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Half-Arrow Slot Antenna for Inter-Satellite Communications

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Abstract—In this paper, a novel HMSIW slot antenna combines a significant bandwidth enhancement and small footprint for inter-satellite communications at C-band. The designed antenna has the capability of achieving a reduction of size with nearly 50% in comparison to conventional SIWs. The results show that the proposed antenna has a bandwidth of 4%, an average gain of 5.8 dB, and the radiation efficiency of $\eta = 93\%$ at 5 GHz.

1. INTRODUCTION

The direct connectivity among small satellites is mandatory in the satellite constellation [1]. However, small satellites face many challenges such as little power budget, light weight and small antennas that provide high gain and do not obstruct the solar panels [2–4]. The substrate integrated waveguides (SIW) technology is one of the planar solutions available to development of antennas for inter-satellite communications, which have the advantages of high power capacity, reduced size, and easy integration with other planar circuits [5–7]. Therefore, the SIW technology is used widely in the modern wireless communications. There are many slotted antennas in the literature utilizing planar SIW, where both of longitudinal slot [8] and transverse slot [9] on the broad wall of an SIW can be used as radiating elements for a linearly polarized SIW slot array. A nonlinearly polarized SIW slot antenna array can be designed by rotating the slots [10–13] or cavities with compound slots [14–18], or even using annular, triangular or split ring slots [19–21]. However, sometimes sizes of these antennas may be too large for practical applications and highly affect the integration process. For this reason, novel antenna solutions have been proposed to miniaturize the footprint of the rectangular SIW cavity by including folded configuration or bisecting the structure along virtual magnetic walls, as such obtaining half-mode (HMSIW) or quarter-mode (QMSIW) resonant cavities [22–25]. The miniaturized SIW cavities almost completely retain the field distribution of the original SIW, and they exhibit excellent microwave performance [21, 26]. Several antenna designs have been suggested based on the HMSIW cavities [25, 27–29]. In [9], two HMSIW linear array antennas with transverse slots were designed in X-band and Ka-band. A leaky wave antenna using HMSIW with quasi-omnidirectional pattern was demonstrated in [27]. Ref. [30] demonstrated an HMSIW leaky-wave antenna using a series of $\pm 45°$ slots, which provides four cases of polarization based on different input ports. Another HMSIW based CP antenna based on leaky-wave principles was presented in [31]. In [32] a CP U-slot HMSIW antenna was proposed based on a combination of U-shaped slot etched in the HMSIW top wall and a shorting via placed between the area bounded by the slot and the HMSIW bottom wall. In this paper, following a previous effort made on the design of slotted antenna for inter-satellite communications to overcome the large size and narrow bandwidths [33], we have designed, simulated and manufactured a novel HMSIW slot antenna that combines a significant bandwidth enhancement and small footprint for inter-satellite communications

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at C-band. Section 2 presents an overview on HMSIW structures. Section 3 presents the antenna design process including the dimensions. Section 4 shows the simulated results. Section 5 shows the advantages of HMSIW. Finally, Section 6 summarizes the conclusions.

2. HMSIW DESIGN PRINCIPLES

The center symmetry plane of an SIW can be equivalently regarded as a magnetic wall when it operates with its dominant mode TE_{10} [34]. Hence, cutting the SIW into two parts along the symmetry plane, each of the half SIW structures is called as HMSIW as illustrated in Fig. 1, where parameters d, p, h and w denote via diameter, the distance between centers of adjacent vias, substrate thickness and HMSIW width, respectively.

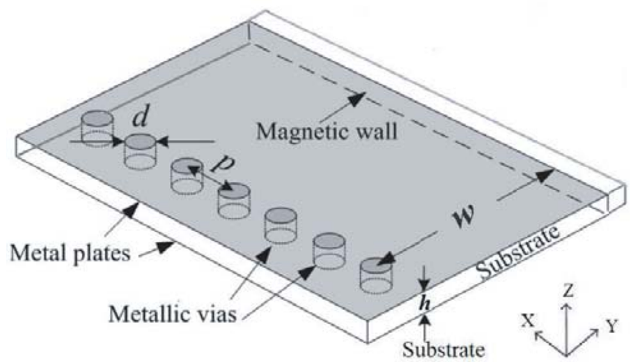


Figure 1. Structure of HMSIW.

