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Solar Cell Integration in Cubesat: A New Era in SatCom

Dixit Dutt Bohra[1], Purneshwari Varshney[2]

[1]Assistant Professor, Department of Electronics & Communication Engineering, Jodhpur National University, Jodhpur, Rajasthan, India

[2]Assistant Professor, Department of Electronics & Communication Engineering, JIET Group of Institutions, Jodhpur, Rajasthan, India

Abstract

This paper presents an innovative solution for small satellite antennas by integrating antennas and solar cells on the same panel to save small satellite surface real estate. The two main advantages of the concept: one, the antenna does not require an expensive deployment mechanism that is required by dipole antennas; second, 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. In order to demonstrate and validate the design method, three fully integrated solar panel antennas are 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. It is shown that the planned 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.

Keywords: *Cubesats, Solar cell, Antenna*

1. Introduction

Satellites have always played an important role in space. Their contributions for space research, extended global communications and surveillance have been instrumental for the advancement of the information age. Autonomous communications systems often involve the use of separate solar cell and antennas, which necessitate a compromise in the utilization of limited surface area available [1]. Cost and weight are always key issues for successful satellite deployment. Limitations on the size of these small satellites leave barely enough room for solar cells, which are essential to power the satellite. This repeatedly impedes the placement of other external elements such as antennas. These separate items may be combined, provided that antennas and solar cell are compatible. To show the compatibility in context of satellite, different antenna designs and concept is studied.

1.1 CubeSats Myth

Satellites are classified according to their weights. Due to the high cost of launching material into space, smaller satellites have recently gained favor among scientists and engineers. Generally, a satellite is called a small satellite if its wet mass (mass including the fuel) is less than 500 kg. Small satellites are cost effective and can be launched to the orbit in a more economic way [2]. 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.

CubeSats are a class of very small satellites called “Nano-satellites.” CubeSats refer specifically to those nano-satellites that adhere to the CubeSat Design Specification (CDS) published by the California Polytechnic State University (Cal Poly) generally with the standard unit of size of 10x10x10 cm. (one litre) and a weight of 1 kg. The size mentioned above is the standard building block of all CubeSats and is referred to as “1 Unit” or “1U” for short. The actual size of a CubeSat may be slightly larger than 10x10x10 cm; specific CubeSat standards can be found in the CDS. Fig. 1 below is of a standard 1U CubeSat. [4]

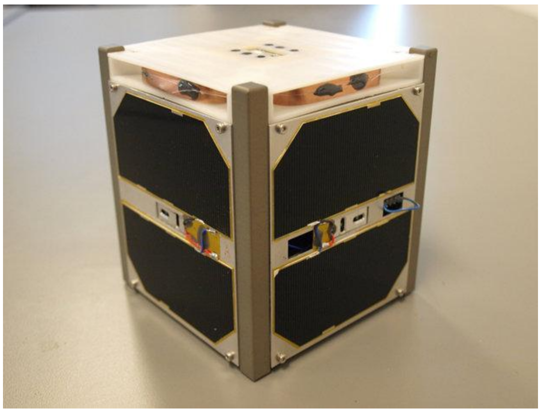


Fig. **Error! No text of specified style in document.** Standard CubeSat [4]

The standardized launching process, CubeSats has become a viable testing ground for universities. The CubeSat initiative started in 1999 as a collaborative effort between Prof. Jordi Puig-Suari at California Polytechnic State University, and Prof. Bob Twiggs at Standford University Space Systems Development Lab. The purpose was to provide a standard for pico-satellites to reduce the cost and the development time, increasing the accessibility to space, and sustain frequent launches.

1.2 Solar Energy and Panel

The energy from the sun is supplied in the form of radiation. Solar panel is only and best energy supplier for the satellite in space. A solar panel is a collection of solar *cells* which convert light into electricity. They are called "solar" panels because, most of the time, the most powerful source of light available is the Sun (called Sol by astronomers). Lots of small solar cells spread over a large area can work together to provide enough power to be useful. Some scientists call them *photovoltaic* which means, basically, "light-electricity." A photovoltaic system is based on the ability of certain materials to convert the radiant energy of the sun into electrical energy. Physically, a PV panel consists of a flat surface on which numerous p-n junctions are placed, connected together through electrically conducting strips. The PV panel ensures the conversion of light radiation into electricity and it is characterized by a strong dependence of the output power on the incident light radiation. The total amount of solar energy that lights a given area is known as irradiance (G) and it is measured in watts per square meter (W/m^2). The instantaneous values are normally averaged over a period of time, so it is common to talk about total irradiance per hour, day or month. More light hits a cell, the more electricity it produces, so spacecraft are usually designed with solar panels [3].

