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C-Band Transparent Antenna Design for Intersatellites Communication

Maha A. Maged, Fatma Elhefnawi, Haitham M. Akah, Hadia M. El-Hennawy

Abstract—The growing trend toward low-cost satellites constellation to act as a unified system is required to enable complex sensing tasks. Antennas are emerging as one of the keys that can improve and satisfy the requirements of the crosslink communications performance of the constellation. However, antennas types for small satellites have posed some challenges such as limited size shared by solar panels. This paper offers a novel transparent antenna solution for solar panel that fit on the face of CubeSats and address previous challenges suited for intersatellite communication. The designed antenna module consists of two patch elements with truncating of two opposite sides from Fluorine-doped Tin Oxide (FTO) on glass substrates. Four antenna modules were been fixed above solar panels on each face of the CubeSat to offer communication between satellites in all directions.

Index Terms— antenna, intersatellite link, transparent antenna, CubeSat, small satellites.

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1 INTRODUCTION

Recently, small satellites have increased due to its technological capabilities expanding rapidly. These satellites commonly encompass micro-satellites and nano-satellites and form distributed satellites system that can communicate, coordinate and interact to achieve a common mission [1]. As shown in Figure 1, such autonomous satellites system expected increased mission flexibility and success by distributing the tasks and subsystems typical of a single large satellite. Moreover, it can reduce the possibility of failures and minimizes the power consumption of satellite-ground communications.

Fig. 1 Distributed satellites system.

Currently, there is an ongoing revolution in the development and deployment of small satellites, which can be utilized for complex missions such as earth observation, remote sensing and intersatellite mission purposes. Interestingly, CubeSats can be networked to form satellite constellations or swarms missions involving earth observation and communications. Crosslink communication among CubeSats in a swarm is important because it provides direct connectivity among CubeSats without intermediate ground stations. They can jointly maintain a fixed or relative position with each other in a distributed manner [2]. However, small satellites faces many challenges such as small power budget, lightweight and small antennas that provide high gain and do not obstruct the solar panels [3], [4], [5]. Transparent antennas constitute a great potential for tackling these challenges. Transparent antennas are designed most commonly from meshed conductor [6], [7] or transparent conductive films (AZO, ITO, AgHT) [8], [9], [10], [11], [12]. The uniqueness of the transparent conductive films was the discretion and the conformability they provided by merit of the flexible nature of the substrate. This unique feature helps to design antennas that can be integrated on top of solar cells, which is promised to a CubeSat system that facilitates a possible modular design [13]. Montano et al. [14] demonstrate low-profile transparent microstrip antennas that are conformal to the surface of the solar panels of a CubeSat. These previous transparent-antennas research has offered little insight into the use for intersatellite communication applications. In this paper, design a novel transparent circular polarization antenna based on fluorine-doped tin oxide (FTO) films integrated with solar panels for intersatellite communication is evaluated and compared with copper patch antenna counterparts. The FTO was chosen due to it has many advantages such as thermal stability as well as low cost. The circular polarization recommended for intersatellite antennas, which required specific antenna geometry together with appropriate design for feeding network. The main goals of this paper are as follows:

§ Offer a novel design of circular polarization transparent antennas for photovoltaic solar-panel integration for intersatellite communication made from FTO thin film.
§ Design an antenna feed network that supplies the desired signal distribution for the antenna array elements while maintaining its transparency.

· Maha Maged is currently pursuing PhD degree program in electronics and communicationss dept. at Ain Shamis University, Egypt. E-mail: maha_maged@narss.sci.eg
· Haitham M. Akah is currently a researcher in space program in space communicationss department in NARSS, Egypt. E-mail: haitham_akah @narss.sci.eg
· Fatma Elhefnawi is currently professor in microvaes dept, Electronics Research Institute, Egypt. E-mail: fatma.hefnawi@gmail.com
· Hadia M. El-Hennawy is currently professor in electronics and communications dept. at Ain Shamis University, Egypt. E-mail: helhennawy@ieee.org

The outline of this paper is as the following. Section II discusses the intersatellite communications concept. Section III discusses the proposed antenna system for CubeSat intersatellite communication. Section III presents the intersatellite antenna configuration. Section IV presents the antenna design and its dimensions. Section V presents the simulation results with discussion. Finally, section VI, closing out the paper by conclusions.