One side wall of the HMSIW is composed of a linear array of metallic vias, and the other side is open. Due to the large ratio of the waveguide width to height, the open side can be equivalent to a magnetic wall. As a result, only the quasi-$TE_{m-0.5,0}$ modes can propagate in the HMSIW. To design an HMSIW antenna, the width of HMSIW operating at the same frequency range should be determined and far away from the HMSIW cutoff frequency [35]. Then, the width of HMSIW could be set approximately a half of the corresponding SIW structure, where the effective width w_{eff} calculated using the formula (1) to model the HMSIW as a waveguide with a perfect short wall [34].

$$w_{eff} = w - 0.54\frac{d^2}{p} + 0.05\frac{d^2}{2w} \tag{1}$$

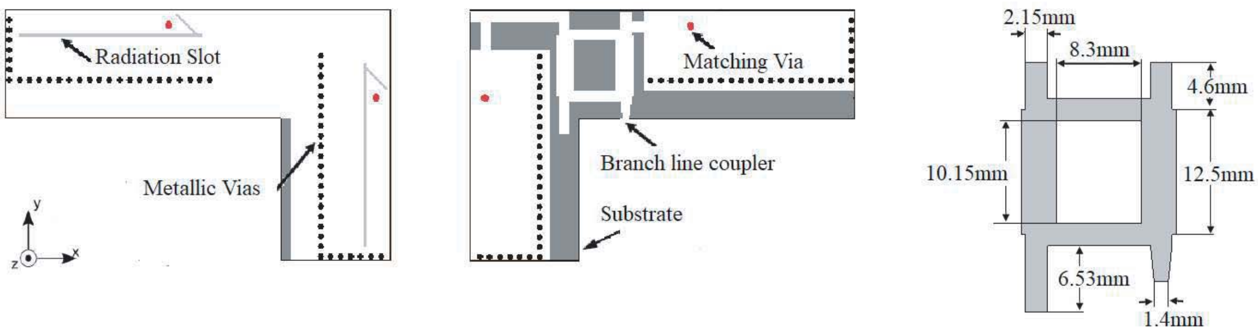
The HMSIW cutoff frequency is calculated using formula (2).

$$f_c = \frac{c}{4\sqrt{\epsilon_r} w_{eff}} \tag{2}$$

Use the known parameters w_{eff}, d, p, h and ϵ_r to calculate the HMSIW physical width w, which is the only unknown in that set of design formulas. A full design methodology for the HMSIW has been presented in [34].

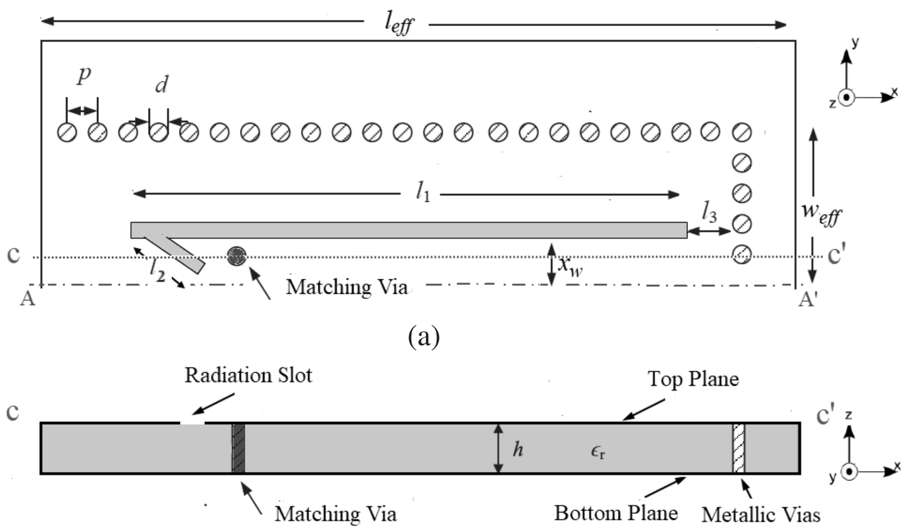
3. ANTENNA DESIGN AND DIMENSIONS

The configuration of HMSIW circular-polarization (CP) antenna is constructed by a 3-dB directional coupler and two linear polarization (LP) antennas. The 3-dB directional coupler is employed to realize the 90° phase difference feeding mechanism as illustrated in Fig. 2. The lengths of the branch and through lines in the coupler designed using microstrip technology for 5 GHz central frequency are 8.3 and 10.15 mm, and the widths are 2.15 and 3 mm, respectively, as illustrated in Fig. 2(c). The single LP antenna structure of HMSIW half-arrow slot antenna with a single via placing near the slot and its related geometric parameters are illustrated in Fig. 3. The half-mode field distribution of the structure



(a) (b) (c)

Figure 2. Configuration of CP antenna (a) front view and (b) back view, (c) coupler.



