polarization (CP) configuration, wide range of operation frequency, and minimum occupation of surface area. But this type of antenna needs a complicated deployment mechanism, which may cause failure in communication and hence loss of a whole satellite. Another type of antenna frequently used on small satellites is microstrip patch antenna. Despite its advantages of being low-profile, cost-friendly and highly reliable, its application on small-sized satellites has been limited primarily because the use of patch antennas unavoidably results in reduction in solar array capacity of satellites.

Many research initiatives are focused on antenna integration with solar cells in an attempt to achieve

both good antenna performance and maximized solar array capacity. It has been reported that a patch antenna can be placed under solar cells to obtain compatibility of antennas and solar cells [1]. However, this method involves a complicated multilayer structure. Solar panel integrated slot antennas suggested in [2] seem to be a good solution for this issue. But the major drawback is that slot antennas have to be located in the gap between solar cells, significantly restricting design flexibility, especially for array configuration.

This paper proposes optically transparent multifunctional meshed patch antennas that are highly compatible with solar cells. These antennas are electrically similar to conventional patch antennas except that the openings in their mesh structure are utilized to offer optical transparency. To verify the feasibility of solar cell integrated meshed patch antennas, one circular meshed patch and one rectangular meshed patch, both highly transparent, have been prototyped and tested.

It is shown that one can flexibly design meshed patch antennas to achieve a variety of radiation properties. In particular, a circularly polarized meshed patch and a design topology for a multifunctional meshed patch with harmonics suppressing capability are proposed. Additionally, some array configurations comprised of meshed patch elements are shown, including a tightly coupled array that can greatly improve the bandwidth.

II. DESIGN BASIS

A. Mechanism of Solar Cell Integrated Transparent Patch Antennas

Small satellites, in comparison with ordinary ones, impose more challenging constraints on their energy and power system. While electronics mounted on small satellites should be highly efficient in terms of power consumption, designers also need to allocate as much surface area as possible for solar arrays such that sufficient solar energy can be collected. As seen in Fig. 1, most surface area of a typical small satellite is covered with solar cells.



Fig. 1 Small Satellite

A closer observation of the small satellite assembly shows the possibility of integrating optically transparent patch antennas onto solar cells. Fig. 2 illustrates the external structure of a small satellite. A conductive shielding is built to contain and protect internal electronics. And solar arrays are placed on the shielding and then covered with a protection layer, which is optically transparent and physically stable in space environment. This scheme resembles the structure of conventional patch antennas as described in Fig. 3. Solar cells, together with the conductive shielding, can be considered as the ground plane [3]. The protection layer can be treated as dielectric substrate, on which one can mount highly transparent patch antennas.



Fig. 2 Small Satellite Assembly



Fig. 3 Traditional Microstrip Patch Antenna Structure

Such antennas can be designed for a wide range of operation frequency by changing the patch size provided that appropriate radiation efficiency and high transparency can be achieved. Therefore, transparent patch antennas have the potential to replace the currently dominant wire antennas for small satellite application, resulting in higher reliability of the antenna system and reducing the payload by eliminating the deployment mechanism for wire antennas.

B. Optimal Transparent Patch Antennas for Small Satellites

In order to find an optimal candidate for transparent patch antennas to be integrated with solar cells, different approaches were considered. The first method is to construct transparent patches by utilizing transparent conductive films, such as AgHT (silver coated polyester film), ITO (indium tin oxide) and CNT's (carbon nanotubes). They are usually of high loss, especially if high transparency is required, due to its inherent material limitation [4]. Designing patch antennas using such transparent conductive films involves a tradeoff between radiation efficiency and optical transparency [5].

An alternative for fabricating transparent patch antennas is to create them from a sheet of meshed conductive. The openings in the conductor allow light to go through while the mesh can be still designed into effective radiators. The typical geometries of rectangular and circular meshed patches are shown respectively in Fig. 4(a)-(b). Preliminary studies have addressed that meshed patches can radiate in almost the same manner as solid patches [6].