2 A LITERATURE REVIEW ON INTERSATELLITE ANTENNAS

The crosslinks can take a variety of forms, depending on the orbital geometry of the satellites involved. One of the important usages of crosslinks lies in the capability to communicate to a satellite when it is not visible from a ground station. It also allows infrastructure to be removed from ground facilities and placed on the satellite to allow onboard switching of data channels. The crosslinks represent technological challenges, especially because of the required antenna steering and circular polarization. The beam steering techniques used to increase gain and achieve directivity and tracking capability to compensate the satellite attitude changes and vibrations [15], [3]. The Iridium system is a prime successful example in the use of intersatellite communications [16]. Iridium comprises 66 satellites in circular orbit distributed in six planes of 86° inclination at an altitude of 780km. The Iridium system uses Ka-Band (23:18 □ 23:38GHz, 200MHz bandwidth) intersatellite links to form a link between each satellite and up to 4 of its nearest neighbours [15]. There are few smart antenna designs for intersatellite crosslinks in the area of small satellites in the literature. The main two basic antenna designs that are identified to be used for intersatellite communications are broad beam width isolated antennas and smart antenna arrays. In the first design, microstrip patch antenna is installed on each face of cube satellite to provides a more compact and simple architecture. This design gives the capabilities to control multiple antennas in the satellite faces depending on a spatial signal signature to maximize directivity for any link direction [17], [18]. The design approach occupies large space that needed for solar cells [5]. The antenna array as a second design, provide beam steering capability and high antenna gain [17], [19]. To enable this feature, the phased-array antenna system and digital beamforming system are very attractive but induces high computational complexity [20], [21], [22], [23]. Murakami et al. [24] described the first antenna for intersatellite communications in CubeSat platforms, which is a retrodirective array of circularly polarized patches. The antenna has the capability to self-steer a transmitting signal without a prior knowledge of its position [19]. However, its main limitation is consuming high power [5]. An antenna system consists of one individual antenna 5dB gain patches per face of the Cubesat is tested for intersatellite links communications using S-band frequency in GAMANET [25]. The individual 5dB gain patches are used with an implementation of beamforming approach for antenna control by combining weighted signals. Another example where a configuration of six individual antennas placed on the different faces of each CubeSat in arbitrarily selected locations [17]. Vourch and Drysdale [18] proposed an antenna package with double V-band antennas for inter-CubeSat communication. The individual antenna can be formed by a sub-array of four patches; the antenna array synthesizes a narrow beam with higher gain than individual antennas. The array must have beam steering capability to explore as much angular area as possible. The same concept is proposed in Ref [26], array elements were formed by a subarray of four patches, fed with sequential phase rotation in order to achieve the circular polarization.

3. MULTIPLE ANTENNA SYSTEM CONFIGURATION

The proposed antenna system has been designed as a 1x2-antenna array module integrated over the solar panel. Each module represents a single array element in a larger array from 4 elements each module provides a radiation pattern with a gain of 5:9dB in the main lobe direction. These modules are mounted on top the CubeSat solar panel faces as shown in Fig. 2, where the radiating antenna module is dynamically selected through a specific digital control switching circuit to activate beams in different directions to conform the radiation patterns accordingly [27]. This digital control switching circuit keeping the high gain functionality of the antenna beam to point into different directions based on the selection input [22], [23].

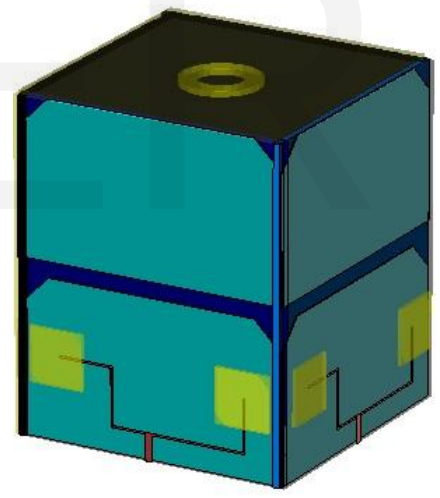

Fig. 2. The exploded view of the antenna system at CubeSat.

4 ANTENNA DESIGN AND DIMENSION

Designing square microstrip patch antenna of width W with substrate hight h theoretically calculated as follows:

$$w = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \qquad (1)$$

where v_0 is the free-space velocity of light and effective dielectric constant of the microstrip antenna calculated using

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left(1 + 12\frac{h}{w}\right)^{-1/2} \qquad (2)$$

Finally, the extension of the length ΔL is calculating using

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{reff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\epsilon_{reff}-0.258)\left(\frac{w}{h}+0.8\right)} \quad (3)$$

The length of the antenna becomes

$$L = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}\sqrt{\epsilon_{reff}}} - 2\Delta L \quad (4)$$

Based on previous equations, the geometry of the proposed transparent antenna is shown in Fig. 3. It consists of two identical square printed patches with truncation of two opposite sides [28].

