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A New Compact and High Gain Circularly-Polarized Slot Antenna Array for Ku-Band Mobile Satellite TV Reception

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ABSTRACT A compact and high-gain SIW-fed circularly polarized (CP) slot-antenna array with a stacked feed structure is presented for the application of Ku-band high-data-rate satellite communications. First, a novel probe-fed SIW cavity with four slots etched on the top surface is proposed as a high-gain radiating element for the array. The four slots in the cavity act as a 2×2 array, and its directivity is 2.15 and 1.43 dB greater than that of the cavity-backed antenna of the same size using ring slot and split ring slot, respectively. Second, a compact 1–4 SIW power divider is designed for exciting a subarray. Third, the 2×2 subarray is further expanded to an 8×16 array by adopting an additional layer of 1–32 SIW feeding network to meet the gain requirement of the Ku-band mobile satellite TV reception. Finally, experiments are carried out to verify the designed prototypes. Measured results show that proposed 128-element array has a relative impedance bandwidth of 4.8% (11.84 to 12.42 GHz), AR bandwidth of 130 MHz (12.01 to 12.14 GHz), and a peak gain of 26.8 dBic at 12.06 GHz. Owing to the simple feeding networks and the compact radiating element, the antenna has a compact size of $6.04\lambda_0 \times 11.96\lambda_0 \times 0.1\lambda_0$. Experimental results show that the proposed CP antenna array is suitable for applications of Ku-band mobile satellite TV reception.

INDEX TERMS Circular polarization, planar slot antenna array, SIW cavity-backed.

I. INTRODUCTION

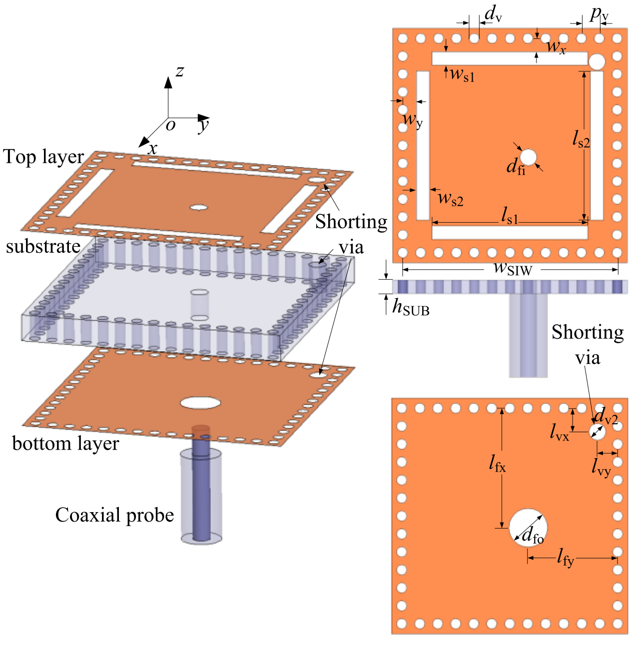
Mobile satellite TV services are becoming increasingly popular in new economies such as China and India along with the rapid growth of the number of vehicles like cars, ships, trains and planes. Antennas mounted on vehicles are critical components to receive the wireless signals from the satellites. To ensure robust communication links and easy implementation, the receiver antennas are required to exhibit sufficient gain, high aperture efficiency, be light weight, compact in size and have a low profile [1]. In order to eliminate the polarization mismatch between the incident wave and the receiver antenna from the polarization rotation which occurs in moving vehicles, circulation polarization (CP) is preferred for satellite communications [2]–[4]. To meet the aforementioned requirements, the substrate integrated waveguide (SIW) cavity-backed slot CP antenna arrays serve as attractive solutions, as they can achieve higher radiation gain, lower mutual coupling between array elements and are more compact in size than traditional microstrip antenna arrays [5].

To date, various SIW cavity-backed CP slot antennas have been proposed for mobile satellite communications and other wireless applications, such as cavities with compound slots [4]–[8], with annular, triangular or split ring slots [9]–[12] and patches or cavities placed above the slots [13]–[18]. The primary design challenge is to improve the gain and radiation efficiency. In [14], for example, the technique of covering the patches above the slots of the SIW backed cavity with a certain angle was used to facilitate the conversion from linear polarization (LP) to CP, which can improve the directivity of the array element. A single radiating element with size of $0.84\lambda_0 \times 0.63\lambda_0$ can achieve a gain of 7.5 dBic. In addition, high-order resonant modes inside the cavity with patches covering the slots excited by one port can function as a subarray and obtain higher directivity. The measured peak gain using TE_{330} mode with size of $1.41\lambda_0 \times 1.41\lambda_0$ [15] and using TE_{440} with size of $1.95\lambda_0 \times 1.95\lambda_0$ [16] are 13.2 dBic and 15.3 dBic, respectively. Furthermore, four slots and a large perturbation, introduced by inserting a metallic via-brick into the SIW cavity, are utilized to achieve a high simulated gain of 10.28 dBic at 6.65 GHz for single element with size of $0.68\lambda_0 \times 0.68\lambda_0$ [7]. Moreover, four linear polarization SIW 2 × 2 slot subarrays fed by a single probe excited by a SIW network with sequential rotation techniques realized a peak gain of 15.9 dBic at 20.6 GHz with size of $2.67\lambda_0 \times 2.67\lambda_0$ [4]. Although the subarrays mentioned above which are excited by only one single port can realize high gain, they need to be relatively large in size and their aperture efficiency could be further improved.