1.3 Antennas for Small Satellites

An antenna (or aerial) is an electrical device which converts electric power into radio waves, and vice versa. Small satellite antennas can vary according to the application required. 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. CubeSat generally uses the transparent antennas, which are placed on the solar cell itself and provide all its operations without affecting working of solar cell.

People from developing and emerging nations often struggle to obtain clean water, sufficient nutrition, adequate healthcare, effective education, economic stability, and basic security. Expenditures on space science and satellite technology in such countries may, therefore seem inappropriate because of the need for diverting resources from near-term social programs. Nevertheless, long-term economic prosperity depends in part on intellectual capital, the advancement of which requires scientific training as well as the use, and eventually the development, of new technology.

In India, Satellite launching is a vital step. Ours is a developing country where the economic development is necessary in each effort. We posit that a recent technological advance, the CubeSat, can contribute on a politically attractive and economically viable basis to the expansion of an emerging nation’s intellectual capital. CubeSat technology offers a uniquely inexpensive pathway to the study of scientific phenomena and the advancement of novel engineering concepts in the unique environment of outer space.

Cube satellites (CubeSats) are modern small satellites that are revolutionizing space research because of their small sizes and standardized architectures. The standardized architectures of CubeSats and their small sizes make it easy to manufacture at low costs within a short period of time. Furthermore, the small sizes of CubeSats make it possible to place a number of CubeSats as secondary payloads on conventional satellites, making the deployment of CubeSats cheap and easy.

CubeSats have numerous space applications - providing aerial geographic images for disaster management which is essential for any developing country like India , providing a cheap way to test space technology before they are applied in mission-critical space applications, providing a miniature platform that allows students to learn about all systems involved in conventional spacecraft development within the short duration of their studies, providing a setup to perform biological experiment in space, and providing low-cost telecommunication access.

2. History and Component

In astronomy, a satellite is a natural body that revolves around a planet and is also called a moon. With the IAU's 2006 decision on the definition of a planet (which changed the definition of Pluto), a satellite (moon) can also revolve around a dwarf planet, as Charon does for Pluto. In aerospace and space exploration, a satellite is a man-made object launched into space to orbit the Earth, moon, sun or other celestial body. Some examples are weather satellites and communications satellites. In general, a satellite is anything that orbits something else, as, for example, the moon orbits the earth. In a communications context, a satellite is a specialized wireless receiver/transmitter that is launched by a rocket and placed in orbit around the earth. There are hundreds of satellites currently in operation. They are used for such diverse purposes as weather forecasting, television broadcast, amateur radio communications, Internet communications, and the Global Positioning System, (GPS).

2.1 History of Satellite

The first artificial satellite Sputnik-I launched by Russia (Soviet Union) on October 4, 1957, successfully. The world's first artificial satellite was about the size of a basketball, weighed only 183 pounds, and took about 98 minutes to orbit the Earth on its elliptical path. That launch ushered in new political, military, technological, and scientific developments. While the Sputnik launch was a single event, it marked the start of the space age. It did nothing but transmit a simple Morse code signal over and over. In contrast, modern satellites can receive and retransmit thousands of signals simultaneously, from simple digital data to the most complex television programming. By 20th century’s end, around 2,200 satellites were orbiting the planet with many of them offering scientific data with shots of earth that were not even imagined before. Along with latest imaging techniques, satellites bestow ordinary human beings with super sight. Remote sensing uses aerial photography and lets humans’ view, which is otherwise not possible with an unaided eye. Different techniques allow identification of vegetation, soil, seasonal crops, mineral resources and changes brought around by floods and storms. These are also use for detecting surface temperatures and finding out groundwater movements etc. [4]

2.2 Components of a Satellite

There are 3 major components in a satellite, they are:

2.2.1 Transponder and Antenna System

The transponder is a high frequency radio receiver, a frequency down-converter and a power amplifier, which is used to transmit the downlink signal. The antenna system contains the antennas and the mechanism to position them correctly. Once properly in place, they will generally function trouble-free from the life of the satellite.

2.2.2 Power Package

It is a power supply to the satellite. The satellite must be powered either from a battery or a solar energy system. In case of communications satellites in the Clarke orbit, a combination of battery power and solar energy is used. A solar cell system supplies the power to run the electronics and change the batteries during the sunlight cycle and battery furnishes the energy during the eclipse.

2.2.3 Control and Information System & Rocket Thruster System

The control and information system and the rocket thruster system are called the station keeping system. The function of the station keeping system is to keep the satellite in the correct orbit with the antennas pointed in the exact direction desired.