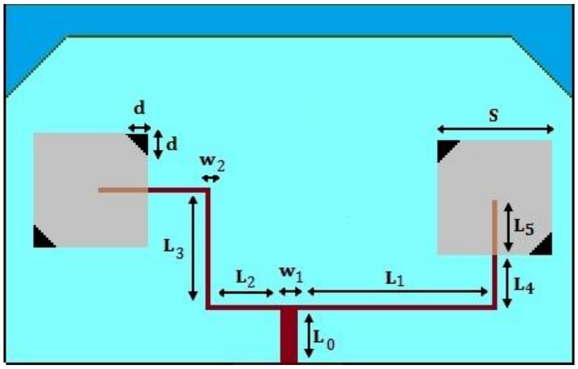

Fig. 3. The geometry of transparent antenna with T-junction power divider.

The dimension of each patch is 14mm×14mm×1mm on a glass substrate with dimension 14mm×14mm×1mm.The feeding of patches are proximity feeding on another substrate with dimension 83mm×69mm×1mm which is the same as the cover glass of the CubeSat. The glass substrate has ϵ_r = 4:5 and loss tangent q = 0:01). For circular polarization, a truncation of two opposite sides was been used with length of 2:9mm. The structure of the transparent antenna is shown in Fig. 4, the thickness of FTO patch antenna is 1000nm with conductivity of (s = 3:0×10^{5}S/m) and whole thickness that introduced between the patch and the lower ground plane to obtain a total substrate thickness of 2mm. The antenna elements are feded by T-junction power divider network with identical path lengths from the feed point 50 to each antenna element 100. Based on, characteristic impedance (Z_0) of transmission line, where Z_0 for $w/h \geq 1$is given by [29], [30].

$$Z_0 = \frac{\left[120\pi\left(\epsilon_{reff}\right)^{-0.5}\right]}{\frac{w}{h}+1.393+0.669\ln\left(1.444+\frac{w}{h}\right)} \quad (5)$$

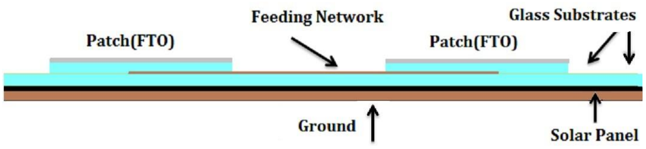

Fig. 4. The geometry of transparent antennar.

So that the transmission line width W_1 = 1:9mm. This line is splited into two 100W lines, with width W_2 = 0:43mm. All the parameters calculated and optimized list in Table 1.

TABLE 1
DIMENSIONS (MM) OF THE ANTENNA GEOMETRY IN FIG. 3

dimensions	value
L_0	13
L_1	24
L_2	10
L_3	13
L_4	7
L_5	6
w_1	1.9
w_2	0.43
S	14
d	3

5 RESULTS AND DISCUSSIONS

The transparent antenna was designed, analysed and simulated on full-wave simulation software CST Microwave Studio, which is based on the finite integration technique [31]. Consequently, in the simulation, we put the solar panel as a lossy conductor with a conductivity s = 5000 S/m. The circular polarization antenna radiated with a gain of 5:9dB at a 5GHz frequency, as shown in Fig. 5. The axial ratio is a very important parameter that evaluates the polarization of the designed antenna. Fig. 6 shows the axial ratio values versus the theta angle at 5GHz of the transparent antenna is 0:9dB. The parameter analysis is been done for further understanding of the antennas functionality. The main parameters are analysed against the truncation parameter. The length of truncating can be calculated from Eq. 6, where S is the actual length of the patch and $\Delta x/x$ is the truncation ratio [32].

$$d = S\sqrt{(\Delta x\ /\ x)}\ and\ \Delta x\ /\ x = 1\ /\ (2Q_0\ ) \quad (6)$$

The truncated ratio is depended on the quality factor of the patch Q_0 which expressed as a function depending of the dielectric constant ϵ_r and substrate thickness h.

$$Q_0 = \frac{c\sqrt{\epsilon_r}}{rf_0h} \quad (7)$$

A pair of truncated corners is of equal side length *d* = 2:9mm and the single probe feed has placed at 6mm along the x-axis and y-axis that produce best operational results. Table 2 shows the simulated results of the proposed antenna with various truncated sizes for d, from 2:8mm to 3:2mm. The truncated size plays a role on the axial ratio, gain, and bandwidth. Selecting the *d* = 2:9mm gives a good operation point with the highest gain and wide bandwidth. For comparison, the simulated return loss versus frequency for the proposed module antenna and copper patch antennas is shown in Fig. 7. The antennas puts over solar panels reduced the gain and increase the bandwidth.