(b)

Figure 3. Layout of HMSIW half-arrow slot antenna element (a) top view and (b) side view along c-c'.

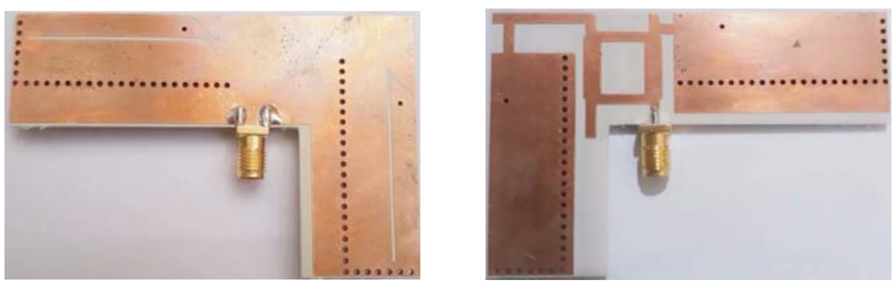
is achieved, when SIW cavity is bisected along the wall A-A'. The dimensions of the antenna elements and their values of the final design are presented in Table 1. The closed side wall of the HMSIW is formed by a row of metallic vias with a diameter of 1.2 mm and spacing of 2 mm. The substrate has a relative permittivity of $\epsilon_r = 3$ and thickness of $h = 1.524$ mm. Moreover, a microstrip line is connected to the waveguide through the directional coupler. The proposed antenna is designed, optimizing the transition microstrip to HMSIW for $Z_0 = 50\,\Omega$ using a full-wave simulator (CST Microwave Studio) [36]. Adjusting the position of tuning via appropriately, placed near the radiating slots, will achieve the required impedance matching.

Table 1. HMSIW slot antenna parameters and their values.

Parameter	Value [mm]	Parameter	Value [mm]
l_1	36.5	l_2	5.8
l_3	4.7	x_w	8.7
p	2	d	1.2
l_{eff}	42	w_{eff}	14

4. MEASURED RESULTS AND DISCUSSIONS

The designed antenna was fabricated and measured to validate the design performance by using an anechoic chamber. The antenna was fabricated on a single-layer substrate through normal PCB process as illustrated in Fig. 4. The R&S ZVB VNA is used to measure the return loss of the proposed antenna. The simulated and measured return loss responses of the CP HMSIW half-arrow slot antenna are illustrated in Fig. 5. The reflection losses (S_{11}) of 23 dB and 35 dB in simulation and measurement respectively have been achieved with impedance bandwidth of 4% around 5 GHz (for $S_{11} = -10\,\text{dB}$). These bandwidths at return losses are 190 MHz and 200 MHz, respectively at designed frequency 5 GHz. Fig. 6 illustrates the normalized radiation pattern of the HMSIW half-arrow slot antenna. The measured and simulated radiation patterns show identical behavior. The antenna has maximum gain of 5.8 dB at frequency with a very stable 3-dB axial ratio (AR) bandwidth 4% from 4.96 to 5.17 GHz. The simulated and measured ARs against frequency are shown in Fig. 7. The resulting patterns for orthogonal cutting planes are illustrated in Fig. 8, which indicates that the proposed antenna satisfies the RHCP generation with a lower cross-polarization at the boresight direction. The variations of simulated and measured peak-gains and radiation efficiencies against the frequency for the HMSIW half-arrow slot antenna are illustrated in Fig. 9. The measured radiation efficiency η is calculated based on the directivity/gain method [37, 38], using the equation $\eta = \frac{G}{D}$. It is found that the measured gain is above 5.8 dB, and the efficiency is higher than 90% in the operating band.



(a) (b)

Figure 4. Fabricated two elements of HMSIW half-arrow slot antenna (a) front view and (b) back view.

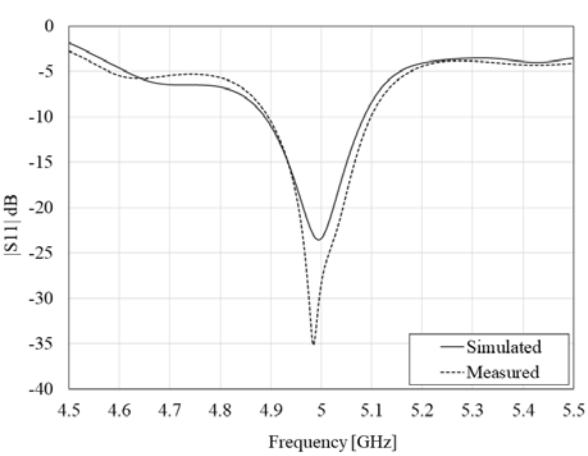


Figure 5. Measured versus simulated input return loss of the half-arrow slot antenna.

