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Design and Realization of Circular Polarized SIW Slot Array Antenna for CubeSat Intersatellite Links

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Abstract—This paper presents the design and fabrication of an antenna based on Substrate Integrated Waveguide (SIW) for intersatellite crosslinks in C-band. The entire antenna consists of two elements of SIW slots array that is fed by a hybrid 3 dB directional coupler. The entire SIW slots array antenna is circularly polarized (CP), and each element has four longitudinal slots. The element's effective field matching is realized with a microstrip to SIW transition. The antenna design has been evaluated with its return loss, gain plot, and radiation pattern characteristics to validate the fabricated antenna. The fabricated prototype antenna radiates a left-handed circularly polarized (LHCP) electromagnetic wave with the peak gain of 5 dB and offers approximately 2% AR bandwidth around 5 GHz.

1. INTRODUCTION

Small satellites are extremely small and lightweight. They have a net mass between 0.1 and 1.33 kg [1]. The most common type of small satellites is CubeSat that made up of $10 \times 10 \times 10\,\text{cm}^3$ units and has a weight less than 1.33 kilograms per unit. CubeSat faces a challenge of extremely stringent accommodation requirements, leading to the need of antenna system to be miniaturized and integrated [1–4]. One approach to the problem is to use planer antennas, which are light weight, planar, compact, and inexpensive. Recently, there has been growing interest in SIW-based antennas [5–7]. SIW structure preserves the advantages of metallic waveguides, namely high Q-factor (low loss) and high powerhandling capability with self-consistent electromagnetic shielding. SIW has many advantages over rectangular waveguide antennas, such as low cost, high isolation, reduced sizes and easy integration [5, 8]. Moreover, SIW can be easily manufactured using simple printed circuit board (PCB) process which allows monolithic integration of SIW with other planar circuits [5, 9]. Because of its advanced features related to loss and narrow-beam waveguide slot array antennas are very attractive for satellites communication applications. The SIW slot antennas in the literature employ planar SIW structures [6, 7, 10–12]. Both longitudinal slot [10] and transverse slot [13] on the broad wall of an SIW can be used as radiating element of a linearly polarized SIW slot array. A nonlinearly polarized SIW slot antenna array can be designed by rotating the slots on the broad wall [14–17]. SIW series-feed arrays [15] and corporate-feed arrays [17] with CP characteristic suffered from narrow AR bandwidth. Using an SIW based power divider with tapered power division, a low side-lobe level (SLL) longitudinal slots array of SIW is implemented in [11]. Slotted SIW antennas usually allocate constant spacing between slot elements. In [12], an optimization on the spacing between elements is done by using a combination of genetic algorithm and conjugate gradient method for a given pattern and efficiency requirements. SIW can also be used to design other types of antennas, such as H-plane sectoral horn antenna [18],

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H-plane horn antenna with split rings or rectangular patches and dielectric loading integrated to the aperture [19, 20], horn antenna covered with SIW cavity frequency selected surface (SIWC-FSS) [21], conformal H-plane horn antenna on a conducting cylinder [22], substrate integrated E-plane waveguide (SIEW) horn antenna [23], half-mode substrate integrated waveguide (HMSIW) [24], an SIW-based hat-shaped dielectric loaded antipodal linear tapered slot antenna (ALTSA) proposed and realized in [25], and leakage antenna [26]. The leaky-wave antennas utilize one of the main characteristics of the SIW, namely, its property to generate radiation leakage when the longitudinal spacing of the metal vias is sufficiently large [26, 27]. A leaky wave antenna using a continuous slot on broad wall of SIW is implemented in [27]. The position of the slot with respect to the center line of the SIW is varied along the SIW to obtain amplitude taper. The same type of leaky wave antenna is implemented in [28] by rarely spacing the vias at both sides of the SIW, and the first higher order mode is used in the SIW structure to obtain better leakage constant than the fundamental mode of the SIW at Ka-band [9]. In this paper, we design and realize a circularly polarized SIW slot array antenna for inter-Cubesats communications.

2. ANTENNA ELEMENT DESIGN AND DIMENSIONS

The proposed longitudinal SIW slots array antenna is designed to operate at 5 GHz for inter-Cubesats communications. The geometry is illustrated in Fig. 1. The antenna consists of an SIW structure with four longitudinal slots etched on the top face of the cavity, alternatively located with respect to the middle on the top metal wall of a straight SIW structure. The antenna is fed using microstrip to SIW transition. A part of the microstrip line connecting the radiating surface is tapered for proper impedance matching. The slots are cut in a copper layer of thickness 35 μm, over a substrate of thickness 0.63 mm made of Roger-RT3010 with relative permittivity of $\epsilon_r = 10.2$, and a loss tangent of 0.0022 to fabricate the SIW slots array antenna operates at 5 GHz. The diameter and inter-spacing of the metallic vias, and the length and width of SIW are considered as 1 mm, 1.9 mm, 70.5 mm, and 23.54 mm, respectively. The length and width of each slot are 11.2 mm and 0.5 mm, respectively, which have been selected to resonate at the design frequency of 5 GHz. The obtained width of the equivalent waveguide for the SIW is 14 mm.