Another key challenge when constructing a large scale antenna array is to produce a compact design of the feeding network. Feeding networks based on SIW are commonly used for planar antenna arrays due to their light weight, low profile, and ease of integration with additional planar circuits. Generally, there are two types of feeding methods: series feeding and parallel feeding. In [7], for instance, the series feeding divider/combiner is employed to reduce the total length of the network and the insertion loss. Unfortunately, it is only applicable to small scale arrays due to the limited practical impedance range. In contrast, the parallel feeding method is more suitable for large scale arrays as it can meet the requirements of the phase and magnitude for each element within a wide frequency band. The input energy can be equally divided into each radiating element, and the surface wave and undesired radiation from the feeding networks can be effectively suppressed. Additionally, in order to maintain their compact size, the feeding networks are commonly constructed over multiple layers as shown in [14]–[17].

In this paper, we propose a planar SIW cavity-backed CP 128-element antenna array with a highly efficient single radiating element and compact stacked feeding networks. The proposed novel single radiating element with four slots on a cavity shown in Fig. 1, is able to achieve a peak gain of 8.49 dBic at 12.06 GHz with a compact size of $0.56\lambda_0 \times 0.56\lambda_0 \times 0.024\lambda_0$. To meet the requirements for high–data-rate mobile satellite communication, an 8 × 16 planar array is further investigated. A compact stacked feeding network for this 128-element array is realized by combining two layers of SIW power dividers together without occupying extra surface area. The total size of the proposed CP antenna array is only 151 mm × 291 mm × 2.7 mm. The measured peak gain and axial ratio (AR) bandwidth of the array is 26.8 dBic and 110 MHz respectively, which meets the mobile TV satellite reception requirements in China.

The rest of the paper is organized as follows. Section II investigates the design and characterization of the SIW cavity-backed antenna with four slots as the single radiating element. In Section III, a compact 1 to 4 SIW power divider to feed the 2 × 2 subarray based on the single radiating element design is analyzed. And then an 8 × 16 array is presented in Sections IV based on the proposed 2 × 2 subarray. The experimental results are presented and discussed in Section V. Section VI concludes the paper.



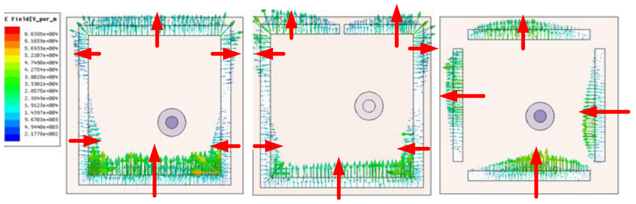
(a) (b)

FIGURE 1. Configuration of the proposed SIW CP antenna element (a) 3-d view (b) dimensions (The optimum physically dimensions are $w_{SIW} = 14.2$ mm, $h_{SUB} = 1.52$ mm, $d_v = 0.6$ mm, $p_v = 1.01$ mm, $l_{s1} = 9.7$ mm, $l_{s2} = 9.1$ mm,$w_{s1} = 0.8$ mm, $w_{s2} = 0.8$ mm, $w_x = 0.75$ mm, $w_y = 0.75$ mm, $d_{f0} = 2.3$ mm, $d_{f1} = 1$ mm, $l_{fx} = 7.9$ mm, $l_{fy} = 6.3$ mm, $d_{v2} = 1.0$ mm, $l_{vx} = 1.45$ mm, $l_{vy} = 1.15$ mm).