2.3 CubeSat Introduction

Access to space has always been a challenge, especially for organizations with limited budgets. In the last decade a group of universities has overcome many of the obstacles associated with placing experiments on orbit by using a nano-satellite standard called the “CubeSat”. The CubeSat origin lies with Prof. Twiggs of Stanford University and was proposed as a vehicle to support hands-on university-level space education and opportunities for low-cost space access. The basic CubeSat standard is a 10x10x10 cm. cube with a mass of up to 1.33kg. CubeSats are carried as piggyback in the launcher and are normally ejected using the Poly Pico satellite Orbital Deployer (P-POD), a container specifically designed to eject CubeSats, capable to carry up to 3 different one-unit pico-satellites. The minimum cost of the launch is ~65.000$, depending on the launcher, being now a days the PSLV launcher of the Indian Space Agency (ISRO) the most economic one. [5]

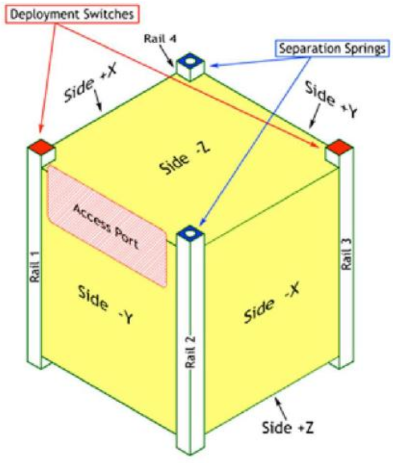


Fig. 2 Standard 1 U CubeSat [5]

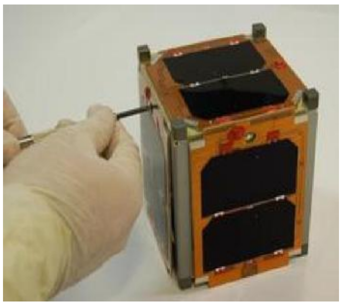


Fig. 3 Pumpkin 1U CubeSat Structure with Clyde Space Solar Panels [6]

CubeSats are scalable and can be two to three times the length of a standard CubeSat. Existing variations include 2U (1 x 1 x 2) and 3U (1 x 1 x 3). One 2U CubeSat is the same size, weight, and approximate centre of gravity (CG) as two 1U CubeSats; and one 3U is the same mass characteristics as three 1U CubeSats [5]. Figure 3 below shows the current CubeSat family including 1U, 2U and 3U CubeSats forms. In addition to the three common sizes, some have speculated usefulness for even larger sizes, such as 5U (1 x 1 x 5), 6U (1 x2 x 3), and for imaging, 20U (2 x 2 x 5), which would allow for optics up to 20cm in diameter [6].

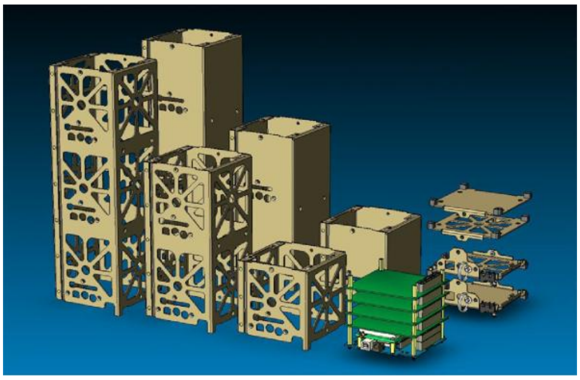


Fig. 4 The CubeSat Family [6]

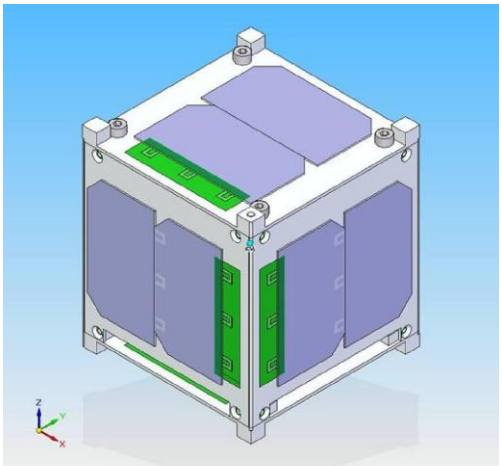


Fig. 5 CubeSat structure, aluminum housing with solar panels (gray)

3. CubeSat Configurations, Technologies, Subsystems, and Operations

3.1 Configurations and Technologies

Most spacecraft comprise a payload, which is transported to and through space in order to execute a measurement, experiment, or other task, and a “bus” that includes critical support functions to operate the spacecraft: command and control; communications; propulsion; attitude determination and control; de-orbit mechanism; power generation and distribution; energy storage; data buffering and storage. CubeSats include varying subsets of these functions; their small size may blur the physical distinction between payload and bus. Of the common configurations—1U, 2U, and 3U, each “U” being a 10-cm cube as stated earlier— the larger two lend themselves to the dedication of one cube to the bus, the other(s) to the payload. These three CubeSat configurations are driven in part by launch-vehicle integration-and-deployment hardware, the most widely used being the Cal Poly P-POD (poly-picosatellite orbital deployer), discussed in next subsection.