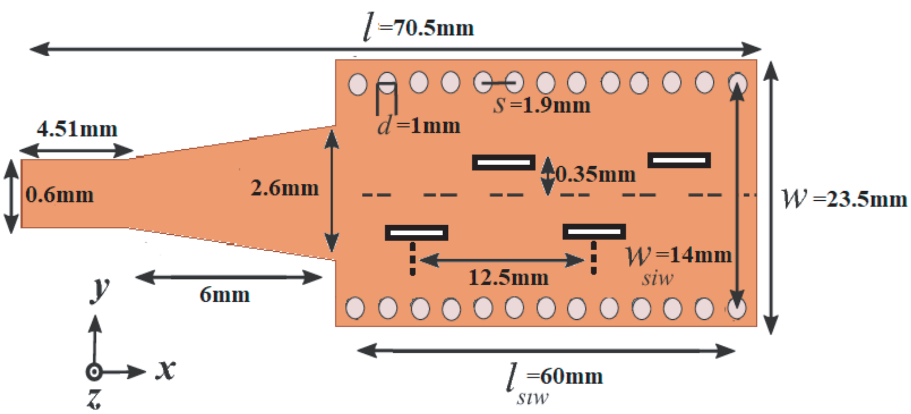


Figure 1. Geometry of longitudinal SIW slot array antenna.

3. CUBESAT ANTENNA STRUCTURE

The antenna system has been designed from two elements of SIW slot array antennas integrated under a solar panel. Fig. 2 shows a possible method of mounting the antenna behind CubeSat wall, in which an aperture slightly larger than the radiating slot array is made, leaving the remaining CubeSat surfaces available for the allocation of other devices and functionalities. Fig. 3 illustrates the exploded structure, satellite walls and four face elements where the radiating antenna module is dynamically selected

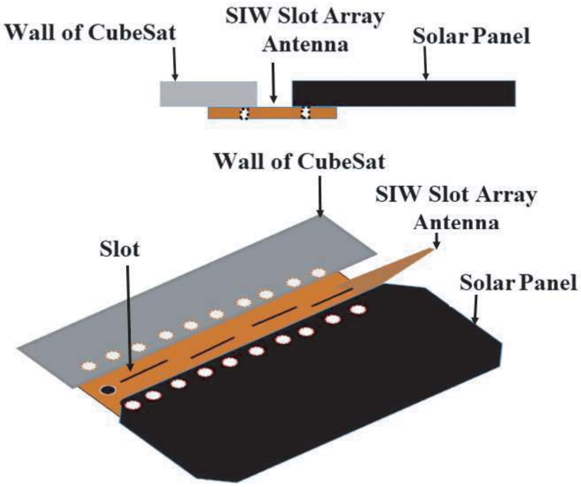


Figure 2. Slot antenna mounted behind the wall of CubeSat.

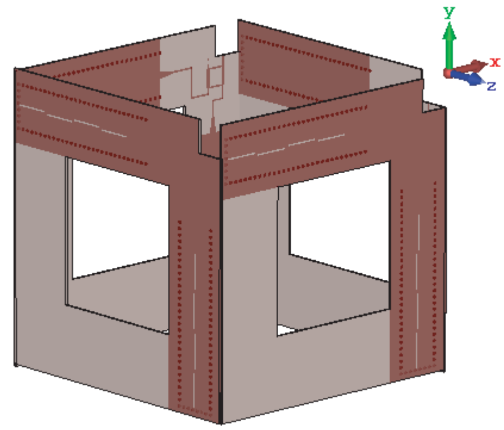
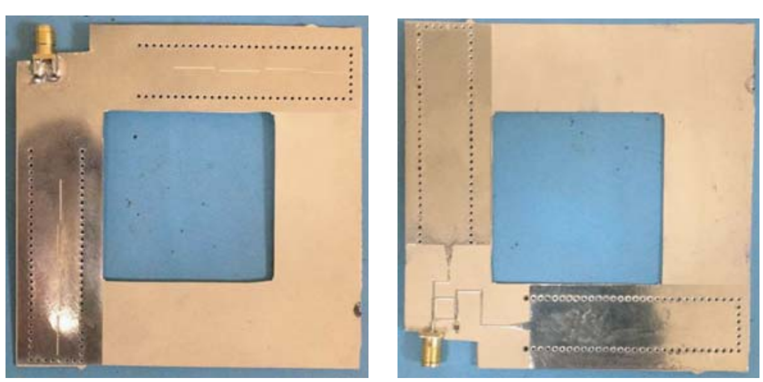