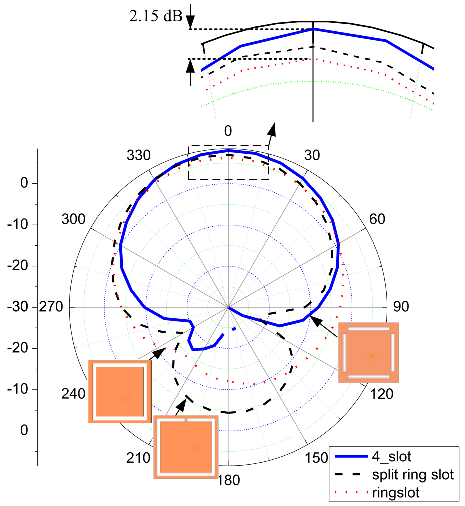
II. 4-SLOT ELEMENT CONFIGURATION AND DESIGN

A. CONCEPT OF DIRECTIVITY IMPROVEMENT

In order to achieve CP antenna arrays that are compact in size, SIW based cavity resonators are usually designed to resonate in TE_{120}/TE_{210} modes with slots etched on the top surface. Most slot antennas employ ring slots or split ring slots [9]–[12], as illustrated in Fig. 2. The resonant frequency is mainly determined by the electrical length of the ring slot and the SIW cavity. As can be seen in Fig. 2 (a), the electrical fields along one pair of edges (horizontal) of the ring slot run in the same direction, while the electrical fields along the other pair of edges (vertical) run in opposite directions. Therefore, the far field radiation of the antenna is mainly attributed to one pair of slots. Although the electrical field distribution changes over time, the total electrical field distribution of the ring slot has a similar effect. This can also be seen in Fig. 2 (b), where the electrical fields along one pair of edges of the split ring slot etched on the SIW cavity run in the same direction, while the fields of the other pair of edges run opposite to each other. The directivities of the ring slot



(a) ring slot (b) split ring (c) four slots



(d)

FIGURE 2. Electrical distribution of (a) ring slot (b) split ring slot (c) 4-slot etched on substrate cavity and the comparison of the radiation patterns for three cases (d).(red arrows denote eletrical field direction).

and split slot SIW antenna are illustrated in Fig. 2 (d). The peak directivities of the ring slot and the split ring slot are 6.27 dBic and 7.0 dBic, respectively. The latter has a slightly higher directivity than the former owing to the more uniform distribution of the electrical field in the split ring slot.

Fig. 2 (c) shows the electrical field distribution of two pairs of slots. The electrical field in both pairs of slots runs almost in the same direction at any time. Consequently, the four slots function as a 2 × 2 array. Considering that the two pairs of slots are excited with different amplitudes and phases, the total directivity of 8.43 dBic has an increment of 2.16 dB and 1.43 dB compared to directivity of the ring slot and the split ring slot, respectively, as shown in Fig. 2 (d).

B. ELEMENT ANTENNA CONFIGURATION

The configuration of the proposed SIW 4-slot CP antenna is illustrated in Fig. 1. Four columns of vias with diameters of d_{v} and distance of p_{v} through the substrate with thickness of h_{SUB} and dielectric of 2.2 are employed to construct a SIW cavity with a dimension of w_{SIW}. Two orthogonal pairs of slots are etched on the top metal layer of the SIW cavity with a width of w_{s1}, w_{s2} and a length of l_{s1}, l_{s2}. The distance from each slot to the nearest edge of the SIW cavity is w_{x} or w_{y}. A coaxial probe with a diameter $d_{\mathrm{fi}} = 1$ mm located in the SIW cavity with offset to the axis of l_{fx} and l_{fy}, is employed to excite the slot antenna. To obtain a good match, a via with a diameter of d_{v2} is loaded at one corner with distance l_{vx}, l_{vy} to the edges of the SIW cavity.

C. PARAMETERS INVESTIGATION OF ELEMENT ANTENNA

For the proposed antenna element, four slots etched on the top layer of the SIW cavity function as the main radiator, which directly determines the resonance characteristics of the antenna. Each slot resonates at the dominant-mode and the central frequency f_{c} of the proposed antenna can be estimated using the following equation,

$$f_c = \frac{0.5 \cdot c}{\sqrt{l_s \cdot (\varepsilon_r + 1)/2}} \tag{1}$$

where c is the velocity of light in the vacuum, l_{s} is length of slots etched on the SIW cavity, and ε_r is the dielectric of the substrate. Equation (1) is reasonably accurate at calculating slot length at 12 GHz.

To understand the operating principle of the proposed antenna, an eigenmode problem of the SIW cavity with four slots was studied using HFSS. When one parameter is varied, the other parameters are kept the same. There are three eigenmodes between 10.5 to 13.5 GHz and the resonant frequencies are 10.76, 12.69, and 12.71 GHz, respectively. The resonance frequencies for each of l_{s2}, w_y and w_{SIW} are shown in Fig. 3 (a), (b) and (c). The electrical field magnitudes of the three modes are illustrated to the right of Fig. 3. As the length l_{s2} of one pair of slots becomes longer, the resonant frequencies of modes 2 and 3 (mode TE_{120} and TE_{210}) will be smaller and the resonant frequency of mode 1 (SIW cavity dominant-mode) will decline slightly. It can be seen that mode 3 falls more quickly than mode 2 because the length l_{s2} has a much stronger effect on the resonant current of mode 3. When w_{y} is increased, that is, the distance between the pair of horizontal slots is decreased, the resonant frequencies of modes 2 and 3 will increase simultaneously and the resonant frequency of mode 1 remains almost the same. The size w_{SIW} of SIW cavity has similar effect on three modes. When w_{SIW} is increased, the resonant frequencies of all three modes decline. It is observed that modes 2 and 3 which are used to generate a circular polarized wave can be controlled by the length of the slots, the distance between a pair of slots and the size of the SIW cavity.