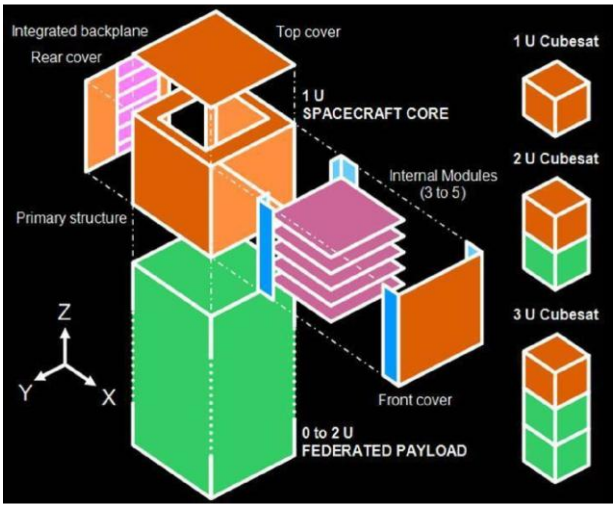


Fig. 6 Sub-Parts of CubeSat

The breadth of CubeSat applications has increased dramatically in the past decade due in part to advances specific to the conventional satellite industry, and in larger measure due to general technological progress in rapidly evolving fields including microelectronics, low-power communications, high-efficiency solar cells, low-cost precision fabrication, high-energy-density batteries, microelectromechanical systems (MEMS), high-density memory, field-programmable gate arrays, miniature high-efficiency motors and actuators, advanced materials, integrated optics, microsensors, and microfluidics. Often, commercial off-the-shelf (COTS) components are used without modification to develop the various CubeSat subsystems; the overall design of the CubeSat and the density at which the subsystems are integrated, as well as methods of assembly and ruggedization, are often the requirements unique to operation in the space environment. [5]. Nonetheless, subsystems and instruments developed for demanding industrial and consumer environments often need minimal modification for use in small satellites. For example, a typical consumer mobile telephone “drop” requirement, 1 m onto a concrete floor produces shock levels well in excess of those required for launch and deployment on and from typical space vehicles.

3.2 Poly Picosatellite Orbital Deployer (p-pod)

The Cal Poly Picosatellite Orbital Deployer (P-POD) was introduced shortly after the CubeSat concept had developed. Although named the “Picosatellite” Orbital Deployer it is designed specifically to deploy CubeSats—not just any Pico-satellite [6]. The P-POD Mk I was designed to deploy 4 CubeSats, while the subsequent Mk II and Mk III P-PODs have each been designed to deploy 3 CubeSats.

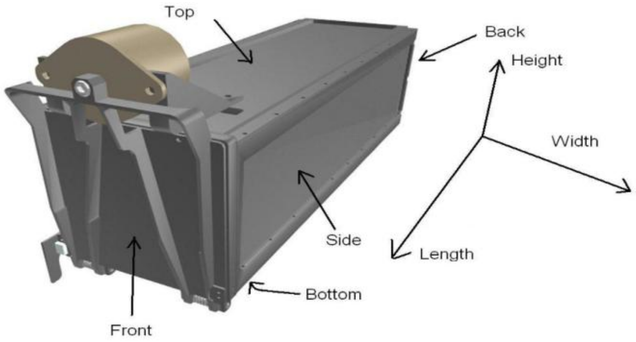


Fig. 7 P-POD MK II [5]

Fig. 7 shows a P-POD Mk II. As mentioned earlier, CubeSats are scalable. This is an important feature because it allows the P-POD to deploy various CubeSat sizes since larger (2U and 3U) CubeSats are multiples of the basic 1U CubeSat. A P-POD Mk III can deploy a volume of 3U CubeSats, which means it could deploy one 3U CubeSat, three 1U CubeSats, or one 2U CubeSat and one 1U CubeSat without any modification to the P-POD.