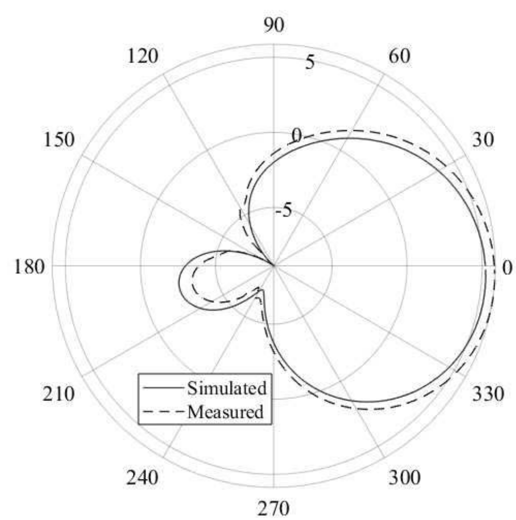


Figure 6. The E-plane radiation pattern of half-arrow slot antenna.

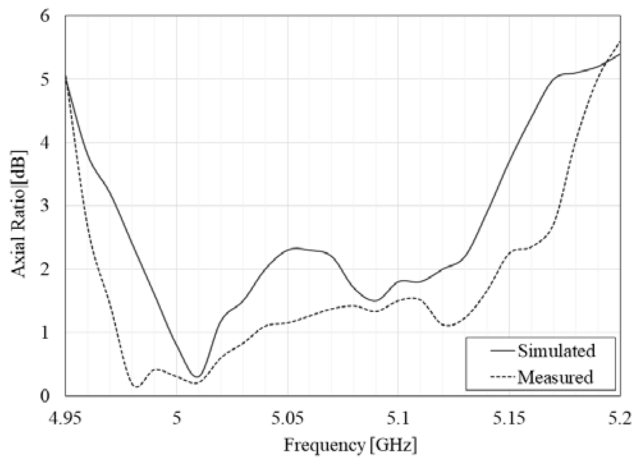


Figure 7. The axial ratio of half-arrow slot antenna.

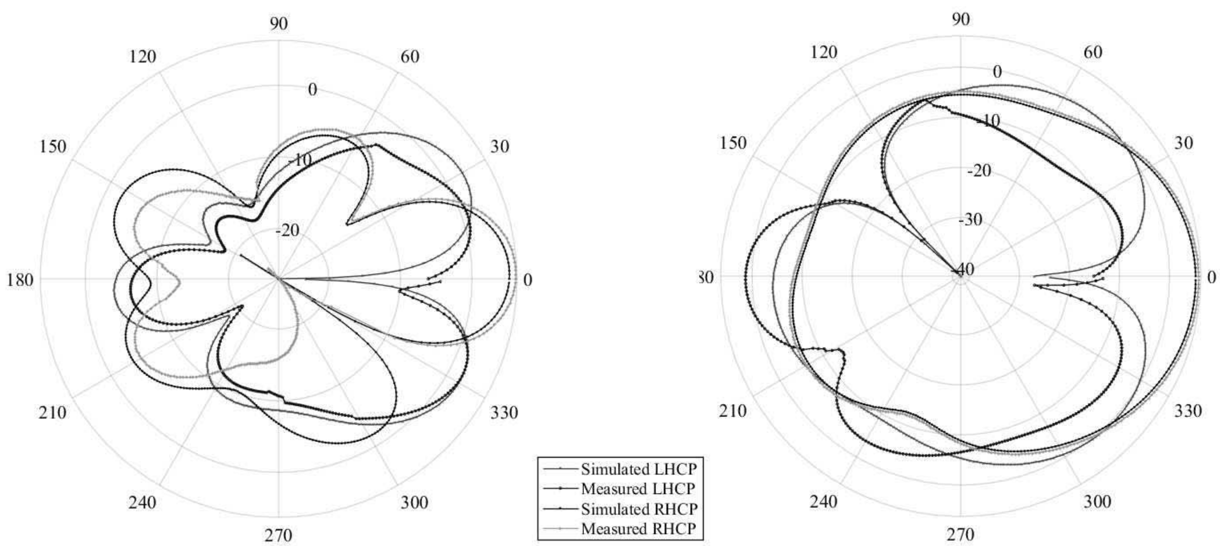


Figure 8. Simulated and measured radiation patterns in the XZ-plane ($\varphi = 0°$) and YZ-plane ($\varphi = 90°$).