The SIW cavity with four slots etched on the top surface and a via loaded in the corner excited by an axial probe with distance l_{fx} and l_{fy} to SIW cavity edge can achieve a circular polarization wave. The influence of the coaxial probe position on the match characteristic and axial ratio is shown in Fig. 3 (d). It can be seen that when l_{fx} is varied from 7.5 mm to 8.3 mm while l_{fy} remains the same, the intensity of mode TE_{120} will be strengthened. As a result, the axial ratio and the match characteristic will get better and then worse. Meanwhile, the 3-dB axial ratio bandwidth will no longer overlap with the impedance matching bandwidth when the l_{fx} set an improper value.

It can also be seen from Fig. 3 (d) that the via load at the corner of the SIW cavity can enhance the match performance and the axial ratio of the proposed antenna.

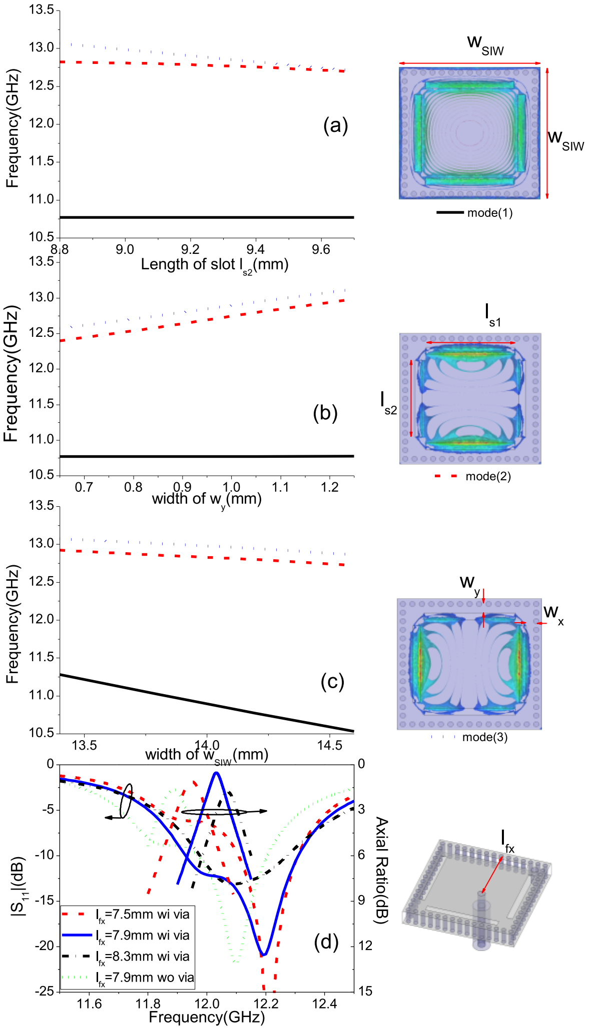
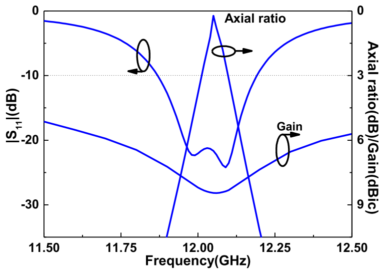


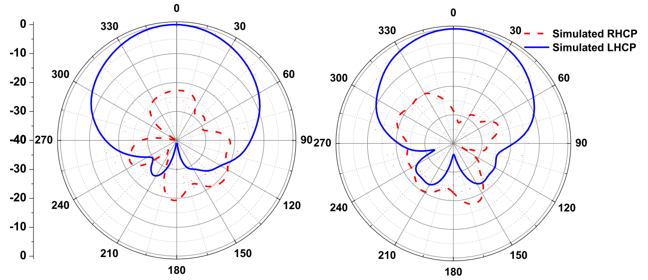
FIGURE 3. (a) Length of slot l_{s2} (b) Size w_{SIW} of substrate cavity (c) Width w_y effects on the resonant frequency and (d) The position l_{fx} of coaxial probe effect on the impedance match and axial ratio of 4-slot antenna element.