Fig.8 Front View of P-POD MK II [6]

As mentioned earlier, since CubeSats all have approximately the same mass properties, a P-POD with any combination of CubeSats should still have approximately the same overall mass as it would with any other combination, this is an important note since it makes mission planning much easier than with custom designed and built payloads where each is unique. The P-POD has been used to deploy 75% of all CubeSats launched. [6] The CubeSat as initially proposed did not set out to become a standard; rather, it became a standard over time by a process of emergence. CubeSat concept is the standardisation of the interface between the launch vehicle and the spacecraft, which allows developers to pool together for launch and so reduce costs and increase opportunities. As a university-led initiative, CubeSat developers have advocated many cost-saving mechanisms, namely:

- A reduction in project management and quality assurance roles.
- Use of student labour with expert oversight to design, build and test key subsystems.
- Reliance on non-space rated Commercial-Off-The-Shelf (COTS) components.
- Limited or no built-in redundancy (often compensated for by the parallel development of CubeSats)
- Access to launch opportunities through standardised launch interfaces.
- Use of amateur communication frequency bands and support from amateur ground stations.
- Simplicity in design, architecture and objective.

4. Integration of Solar Cell and Antennas

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 specification 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.[9]

The most common CubeSat transmission frequency is 437 MHz, which is in the Ultra High Frequency (UHF) band. It is often utilized because it is in the amateur radio frequency band, thus not requiring a special license to operate. Another reason for this is that the antenna can be relatively small. This paper 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 choos 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 custommade solar cells. The proposed antennas are based on slot antennas. Prototype slot antennas with Linear Polarization (LP), Circular Polarization (CP), and Array configuration are studied with its design and fabrication; the measurements agree well with the design data.[10]

Autonomous communications systems normally use separate solar cells and antennas, which compete for the use of the limited surfaces available. A combination of them can save valuable ‘real estate’, provided that antennas and solar cells are compatible. A way to do this is to combine the two kinds of devices on the same element. In particular, solar panels form a large part of communications satellites, providing large flat surfaces over which antennas can be mounted or printed. Printed antennas, commonly used in microwave communications, are naturally suited for this combination, in particular when their radiating patches can be isolated from the feed circuits. The technology for the fabrication of solar cells is amorphous silicon cells on polymer substrate. This choice provides flexible and inexpensive designs which can be adapted to the shape of the antenna. The combination also could be of interest for terrestrial systems. [10]

4.1 The Solar Antenna Concept 'SOLANT'

An increasing amount of research has recently been conducted in order to provide low-profile compact solar antenna designs capable of generating DC power output whilst receiving and transmitting RF/microwave signals.

Two solutions have arisen to mitigate the difficulty of solar cell and antenna integration. The first solution entails the placement of a slot antenna on the back side of the solar cell. This solution has been proven effective if custom built solar cell antennas are assembled for small satellites, but is not viable if the small satellite is being built from off-the-shelf components. The second solution suggests the placement of meshed see-through copper antennas on top of the solar cell. See-through meshed antennas are still in the early research phase, but show some promise as transparent antennas.[10]

4.2 Transparent Antenna Design

Transparent conductive materials have been prepared with oxides of tin, indium, zinc and cadmium. These transparent conducting oxides (TCOs) are employed in a wide spectrum of applications such as solar cells, electromagnetic shielding and touch-panel controls. [13]

4.2.1 *ITO (Indium Tin Oxide) Design*

One method of designing antennas is to use transparent conductive oxide such as indium tin oxide (ITO) films because of their reasonable trade-offs between optical transparency and conductivity.

A variety of experiments have been conducted to determine the viability of using optically transparent materials such as ITO for antenna design. Monopole and patch antennas have been made with ITO. It was found that patch antenna radiators are not as effective or as monopole antennas. Efficiency is controlled by how much current runs on the ITO imperfectly conducting antenna surface. IPIFA (Planar Inverted F Antenna) is found to have a higher radiation resistance, because it behaves like a cavity and excites a larger current on the whole patch. The trapezoidal monopole requires less current to be excited on its surface and therefore is more efficient. None of the previous designs have been placed on a solar cell. [13]

Some experiments have found that ITO antennas optical transparency is inversely proportional to the sheet resistivity and therefore ITO antennas have poor conductivity. This results in a trade-off between transparency and efficiency for ITO antennas for solar cell applications. Chemical spray deposition, DC sputtering and RF sputtering are a few of the methods used for performing ITO deposition.

4.2.2 *Meshed Patch Antennas*

An alternative to antennas made of transparent materials are meshed antennas. Although the optical transparency of meshed antennas is typically lower than ITO antennas but meshed antennas have higher efficiency and overall gain. Microstrip antennas are attractive due to their light weight, conformability and low cost. These antennas can be integrated with printed strip-line feed networks and active devices. [11]