Fig. 4 Meshed Patch Antennas: a) Rectangular; b) Circular

As a term to be frequently quoted in this paper, transparency (T) of a meshed patch antenna is defined by the ratio of the area of the openings within the patch to the whole area of the patch, which is given by the following formula.

$$T = \left[\frac{A_{see-through}}{A_{patch}}\right] \cdot 100\%$$

Given a patch size, which determines the antenna's operation frequency, the patch transparency depends on two parameters: the line width and the line number of the mesh geometry. In order to achieve higher transparency, one can employ a less number of lines or a smaller line width or both. However, a mesh structure containing only a few lines that are very narrow may result in a patch with very high transparency but not necessarily an acceptable antenna performance. Sufficient lines with a reasonable line width should be maintained in a meshed patch to achieve comparable radiation properties which are offered by its solid counterpart. The highest transparency of a meshed patch that can radiate properly was reported to be 93% [7].

Although the mesh pattern of a meshed patch can be made arbitrarily, it should be carefully designed to obtain optimal performance. It is already well known that, regardless of radiation mechanism, currents flowing on the surface of a traditional solid patch play an important role and their pattern is correspondingly related to the radiation mode excited. Since a meshed patch antenna is derived from and should behave like its solid counterpart, the mesh geometry should enable effective conduction of a certain current pattern required by the radiation mode of interest. For example, a rectangular solid patch antenna radiating in its fundamental mode has currents flowing in a parallel way from the back edge to the front edge. So a rectangular meshed patch should be designed as shown in Fig. 4(a), where one set of parallel lines offer current paths while the other set of orthogonal lines connect the current path lines to form a patch. A similar pattern for a circular meshed patch promoting its fundamental radiation mode is depicted in Fig. 4(b).

As a quick comparison between these different methods for fabricating transparent conductive patches, the typical values of their electric property and optical transparency are listed in Table 1.

Table 1.	Transparent	conductive	film com	parison [8]
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Material	Sheet Resistance	Transparency
AgHT	4.5Ω/sq	75%
ITO	4.6 Ω/sq	90%
Mesh	<0.05 Ω/sq	93%

According to Table 1, conclusion can be made that meshed conductor is the optimal candidate to fabricate transparent patch antennas in terms of both electric property and optical transparency. Moreover, meshed conductor is also superior to the other options from the prospective of manufacture cost.

III. PROTOTYPE OF MESHED PATCH ANTENNAS

In an attempt to actually verify whether the proposed meshed patch antennas can function properly for small satellite application, two meshed patch antennas radiating at two different frequencies in S-band were prototyped using inkjet printing method suggested in [9]. The first one was a 90% transparent circular meshed patch constructed on transparent substrate. The other one was solar cell integrated rectangular meshed patch with 95% transparency. The measurements are as expected, demonstrating that meshed patch antennas are suitable for solar cell integration on small satellites.

A. Feed Design

Many feeding schemes have been developed for patch type antennas such as probe feed, microstrip line feed, coplanar waveguide feed and various coupling feeds. For applications discussed in this paper, feed structures should avoid covering area above solar arrays. For this reason, probe feed is favored, in particular when an array configuration with a complex feed system is involved. Nevertheless, microstrip line feed is a good option as well. Since, it can be aligned right above the gap area between solar cells, or the line itself can also be meshed.

For prototype, emphasis is on verification of meshed patches instead of optimization of feed design. Thus the primary factor to be considered about the feed is the ease of fabrication. Therefore, a conformal proximity feed called T-coupling feed [9] was adopted in this study, as illustrated in Fig. 5(a)-(b). This feed structure consists of a major feed line and two symmetric branches on one end, which are perpendicular to the feed line and parallel to the patch antenna's periphery.



Fig. 5 T-Coupling Feed for: a) Rectangular Patch; b) Circular Patch

Usually, the major feed line of the T-coupling scheme has a fixed characteristic impedance of 50 Ω or other values, which are distinct from the load antenna's input impedance. To match these two impedances, the gap between the patch and the feed structure, together with the thickness of T-coupling feed's branches, can be adjusted.