5. THE HMSIW HALF-ARROW ANTENNA ADVANTAGES

The 3-dB axial-ratio (AR) and 10-dB bandwidths exhibited by previously realized SIW slot array antenna are very narrow. Therefore, enhancing and miniaturizing the design with increased AR bandwidth is desirable in our application. The measured results of the HMSIW half-arrow slot antenna demonstrate a 10-dB impedance bandwidth of 4%, from 4.9 GHz to 5.1 GHz, and the 3-dB axial-ratio bandwidth is 4.2%, from 4.96 GHz to 5.17 GHz with a maximum gain of 5.8 dB. Therefore, the HMSIW half-arrow slot antenna has enhanced the bandwidths and gain of the previously designed SIW antenna for inter-satellites communications. A comparison between the performances of the HMSIW half-arrow slot antenna and the previously reported SIW slot array antenna [33] is presented in Table 2. The performance of SIW slot array is less than HMSIW half-arrow slot antenna, taking the consideration that the losses of the HMSIW are higher that SIW [34], because their permittivity and thickness h are different [5]. Moreover, the leakage from HMSIW magnetic wall has been negligible since its width to height ratio is large.

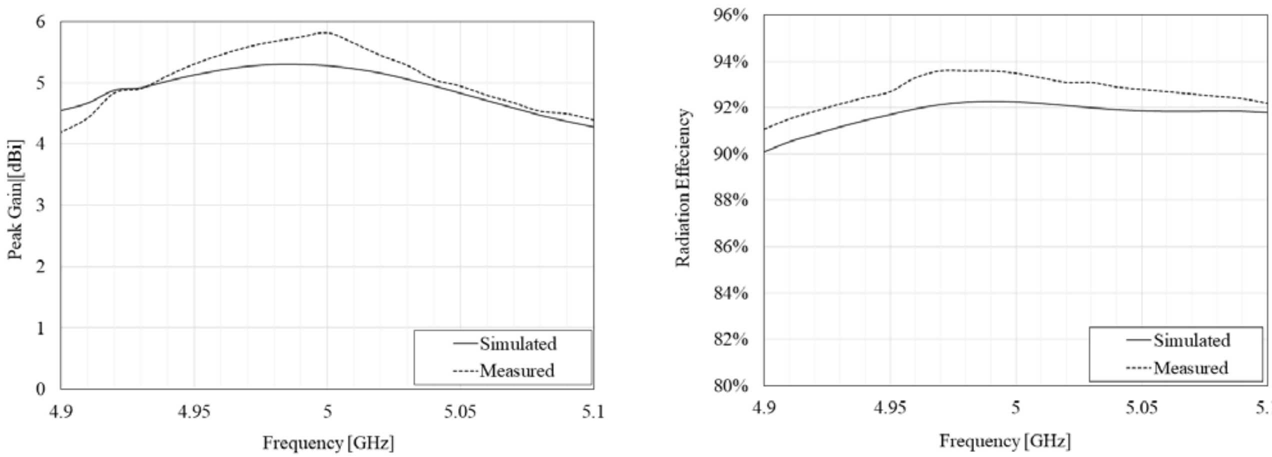


Figure 9. Gain and radiation-efficiency of the half-arrow antenna.

Table 2. The performance of proposed antenna in comparison with SIW slot array antenna.

	SIW slot array antenna [33]	HMSIW half-arrow slot antenna
Techniques	SIW	HMSIW
Elements	1×2	1×2
CP	✓	✓
Solar Integration	✓	✓
AR Bandwidth	100 MHz	220 MHz
Impedance Bandwidth	70 MHz	200 MHz
Return Loss	-12 dB	-35 dB
Dimensions	$10 \times 10\,\mathrm{cm}^2$	$5 \times 7.7\,\mathrm{cm}^2$
Gain	5 dB	5.8 dB
Radiation efficiency	58%	93%
Minimum AR	0.6 dB	0.4 dB
f_0	5 GHz	5 GHz
ϵ_r	10.2	3
thickness(h)	0.63 mm	1.524 mm

6. CONCLUSIONS AND FUTURE WORK

This paper presents the design, fabrication and measurement of a novel CP half-arrow slot antenna for inter-satellite communications designed at C-band frequency. The proposed antenna is miniaturized by an HMSIW substrate which supports a pair of LP antennas. Integrating HMSIW half-arrow slot antenna with solar cells is essential for the payload reduction of small satellites. The antenna resonates at the center frequency of 5 GHz with 4% impedance and 4.2% AR bandwidths, respectively. The measured gain is 5.8 dB in the boresight direction with a low cross polarization of -25 dB at 5 GHz.

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