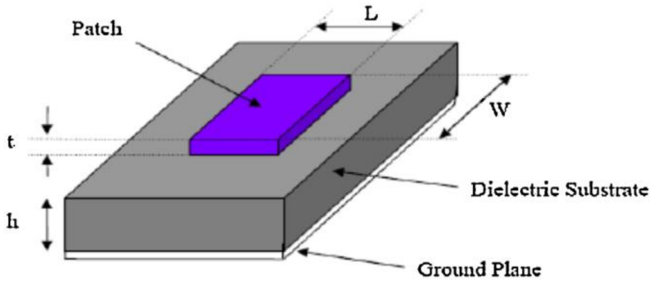


Fig. 9 Schematic View of Microstrip Patch Antenna [11]

4.2.3 *Integrated Solar Cell Antennas*

Integrated solar cell antennas have been developed with great success. The first reported attempt to combine solar cells with printed antennas merely placed commercial solar cells next to a patch antenna. The present approach presents a more advanced concept, in which specifically designed solar cells are intimately combined with printed antennas, providing a new device called SOLANT. To obtain antennas and solar cells allowing a perfect and optimized combination, it is necessary to work on both domains during all of the phases of development. They provide virtually no obstruction or degradation to the solar cell and still are able to maintain high gains and radiation efficiency. [7]

The SOLANT (SOLar ANTennas) design incorporates a slot antenna in the ground plane of a solar panel. With this design solar panels are able to function at their maximum capacity because the antenna blocks no light to the solar panel. The SOLANT design was able to achieve gains of up to 30 dBi. The integrated slot antenna design requires antennas to be custom fabricated, which is cost prohibitive for small satellites.

4.3 Fully Integrated Solar Panel Antennas for Cube Satellites

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

4.3.1 *Two-Element Linearly Polarized Antenna*

In this section, accentuate on the design of linear array antennas consisting of two series elements. The structure of design is as follows: there are two substrates, the lower substrate for the feeding network and the upper for the slot antennas etching. The substrate is made from Polyimide, a material which is commonly used for space applications. Finally, a layer of solar cells is integrated with antennas on the top layer as shown in Figure 4.3 [2]. For the feed layer (shown in Figure 4.4) 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 is 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 are modelled as very thin silicon layers with certain conductivity.

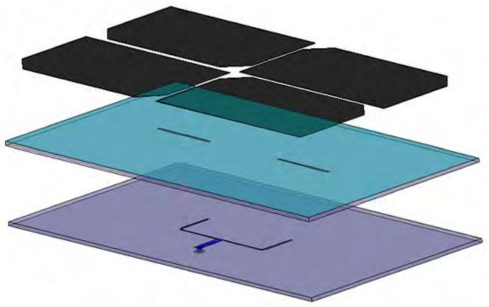


Fig. 10 Layers of 2- Element Antenna Array

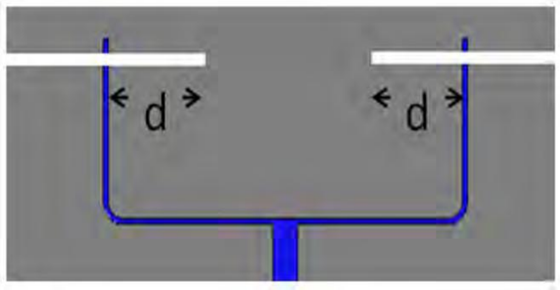


Fig. 11 Feed Design for the 2-Element Antenna Array.

4.3.2 *One-Element Circularly Polarized Antenna*

Circular polarization is preferred in satellite communication. 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, [14] and the direct result is the reduced cost. The design is composed of three layers as explained in the previous section (Fig. 12). The parameter d (Fig. 13) [10] was used to match the antenna.

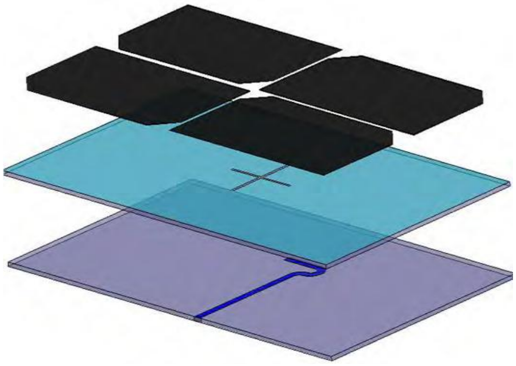


Fig. 12 Layer of Circularly Polarized Antenna

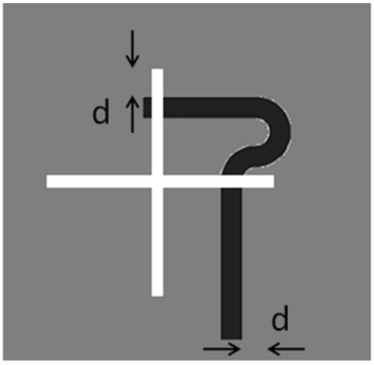


Fig. 13 Feed Design for the Circularly Polarized Antenna.