B. Circular Meshed Patch Antenna

Utilizing the inkjet printing technique reported in [9], circuits containing very fine geometry, such as meshed patch antennas studied in this paper, can be printed on flexible thin substrates with high accuracy at a low cost. One circular meshed patch with 90% transparency resonating at 2.5 GHz was designed using Ansoft's HFSS and inkjet printed with Epson C88+. The conductive ink (containing silver particles) used for printing was JSB-35P from NovaCentrix. Since hard thick substrates like plexiglass cannot be used directly for inkjet printing, a flexible substrate called PET (polyethylene terephthalate) film coated with a special ink capture layer was used. A careful and immediate curing according to the instructions from NovaCentrix was performed to achieve optimal electric properties of the printed antenna.

The prototyped circular meshed patch antenna is shown in Fig. 6, where the patch is printed on the PET film, which is attached on top of the transparent plexiglass substrate, whose bottom side is grounded with copper tape. The plexiglass has relative permittivity, thickness, and loss tangent of 2.6, 2.032 mm and 0.0057 respectively. The printed T-coupling feed line is extended using copper tape to enable a better soldering of the SMA connector. The dimension of the ground plane is 150×150 mm², and the circular patch has a radius of 21 mm.



Fig. 6 Circular Meshed Patch Antenna Prototype

A vector network analyzer (VNA) 8510C was used to measure the prototyped antenna's S_{11} , which is

plotted in Fig. 7. It can be seen that S_{11} is about -17 dB at the resonance frequency 2.48 GHz, which agrees very well with the initial design goals. But S_{11} value beyond the resonance frequency varies from -0.5 dB down to -2 dB, indicating a certain amount of undesirable loss. This may be due to the conductive ink, which has worse conductivity than copper. For a prototype study, however, it is still acceptable.



Fig. 7 S₁₁ Parameter of Circular Meshed Patch Antenna

The antenna's normalized radiation pattern, as displayed in Fig. 8-9, was measured with NSI's near-field antenna range. One can observe that on both E-plane and H-plane the difference between co-pol and cross-pol is higher than 15 dB, indicating a fairly good linear polarization.

In an overall sense, the pattern of this circular meshed patch resembles that of its conventional solid counterpart. So it can be concluded that meshed patch antennas function in a similar way as solid patches.



Fig. 8 Co- and Cross-pol Radiation Pattern of Circular Meshed Patch (E-plane)



Fig. 9 Co- and Cross-pol Radiation Pattern of Circular Meshed Patch (H-plane)

C. Rectangular Meshed Patch Antenna Integrated with Solar Cells

In order to further verify the feasibility of integrating meshed patch antennas with solar cells, a rectangular meshed patch with 95% transparency was manufactured in the same way as introduced previously in the section. The antenna was designed at 3.5 GHz and the initial simulation was carried out in Ansoft's HFSS. Its prototype is shown in Fig. 10, where the patch and its T-coupling feed are printed on a thin PET film, and a copper board mounted with two pieces of solar cells is used as the ground plane. The transparent dielectric with relative permittivity of 2.73 and thickness of 1.005 mm is placed under the PET film and above the solar cells and the copper board. The ground plane size is 150×150 mm² while the meshed patch has a length of 24 mm and a width of 30 mm.



Fig. 10 Solar Cell Integrated Rectangular Meshed Patch Antenna Prototype

The resonant frequency of the rectangular meshed patch was measured with the same VNA 8510C and Fig.11 describes the measured S_{11} results. It can be seen that the antenna has a resonance frequency of 3.56 GHz, where the reflection coefficient is -19.5 dB. These measurements were well predicted in the HFSS simulation.



Fig. 11 S11 Parameter of Rectangular Meshed Patch Antenna

The normalized radiation pattern of this solar cell integrated rectangular meshed patch was measured using the same NSI's antenna range system. And the results are presented in Fig. 12-13, where it is apparent that co-pol component of the radiation is 20 dB higher than cross-pol one almost in all directions on both Eplane and H-plane. This indicates that this antenna is featured by highly linear polarization. It can be noticed that the radiation pattern is distorted to some extent. This may be because of the presence of reflection in the measurement environment.



Fig. 12 Co- and Cross-pol Radiation Pattern of Rectangular Meshed Patch (E-plane)



Fig. 13 Co- and Cross-pol Radiation Pattern of Rectangular Meshed Patch (H-plane)

It should be noted that the effect of solar cells on the antenna's properties is negligible. The reason is that the solar cells with sufficiently high conductivity can be considered as part of the metallic conductor, on which they are mounted [2], [3]. This was indirectly verified by the measurements given above as well.