Figure 3. The exploded view of the antenna system at CubeSat with feed-line.

through a specific digital control switching circuit to activate beams in different directions to conform the radiation patterns accordingly [29]. This digital control switching circuit supporting the high gain functionality of the antenna beam to point into different directions based on the selection input [30, 31]. The Antenna system is circularly polarized by a quadrature hybrid coupler where two radiating antenna modules are fed using a 90° phase difference to enable boresight circular polarization. The hybrid coupler is used to split the input power equally between the coupled and through ports [32, 33].

4. FABRICATION AND MEASUREMENTS

The integrated two elements SIW slot array antenna was designed, analyzed and simulated on full-wave simulation software CST Microwave Studio [34]. Fig. 4 shows the prototype of the fabricated and tested antenna which is coated with silver, and a 50 Ω SMA-connector was mounted on each module. The radiation performance of the two elements of SIW array antenna was experimentally measured using an anechoic chamber by an automated measuring system, and the E-plane radiation pattern of the antenna was measured at resonant frequency 5 GHz. Fig. 5 shows a very good agreement between the simulated and measured radiation patterns. Simulated and measured gains at 5 GHz are about 5.08 dB and 4.98 dB for simulation and measurement, respectively.



(a) (b)

Figure 4. Fabricated two elements of longitudinal SIW slot array antenna. (a) Front view, (b) back view.

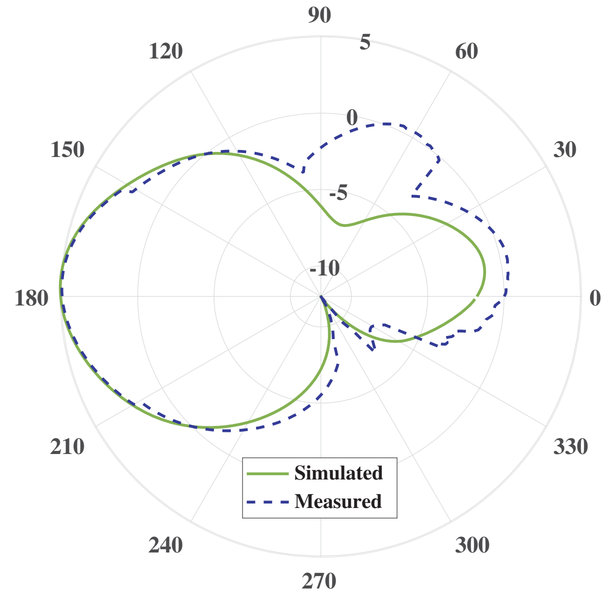


Figure 5. Simulated and measured E-plane radiation patterns at 5 GHz.

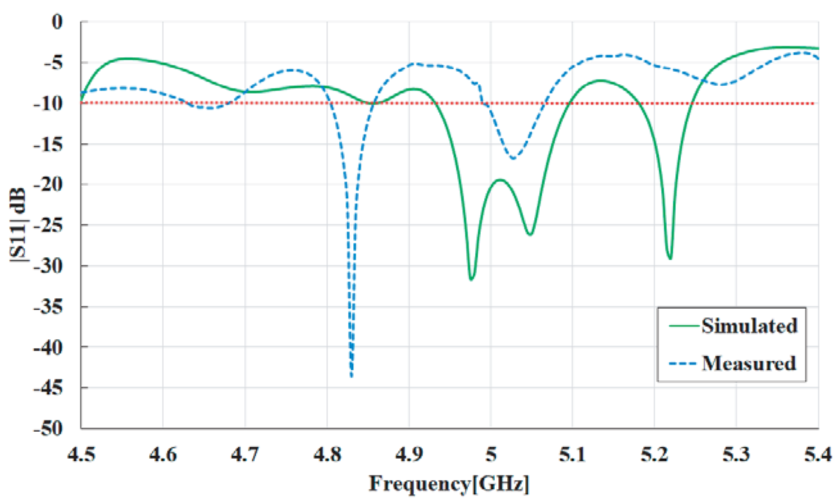


Figure 6. Simulated and measured scattering parameters of the SIW antenna.