D. SIMULATED RESULTS OF ELEMENT ANTENNA

Using HFSS, the element antenna was optimized and all parameters are listed in Fig. 1. The full-wave simulated return loss of the proposed CP element antenna is shown in Fig. 4 (a). It has a -10 dB impedance bandwidth from 11.87 to 12.19 GHz, approximately 2.7% fractional bandwidth. Fig. 4 (a) also presents the boresight gain and the AR. The 3-dB AR bandwidth is 12.0–12.11 GHz. The simulated maximum gain within the AR bandwidth is 8.49 dBic at 12.06 GHz. Figs. 4 (b) and (c) present the simulated 12.06 GHz radiation patterns of two orthogonal cut-planes, including the left-handed circularly polarized (LHCP) radiation pattern, and the right-handed circularly polarized (RHCP) radiation pattern. The cross-polarization level (CPL) of both cut-planes is lower than -23.25 dB, which indicates that the designed antenna has a good CP performance within the operating band. The front-to-back ratio (FTBR) is higher than 32.8 dB, and the half-power beam width (HPBW) of the phi = 0° and phi = 90° cut-planes are 53.8° and 47.5°, respectively.



(a) reflection coefficient, AR and gain



(b) *xoz* plane (c) *yoz* plane

FIGURE 4. Simulated (a) Reflection coefficient, AR and gain (b) Radiation pattern at xoz plane and (c) at yoz plane at 12.04 GHz of the proposed CP SIW slot antenna element.

III. 1-4 SIW SUB DIVIDER AND 2×2 SUBARRAY

To accommodate the power divider for 2×2 Subarray excitation, a distance of approximately 0.73 free-space wavelength between the adjacent elements has been chosen. Due to the high directivity of the element, the simulated mutual coupling between each element is lower than -26 dB and has little influence on the radiation performance of the array. The 1-4 SIW in-phase power divider is designed on Rogers-Duroid 5880 (where the same material is used for the antenna's radiator and the feeding network in order to reduce the discontinuity between the elements and divider) with a thickness of 0.508 mm to excite the 2×2 subarray evenly.

As shown in Figs. 5 (a) and (b), the reported SIW power divider consists of four SIW rectangle cavities with tapered openings surrounding a combining coaxial port. There are four probes located at the center of each SIW cavity to excite the antenna elements. Another probe is placed at the center of the power divider to serve as the combined port. The impedance of the combined port and divided ports can be adjusted by using a different width w_{po} of SIW cavity tapered wave port and distance l_{p2} from divided probe to vias, respectively, as shown in Figs. 5 (c) and (d). It can be seen that a simulated minimal loss of 0.1 dB of each divided port and -10 dB impedance bandwidth of 4.9% (from 11.84 to 12.44 GHz) have been achieved by selecting a set of optimized parameters listed in Fig. 5. The phase difference between each divided port is negligible due to the symmetrical structure.

The configuration of the subarray consists of the proposed 1-4 SIW power subdivider and four 4-slot SIW antenna elements as illustrated in Fig. 6 (a). The 2×2 antenna elements are stacked on top of the divider to save the feed network

TABLE 1. Performance comparison of the cavity-backed siw/hmsiw antennas and antenna arrays.

Item		Frequency (GHz)	Technique	Size(λ_0)	Peak gain(dBic)	Bandwidth	AR Bandwidth
Element	[4]	10.3	SIW	1.04×1.04×0.05	7.8	14%	2.4
	[6]	8	HMSIW	0.72×0.36×0.02	4.2	6.0%	0.7%
	[7]	28	SIW	0.65×0.51×0.05	5.9	6.3%	1.8%
	[11]	10.1	SIW	0.81×0.81×0.017	6.3	3%	0.8%
	Our work	**12**	**SIW**	**0.56×0.56×0.06**	**8.49**	**2.5%**	**0.9%**
subarray	[4]	8.3	SIW & sequential rotation(2×2)	3.04×3.04×0.09	10.9	13.3%	7.2%
	[7]	28	SIW & sequential rotation(2×2)	3.6×3.6×0.10	10.8	23.3%	7.7%
	Our work	**12**	**SIW(2×2)**	**1.44×1.44×0.08**	**13.94**	**4%**	**1.2%**
array	[2]	20	SIW LP elements & sequential rotation(16×16)	12×12.7×0.13	25.9	15.9%	13.8%
	[16]	23.5	Patch fed by SIW slot(2×8)	5.5×4.72×0.07	15.9	10.6%	5.5%
	Our work	**12**	**SIW(8×16)**	**6.04×11.96×0.1**	**26.8**	**4.8%**	**1.1%**