The prototyped rectangular meshed patch has a high transparency of 95%. In other words, the patch blocks an area, equal to 5% of the patch area, of solar cells beneath. Taking into account the fact that the patch itself is much smaller than a single solar cell, as shown in Fig. 10, the detrimental effect of meshed patches on solar cells can be very trivial. Actually, the wire antennas may block more solar cell area due to their possible shadow onto solar panels.

The conclusion can therefore be made that meshed patch antennas integrated directly onto solar cells are suitable for small satellite applications.

IV. ACTIVE INTEGRATED MULTIFUNCTIONAL MESHED PATCH

The study in Sections II and III has shown that a meshed patch antenna can be an effective radiator and enable increased surface real estate for solar arrays, resulting in more energy collection. On the other hand, to further cope with the power constraint of small satellites, electronics with high efficiency in terms of power consumption are preferred.

As part of the wireless communication system of a small satellite, an antenna may generate harmonic radiations, which not only waste precious power but cause electromagnetic interference (EMI). Usually, a harmonic suppression filter is placed between a power amplifier and an antenna, as illustrated in Fig. 14. But it is not an optimal option, for a filter adds to system complexity and cost. One technique for solving this problem is the active integrated antenna (AIA) approach, where the antenna functions as a filter, harmonic tuner, load and radiator [10]. A separate harmonics filter is not needed and the overall payload can therefore be significantly reduced. Harmonic radiations have been reported to be related to the input resistance levels of the antenna at harmonic frequencies [11]. If reactive terminations are realized at harmonic frequencies, then the harmonic radiations will be suppressed and hence the power added efficiency (PAE) of the power amplifier can be improved.



Fig. 14 Traditional Implementation of Harmonic Suppression

The mesh pattern for circular patch antennas, as described in Fig. 15, was found to be capable of suppressing the second and the third harmonics. This antenna was designed and simulated with Ansoft's HFSS. In order to accurately model the substrate of the antenna, standard dielectric Roger's RO4003 with relative permittivity of 3.55, loss tangent of 0.0021 and thickness of 1.524 mm was adopted. Although it is not transparent, it is still acceptable since the current emphasis is the functionality research instead of real product manufacture. The radius of the circular meshed patch is 21 mm, leading to a resonance around 2.1 GHz.

The variation of this circular meshed patch's input impedance versus frequency from the HFSS simulation is plotted in Fig. 16, where the input impedance at the second and the third harmonics are almost purely reactive with the resistance values close to zero. This characterizes the potential harmonic suppression capability of the antenna.



Fig. 15 Circular Meshed Patch with Harmonic Suppression Functionality



Fig. 16 Input Impedance of Circular Meshed Patch with Harmonic Suppression Functionality

Next step is to integrate the proposed circular meshed patch directly with an amplifier to find out whether its PAE can be improved. This part of study was performed with Advanced Design System (ADS). Fig. 17 illustrates the direct integration of the circular meshed patch with an RF power amplifier biased for Class B. The whole circuit, including the antenna, is built on RO4003C substrate. The RF nonlinear model of the transistor NESG2021M05 used for designing the amplifier is from California Eastern Laboratories.



Fig. 17 Active Integrated Circular Meshed Patch with Harmonic Suppression

The simulated result of the power amplifier's PAE against RF input power level is displayed in Fig. 18. The blue curve was achieved when using a random circular meshed patch as the amplifier's load while the red curve was obtained when connecting the proposed circular meshed patch for harmonic suppression. The maximum value of the amplifier's PAE is increased from 71% to 77%.

The circular meshed patch that can suppress harmonics enables a more compact system design by eliminating the filter traditionally placed between the power amplifier and the antenna. It also significantly reduces undesirable electromagnetic interference. In addition, its advantage of improving the power amplifier's PAE equates to enhancing energy generation. Therefore, even a few percent of improvement in PAE can be considered to be significant, especially for small satellite applications.