The simulated and measured reflection coefficients of the integrated two elements SIW slot array antenna were measured with Agilent network analyzer, and the results in comparison with simulation are shown in Fig. 6. The return loss of the SIW slots array antenna was measured from 4.5 to 5.5 GHz and is higher than 10 dB within a relative bandwidth of 3%. Worthy impedance matching of measured and simulated S_{11} is obtained which indicates how efficiently the circuit is able to radiate the input signal.

The simulated and measured bandwidths at return losses of -10 dB are 165 MHz and 70 MHz, respectively at designed frequency 5 GHz. This decrease in bandwidth between simulated and fabricated antennas may be due to many factors which were not accounted for in simulation, such as the discrepancies in the fabrication process, the losses in solders of the connector to the input microstrip line which is not matched properly where components were assembled by hand, and numerical errors. Simulated and measured results of the axial ratio (AR) at boresight direction versus frequency are plotted in Fig. 8. It is seen that the proposed fabricated antenna has a very stable 3 dB AR bandwidth

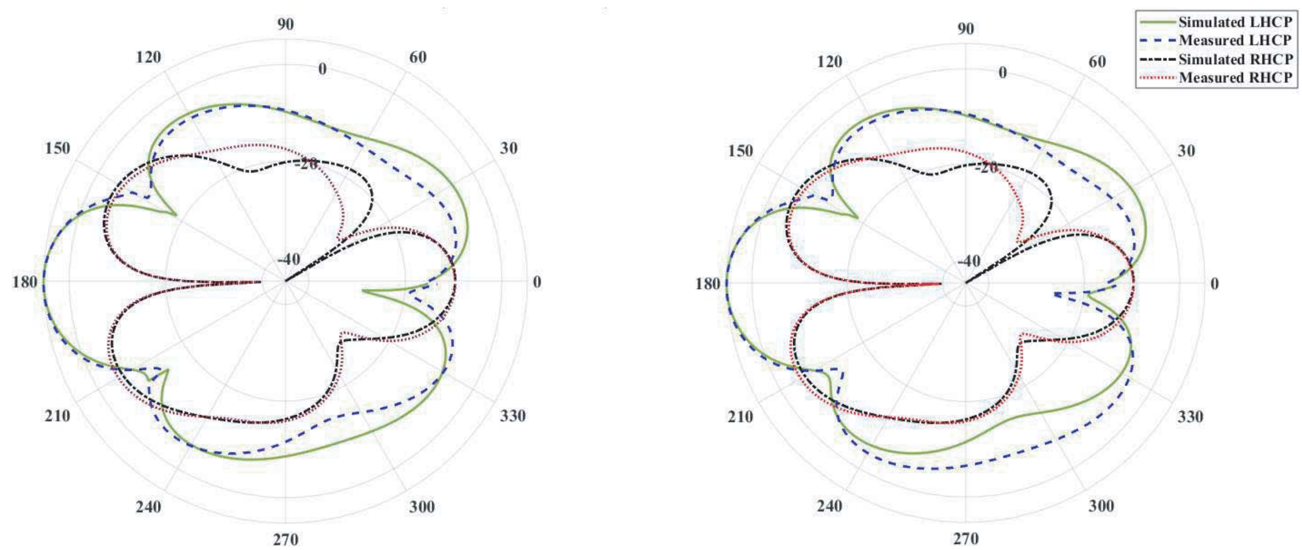


Figure 7. Simulated and measured radiation patterns in the XZ-plane ($\varphi = 0°$) and YZ-plane ($\varphi = 90°$).

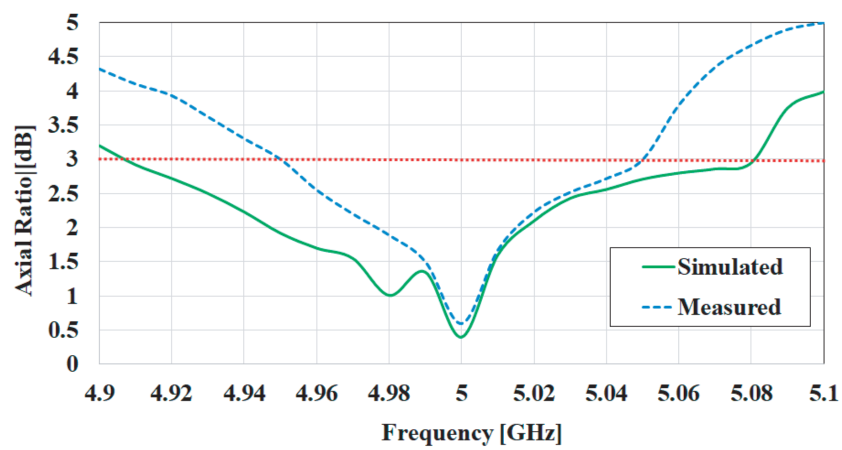


Figure 8. Simulated and measured AR bandwidth for SIW antenna.

of 100 MHz around 5 GHz.