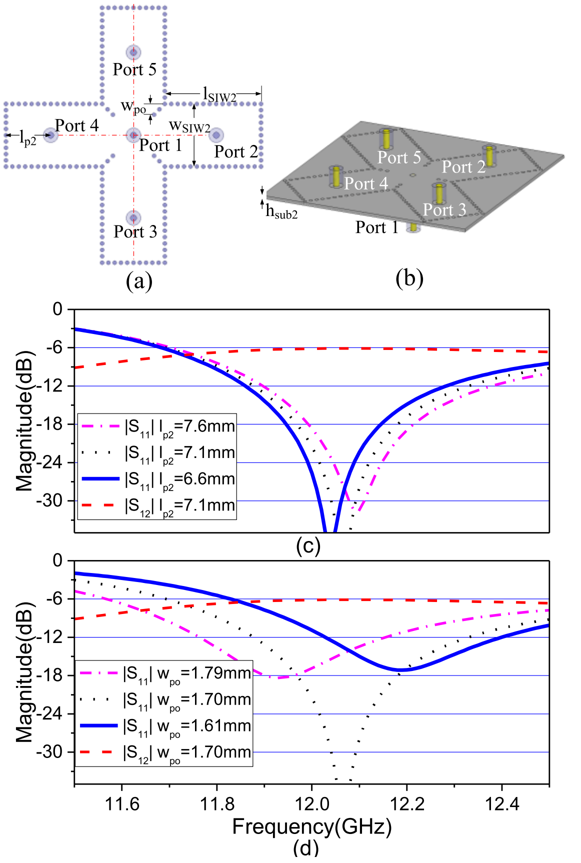


FIGURE 5. (a) Top view of the 1 to 4 SIW power divider, (b) 3D view, (c) Position of port 2 to 5 and (d) Width w_{po} effect on reflection coefficient of the 1 to 4 SIW power divider (The optimum dimensions are $h_{sub2} = 0.508$ mm, $l_{p2} = 7.1$ mm, $W_{SIW2} = 9.9$ mm, $l_{SIW2} = 15.2$ mm, $w_{po} = 1.70$ mm).

area and reduce the insertion loss resulting from the feeding circuit. Each element is excited by using a probe with a diameter of 1.0 mm through a hole with a diameter of 2.3 mm etched on metal layer between the two substrates. It was found that such a hybrid coupling configuration provides not only much better matching between the divider and the antenna elements but also a better radiation performance than adopting the conventional aperture coupling approach.

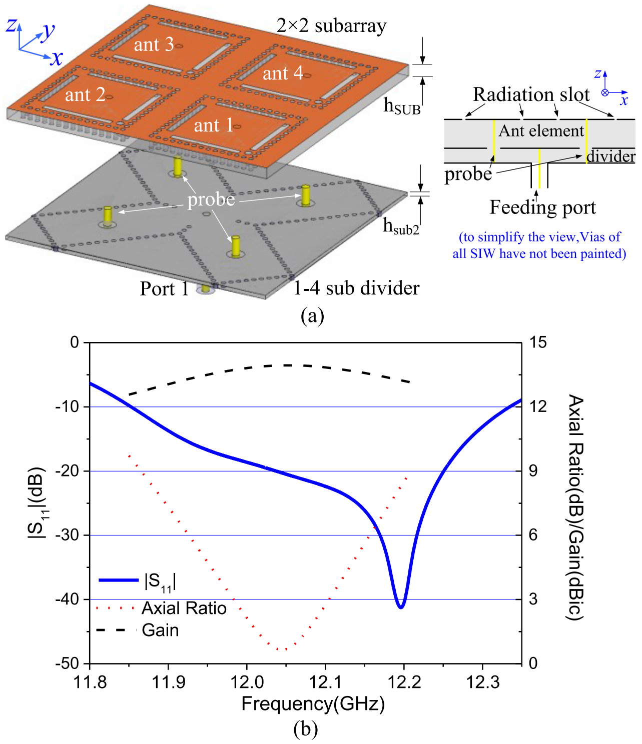
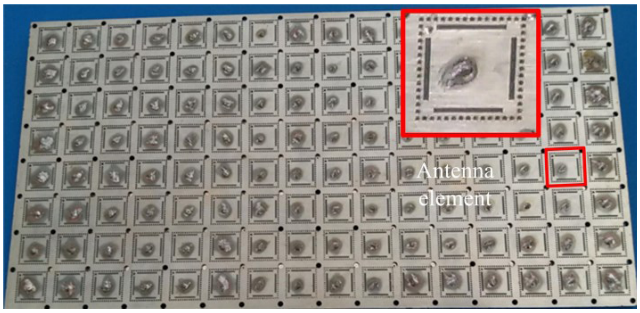


FIGURE 6. (a) 3D antenna assembly view, (b) The reflection coefficient, axial ratio and gain of the 2×2 CP SIW slot antenna subarray fed by the proposed 1 to 4 SIW power divider.

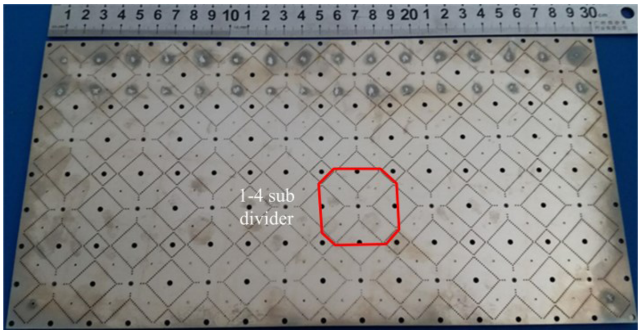
The simulated return loss, axial ratio and gain of this 2×2 subarray are shown in Fig. 6 (b). The -10 dB impedance bandwidth is 4% from 11.85 to 12.34 GHz. The peak gain within 3-dB bandwidth from 11.98 to 12.12 GHz reached 13.94 dBic, which means that approximately 0.55 dB loss is caused by the 1-4 divider.