Fig. 18 PAE of Amplifier Integrated with Circular Meshed Patch: with and without Harmonic Suppression

It should be pointed out that the input and output impedance matching networks are indispensible and that they can be placed inside the satellite shielding to avoid solar cells being covered.

V. CIRCULAR POLARIZATION

Communication between ground and satellites forces the use of circular polarization (CP) for antennas on both sides due to the ionospheric effects. To meet this requirement, the CP scheme for meshed patch antennas is needed.

Traditionally, for a single element patch type antenna, there are usually two methods to obtain CP: single feed and dual feeds [12]. Using a single feed requires modification of the geometry of the patch antenna such that the currents flowing on the patch surface can rotate with time, resulting in rotation of propagating waves. This technique is not suitable for meshed patches as their fixed mesh structure is unable to provide the possibility for surface currents to rotate. Therefore, two feeds have to be involved for designing CP meshed patch antennas. The antenna must be symmetric as well to achieve a good axial ratio. For this reason, a square meshed patch antenna, as shown in Fig. 19, can be a good candidate.

To mimic designing a CP antenna on a CubeSat's panel, a meshed antenna operating at about 2.4 GHz

was designed and studied with HFSS. As displayed in Fig. 19, the square meshed patch with a dimension of $33 \times 33 \text{ mm}^2$ was built on top of a plexiglass substrate with the same electric properties and thickness as described in Section III. The ground plane size is $83 \times 83 \text{ mm}^2$. Two T-coupling feeds perpendicular to each other in space and 90 degrees out of phase were used to excite the square meshed patch. Several types of simulation results were examined.



Fig. 19 Square Meshed Patch Antenna for CP

First, the return loss of each feed and the insertion loss between the two feeds were examined in order to find out the matching on each feed and the isolation between the two feeds. From the results plotted in Fig. 20, one can tell that the antenna is well matched to either feed and that the isolation between these two feeds is sufficiently strong, which is a good design for dual feed structure.



Fig. 20 Return Loss of Single Feed and Insertion Loss between Two Feeds of Square Meshed Patch for CP Design

Secondly, the radiation pattern at the resonance frequency was examined, with the simulation result displayed in Fig. 21. The patterns on both E-plane and H-plane are almost the same, which is a good sign of CP. Actually, the axial ratio at the resonance frequency 2.45 GHz calculated by HFSS is less than 2 dB, further confirming that this design is acceptable for CP purpose.



Fig.21 Radiation Pattern of Square Meshed Patch for CP Design

VI. ARRAY CONFIGURATION

Antenna arrays can provide some special features that a single element cannot, such as high directivity, high gain, beam scanning, etc. The limited bandwidth of microstrip patch antennas may be a disadvantage, but their thin and conformal structure adds to their value in array application. Array comprising of meshed patch antennas are also expected to have similar advantages and properties. Since very high transparency can be achieved using meshed patch antennas, array configuration become compatible with solar cells for small satellite application. In this section, several different meshed patch arrays designed for different radiation properties are presented.

A. Array with Omnidirectional Radiation Pattern

If the antenna system of a small satellite provides an omnidirectional radiation pattern, then it can eliminate the pointing requirements on the satellite for communication, hence reducing the overall payload. Omnidirectional pattern construction utilizing patch type antennas involves array design. Conventionally, patch antennas have been undesirable for array configuration on small satellites, particularly on CubeSats, due to limited surface area. However, applying arrays of meshed patch antennas are affordable owing to the high transparency that can be achieved.

It was found that the meshed patch array configuration schematically shown in Fig. 22 can

radiate in an omnidirectional manner. The blue box mimics the conductive shielding of a small satellite covered with a transparent protection layer, which is treated as plexiglass substrate for meshed patches. Each antenna is located at the center of that face of the satellite. The dimension of the meshed patches is the same as in Section V. The cube shaped box can represent a CubeSat in real application. All the element antennas are excited using the lumped port with no phase difference.



Fig.22 Meshed Patch Array on CubeSat for Omnidirectional Pattern

This array was simulated in HFSS and the radiation patterns, both 2-D and 3-D, are given in Fig. 23-24. It can be seen that on any plane perpendicular to y-axis (blue), the radiation pattern is almost perfectly omnidirectional. This array design is of great significance to both satellite-to-satellite and satellite-to-ground communication, especially for CubeSats.