4.3.3 *Dual Band Antenna*

For the dual band antenna array, the slot locations are chosen to be at the edges of the solar panels, rather than the centre, 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. Fig. 14 shows the layer information of the solar-antenna panel. The feed network is more complicated in this case. Fig. 15 shows the feed design in more details. A 50-ohm probe was placed at the centre 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 λ/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.

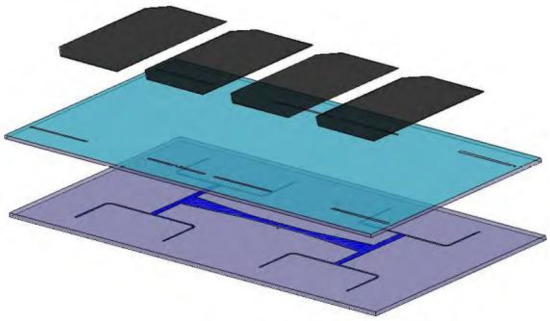


Fig. 14 Layer Structure for the Dual Band Antenna.

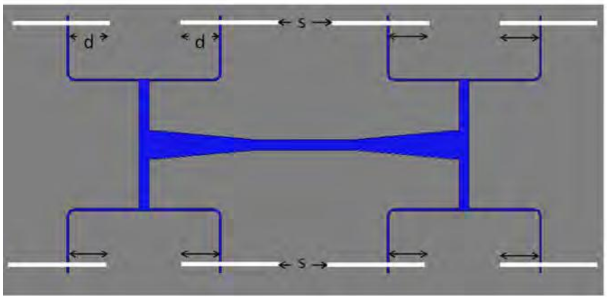


Fig. 15 Feed Design for the Dual Band Antenna.

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 can be realized by adjusting the parameter s [8].

4.4 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 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 projected 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. [10]

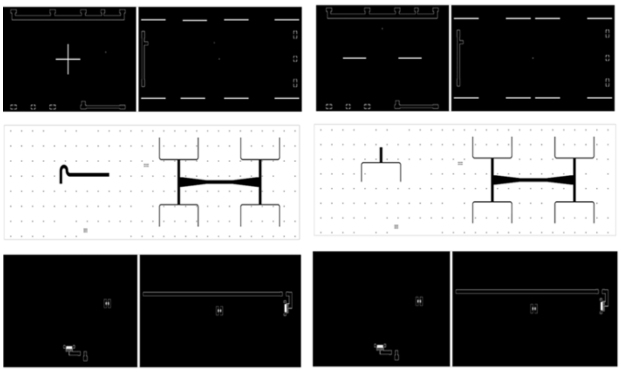


Fig. 16 The Layer Information

When prototyping the proposed antenna with PCB technology, a mask is prepared for each layer and the non-metallic parts are etched out from the layer. Fig. 16 shows the layers organization. A three-layer board is designed; the black colour represents the copper metallic parts, while the white colour represents the non-metallic parts. There are two planes: A lower ground plane and an upper ground plane. They are connected using vias which are separated from each other by $\lambda/4$ 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. All the slot antennas have a length of 28 mm that corresponds to a length of $\lambda/2$ at 2.5 GHz. 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.

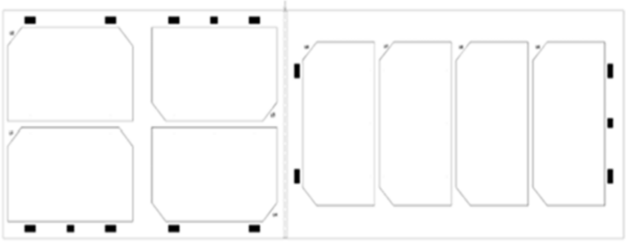
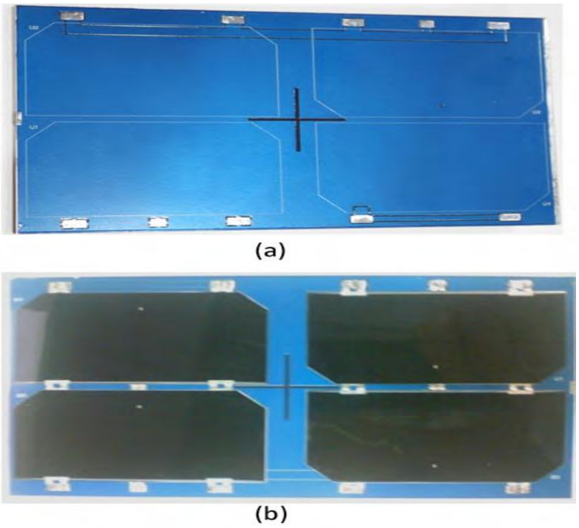


Fig. 17 Solar Cell Information

After the antennas were fabricated, 28.3% ultra triple junction solar cells were assembled in series, as shown in Fig. 17. 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.