IV. 8 × 16 ARRAY

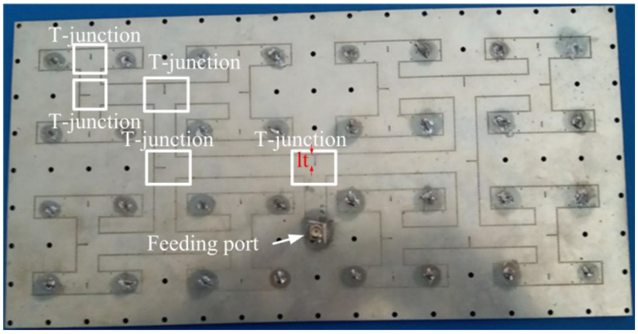
Thanks to the proposed stacked structure, the 2 × 2 array described in Section III is easily expandable as the feed network lies completely underneath the radiators. Figs. 7(a), (b) and (c) show the radiating layer and two feed network layers of an 8 × 16 array expanded from



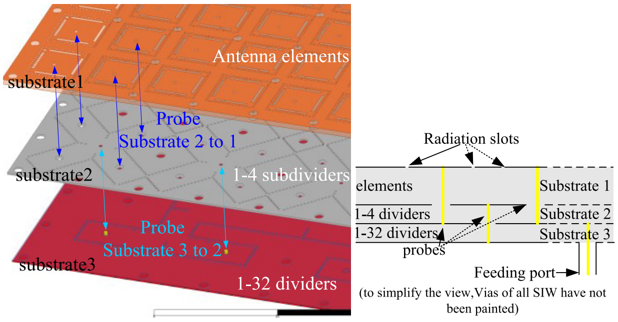
(a) 8 × 16 antenna elements



(b) 4 × 8 "1 to 4" power dividers

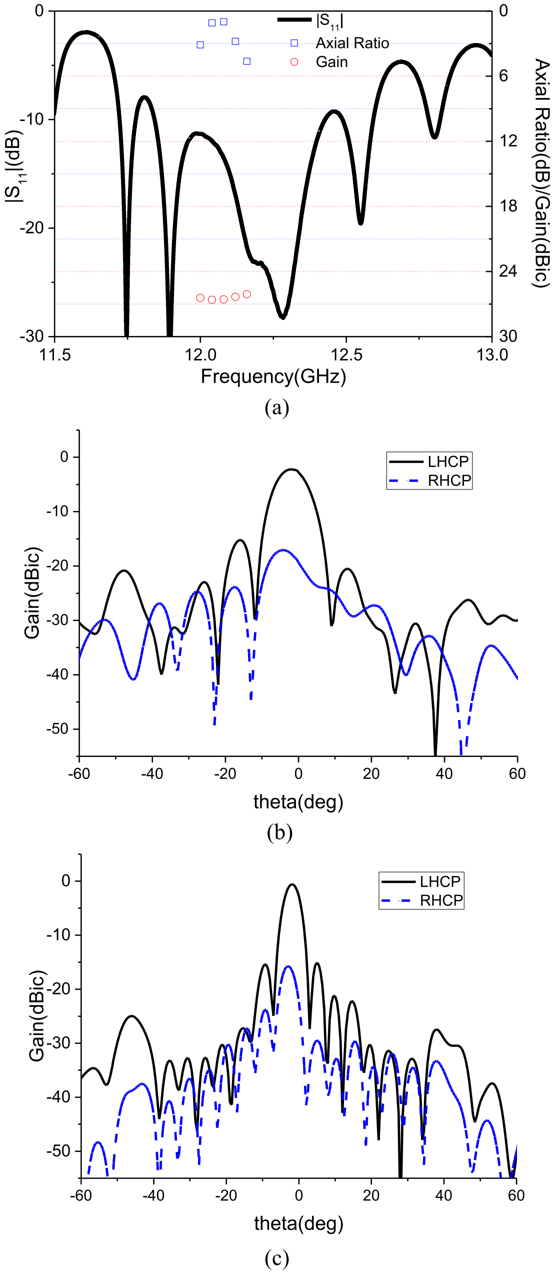


(c)1 to 32 power divider networks



(d) Assembly diagram (e) Sectional view

FIGURE 7. Photos of fabricated (a) Top antenna elements, (b) Middle 1 to 4 power dividers (4×8), (c) Bottom 1-32 divider ,(d) Assembly diagram and (e) Sectional view of the proposed array.