Fig. 23 Omnidirectional Radiation Pattern for CubeSat (3-D)



Fig. 24 Omnidirectional Radiation Pattern for CubeSat (2-D)

B. 1-D Array

In this study, one dimensional array consisting four element meshed patches for 3U CubeSat application was designed and simulated in HFSS in an attempt at obtaining a highly directive radiation pattern.

As depicted in Fig. 25, all the meshed patches are aligned along y-axis on a 3U CubeSat panel. The spacing between two adjacent meshed patch elements is approximately 0.5λ , where λ is the free space wavelength at antenna's resonance frequency 2.45 GHz. Antenna size and structure are the same as in Section V. All the antennas are fed with lumped ports with no phase offset between them.



Fig. 25 1-D Meshed Patch Array on 3U CubeSat Panel

The simulated radiation pattern of this 1-D array is presented in Fig. 26. The maximum radiation occurs in z direction on x-z plane, where the directivity is 11.2 dB. The side lobes, however, may be further diminished by adjusting the array parameters such as spacing or phase difference between elements.



Fig. 26 Radiation Pattern of 1-D Meshed Patch Array on 3U CubeSat Panel

C. 2-D Array

For applications where a larger surface area is available and special design goals are required, 2-D arrays can be considered. Two different 2-D meshed patch arrays characterized by very high directivity and improved bandwidth respectively were designed.

For the first case, a 16-element 2-D array was created by simply expanding the 1-D array discussed above in this section along x-axis (green), as shown in Fig. 27. The antenna and the feed structure remain the same as in 1-D array case. The simulated radiation pattern, as shown in Fig. 28, has a main beam in z direction with a maximum directivity up to 19 dB as expected.

This is obtained at the price of covering more area above solar cells with meshed patches. However, the overall coverage is still limited given that each patch has at least 95% transparency.



Fig. 27 2-D Meshed Patch Array for High Directivity

Another type of 2-D array scheme is called tightly coupled array [12]. The arrays of this type enable convenient design to achieve higher bandwidth. Due to the close proximity, strong coupling between array elements exists and possibly causes different equivalent patch sizes across the array, resulting in multiple resonances. This effect can be utilized to enhance the bandwidth.



Fig. 28 Radiation Pattern of 2-D Meshed Patch Array for High Directivity

An example of tightly coupled array consisting 9 meshed patch elements, as illustrated in Fig. 29, was designed, simulated and optimized with HFSS to improve the bandwidth. The basic antenna structure and dimension are still remained the same as in previously discussed cases in this section. Among the array element, only the central one is excited.



Fig. 29 2-D Tightly Coupled Meshed Patch Array

To evaluate the improvement of the bandwidth, simulated S_{11} of this tightly coupled array is plotted in comparison to that of a single element in Fig. 30, where the 10-dB bandwidth of the array is at least twice as wide. This improvement is achieved at the cost of decreasing effective solar cell area, probably to some acceptable extent. Further enhancement of bandwidth is possible if patch size, separation between patches and feeding position are optimized.

Even if the bandwidth improvement is not very high, it can be still significant for higher data rate communication taking into account the high operation frequency like in S-band.



Fig. 30 S₁₁ Parameter Comparison between 2-D Tightly Coupled Array and Its Single Element

VII. CONCLUSION

Transparent meshed patches as an alternative type for antennas in small satellite applications are presented. Antenna prototypes have been fabricated and measured. It is demonstrated that the proposed antennas and solar cells can be integrated with a high compatibility. While the antenna properties almost do not get affected by the presence of the solar cells as part of ground plane, the antennas mounted directly onto solar cells cast very limited shadow on them.

It is shown that useful antenna features such as harmonic tuning functionality and circular polarization can be achieved by carefully designing the mesh geometry. Moreover, different array configurations for different types of small satellites are discussed, and diverse radiation patterns have been realized, such as omnidirectional pattern, high directivity and improved bandwidth.

Overall, it is feasible to employ the proposed antennas in applications of small satellites, especially smaller ones such as CubeSats, and to carry out a customized design to meet different design goals and requirements.

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