The right-handed circularly polarized (RHCP) and left-handed circularly polarized (LHCP) radiation patterns are compared at frequency 5 GHz in Fig. 7, where it is clearly seen that the antenna is LHCP along the broadside direction, with 5 dB CP gain. The cross-polarization level (CPL) of both cut-planes is lower than −40 dB, which indicates that the designed antenna has a good CP performance within the operating frequency band. A parametric study of S_{11}-parameter values for different via diameters is investigated to study its effect on bandwidth as shown in Fig. 9. We found that the return loss increases when the diameter of vias becomes larger and shifted to a higher frequency band; however, the impedance bandwidth is almost same. The impedance and AR bandwidths are narrow because the slots limit the operating bandwidth of the antenna. These narrow bandwidths are partly attributed to their low profile configurations. The low height substrate increases Q-factor of the antenna, which causes narrow bandwidth [35]. In [36] the AR bandwidth is improved by changing the feeding topology of a CP antenna array.

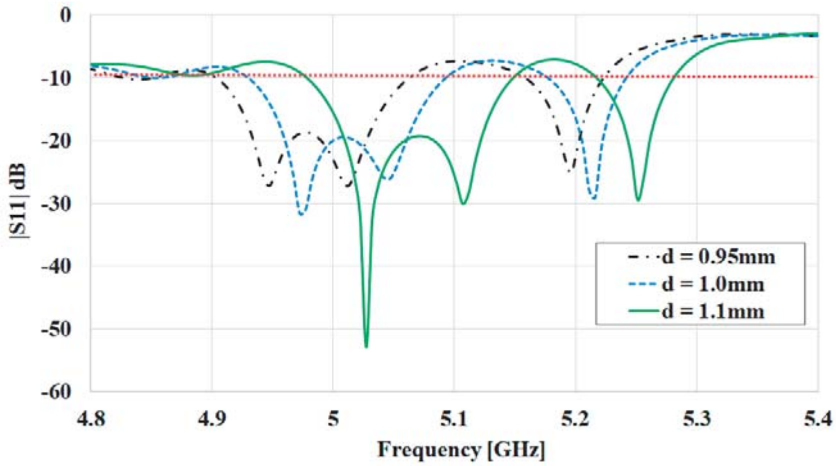


Figure 9. The parametric study of the $|S_{11}|$ value for via diameter d.

5. DESIGNED ANTENNA: PROS AND CONS

The main characteristics of the proposed antenna and other SIW-based antennas discussed in literatures [23, 25] are compared. The comparison is done with a set of evaluation criteria, including bandwidth, gain, return loss, integration with solar cell, polarization, and array elements, the most important factors to consider when choosing an antenna to small satellites cross-links. This result is summarized in Table 1. As shown in Table 1, the SIW is often more efficient and more suited for millimeter-wave communications, so in future work, we plan to enhance our design and fabrication of the antennas that will be operated in millimeter frequency bands. The main advantage of our antenna is overcoming the constraints on small satellite antenna design by the integration with the solar cells, and it is suitable for intersatellite communication applications for low-rate data transfer due to limited available bandwidth.

Table 1. The pros and cons of proposed antenna.

	Our antenna	SIEW horn antenna [23]	ALTSA [25]
Elements	1×2	1×2	1×2
CP	✓	×	✓
Solar Integration	✓	×	×
Bandwidth	70 MHz	3.6 GHz	15 GHz
Return Loss	−12 dB	−10 dB	−17 dB
Gain	5 dB	11.4 dB	18.5 dB
f_0	5 GHz	18 GHz	60 GHz

6. CONCLUSIONS 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 presents the design of a novel circular polarization of a two elements SIW slot array antenna for intersatellite communications with frequency 5 GHz which is integrated on a single substrate. Integrating SIW slots array antenna with solar cells is essential for the payload reduction of small satellites. The proposed technique presents an longitudinal slot array antenna of integrated CP two elements SIW with CubeSat, which have been designed, fabricated and measured. The simulated and measured results show good agreements, which implies that such type of antennas can be constructed and integrated with CubeSat body. Unfortunately, the proposed SIW slot array antenna has very narrow bandwidth. The future work will concern with enhancing the bandwidth of such an antenna by optimizing the distances between slots [37] and enhancing the vias realization. Moreover, we plan to design and fabricate a two-dimensional planar array of slotted SIW with the beam steering capabilities in millimeter frequency bands.

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