4.5 Measurements of Antenna Performance

Fig. 18 [2] shows a picture of the fabricated circularly polarized antenna with and without the solar cells. The antenna was designed at 2.64 GHz. Figure 4.12 shows the 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 centre 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.



(a)

(b)

Fig. 18 Solar Panel with the Circular Polarization Antenna Integrated with it (a) Without Solar Cells, and (b) With Solar Cells.

For the linearly polarized antenna, the prototype has no solar cells integrated due to the cost of high efficiency solar cells. For the dual band antenna array (Fig. 19), the measured and the simulated S-11 parameter are plotted. It should be again noted that after integrating the solar cells, there is an improvement in the matching level.

Fig. 20 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.

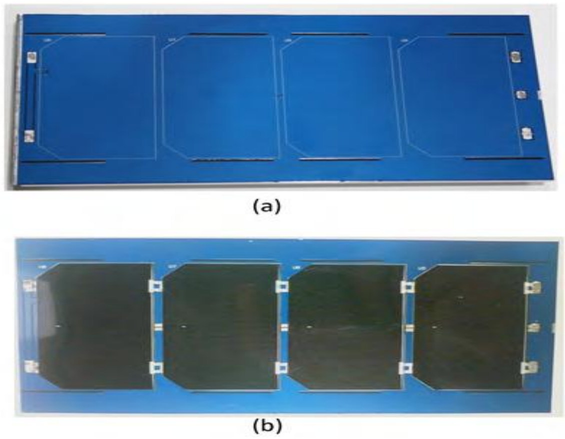


Fig. 19 Solar Panel with the Dual Band Antenna Integrated with it (a) Without Solar Cells, and (b) With Solar Cells.

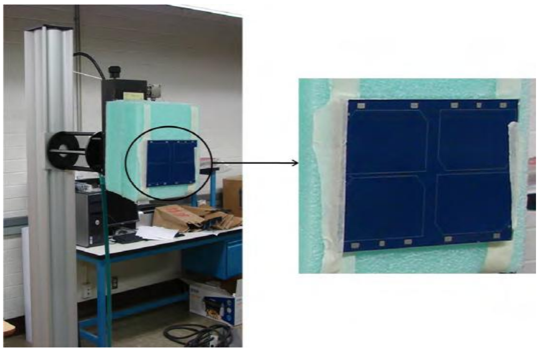


Fig. 20 Setup for Antenna Measurement

4.6 Solar Cells Measurements

The measurements on solar cell functionality are as follows. The solar cells connections at the back of the antenna are connected to an electrical variable resistor and the current is being measured for different voltage corresponding from the variable resistance. Fig. 21 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 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.

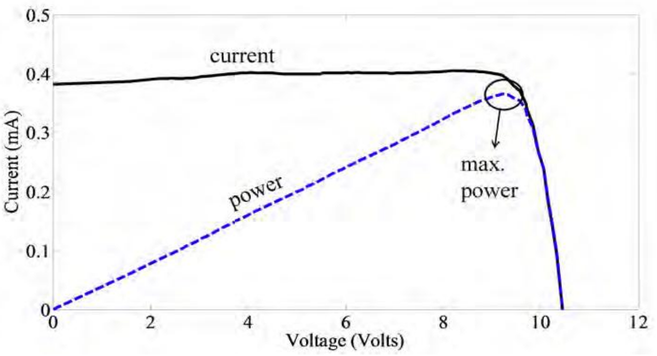


Fig. 21 V-I Characteristic from Small Solar Cell Measurements

5. Conclusions

The paper presents 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 modelling 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 prototypes 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 optimizations 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.

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BIOGRAPHIES

Dixit Dutt Bohra is purusing M.Tech. (Digital Communication) from Electronics and Communication Department of Faculty of Engineering and technology, Jodhpur Naional University, Jodhpur, Rajasthan. He has done his B.Tech. in Electronics and Communication engineering in 2010. He has published 6 international papers in journals and conferences; he has also published papers in national conferences.

Purneshwari Varshney is pursuing Ph. D. from M. B. M. Engineering College, JNVU, Jodhpur (Rajasthan), India. She received her M.E. degree in Digital Communication Engineering from the same college. She has completed her B.E. in Electronics and Communication Engineering from J.I.E.T Jodhpur (Rajasthan), India in 2008. She has teaching experience of 4 years and Research experience of 1 year. She has published 9 papers in International/National conferences. Also she has published 5 papers in International/National Journals. Her areas of interest are wireless sensor networks, VLSI Design, Wireless communication and Mobile communication.