TABLE 2
THE EFFECT OF TRUNCATION ON THE ANTENNA PARAMETERS

Truncation	2.8	2.9	3.0	3.1	3.2
Gain (dB)	5.96	5.95	5.91	5.85	5.8
Axial ratio (dB)	0.88	0.91	0.86	0.86	0.83
Return loss(dB)	-15.6	-15.3	-14.8	-14.3	-14
bandwidth(MHz)	500	517	536	561	571

We infer from the radiation patterns shown in Fig. 8, that the gain of the FTO transparent antenna is nearly identical with copper antenna integration with the solar panel with loss of gain by 0:5dB.

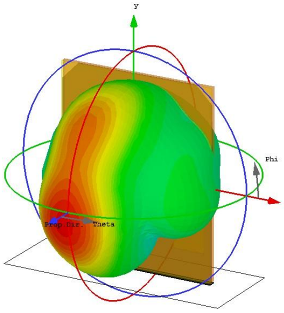

Fig. 5. 3D radian pattern of transparent antenna.

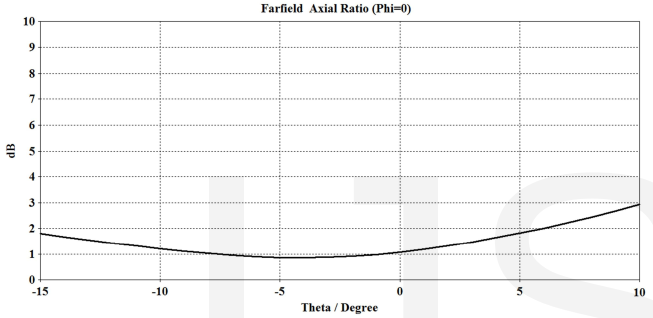

Fig. 6. Axial ratio for polarization mismatch loss.

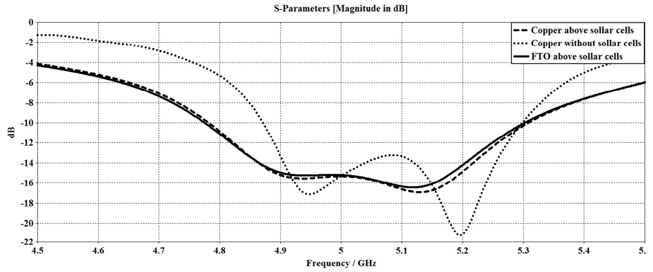

Fig. 7. Return loss of proposed antennas.

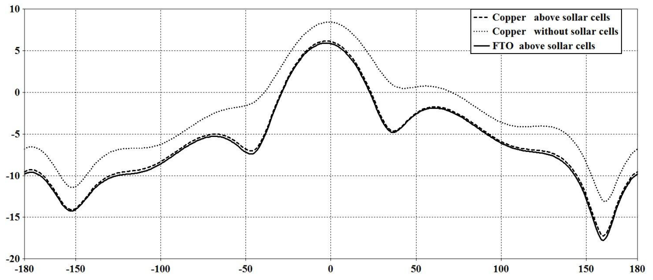

Fig. 8. 2D radiation pattern of proposed antennas at 5GHz.

6 CONCLUSION AND FUTURE WORK

The antennas designed for smaller satellites offer technical solutions, which can be utilized for intersatellite antennas. These antennas often need greater coverage, which can be attained by multiple antenna elements, beam steering or antenna pointing. This paper presented the design of a novel transparent antenna for intersatellite communications with frequency 5GHz. Integrating transparent antennas with solar cells is essential for the payload reduction of small satellites. The proposed module provides a baseline for high data rate inter-CubeSat communication, using directive, transparent antennas. A maximum gain of 5:9dB at 5GHz has obtained. The resulted gain has reduced due to the integration with solar panel and the gain of the FTO transparent antenna is nearly identical to copper antenna with a gain loss of 0:5dB. In Ref [13] studied the interaction between patch antenna and space-certified solar panel concluded that there is a reduction of 2-3dB in the gain of the antenna above the solar panel regardless of its status. The future works concerned with fabricated this antenna and optionally considering some issues such as phased arrays and antenna pointing.

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