(a)

(b)

(c)

FIGURE 8. Measured (a) Return loss, axial ratio and gain, (b) Radiation pattern at phi = 0° and (c) phi = 90° at 12.06 GHz of the fabricated 128-element CP SIW antenna array.

the 2 × 2 array. Each four element sub-array (layer shown in Fig. 7 (a)) is excited by a 1-4 SIW sub divider (layer shown in Fig. 7 (b)) through four probes. Then, all the sub dividers are excited by a 1-32 SIW power divider (layer shown in Fig. 7 (c)) through 32 probes. The assembly diagram and the sectional view of the proposed 8×16 array is illustrated in Figs. 7 (d) and (e). The SIW CP slot array is excited by an SMA adapter connected with the combined port of the 1-32 SIW divider. By adjusting the length of vias array (l_t) in every T-shape junction, the 1-32 SIW divider can achieve a good input impedance match. The antenna array with three layers of substrate is designed on a PCB. Each layer of the array can be fabricated independently by employing standard single-layer PCB technology. Then, all of the layers are stacked and fixed together by using location pins and screws. It is noted that a larger scale array could be realized by simply duplicating the proposed element and sub divider in two dimensions and connecting them with more stages of H-type SIW power dividers. The total size of the proposed SIW CP slot array is 151 mm × 299 mm × 2.54 mm.

The far-field radiation characteristic of proposed antenna array is tested in a microwave anechoic chamber with a near-field configuration from 11.5 to 12.4 GHz. The measured reflection coefficients, axial ratio and gain of the array antenna are shown in Fig. 8 (a). The measured -10 dB impedance bandwidth is 6.2% from 11.84 to 12.60 GHz. There exist some ripples in the measured S_{11}, which are mainly attributed to the reflections between the feed network and the top layer. The measured 3-dB AR bandwidth is 1.1% from 12.01 to 12.14 GHz. The measured gain within the AR bandwidth is from 26.5 to 26.8 dBic and the peak gain is 26.8 dBic at 12.06 GHz, as shown in Fig. 8 (b) and (c). The measured peak gain is lower than the calculated one of about 29 dBic, which is partly due to losses in the metal and solders and partly due to the fabrication process where components were assembled by hand in our lab.

A comparison between the measurement results of the proposed antenna element, 2 × 2 subarray, and 8 × 16 antenna array with the previously reported antennas, subarray and antenna array based on the SIW backed cavities is presented in Table I, where λ_0 refers to the free space wavelength at the operating frequency. The sizes of the elements refer to the SIW/HMSIW cavities, exclusive of the feeding structures. As shown in Table I, the proposed element obtains a higher gain and is compact size in size.

The impedance bandwidth and AR bandwidth of the proposed antenna element and arrays are narrower than those of reported designs in Table 1 due to the high Q factor of the SIW cavity with four slots. Nevertheless, the AR bandwidth of the fabricated array is wide enough to receive over the 50 sets of programs in the middle latitude region of China.

V. CONCLUSION

In this paper, a planar high-gain circularly polarized element antenna is presented for array applications. Four slots etched on the top surface of an SIW cavity function as 2×2 sub array to improve the directivity and gain. The resonant characteristic has been studied to understand the design method of this antenna element. Combing the proposed element antennas, 1-4 SIW sub dividers, and a 1-32 SIW divider constructed on three substrates, a 128 element array was fabricated using low-cost PCB technology and measured using a Vector Network Analyzer in a microwave chamber. The measured results show that the 8 × 16 array antenna has a high gain up to 26.8 dBic, which includes the losses from the SMA connectors. Good agreement is obtained between the experimental and calculated results, which shows that the proposed antenna has a promising CP radiation performance. The proposed element antenna can be utilized for mobile satellite TV reception covering a large region in China.

REFERENCES

[1] S. Ye *et al.*, "High-gain planar antenna arrays for mobile satellite communications," *IEEE Antennas Propag. Mag.*, vol. 54, no. 6, pp. 256–268, Dec. 2012.

[2] W. Lin and H. Wong, "Circularly polarized conical-beam antenna with wide bandwidth and low profile," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 5974–5982, Dec. 2014.

[3] Q.-X. Chu, W. Lin, W.-X. Lin, and Z.-K. Pan, "Assembled dual-band broadband quadrifilar helix antennas with compact power divider networks for CNSS application," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 516–523, Feb. 2013.

[4] D.-F. Guan, C. Ding, Z.-P. Qian, Y.-S. Zhang, Y. J. Guo, and K. Gong, "Broadband high-gain SIW cavity-backed circular-polarized array antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 4, pp. 1493–1497, Apr. 2016.

[5] P. Sanchez-Olivares and J. L. Masa-Campos, "Novel four cross slot radiator with tuning vias for circularly polarized SIW linear array," *IEEE Trans. Antennas Propag.*, vol. 62, no. 4, pp. 2271–2275, Apr. 2014.

[6] G. Q. Luo, Z. F. Hu, Y. Liang, L. Y. Yu, and L. L. Sun, "Development of low profile cavity backed crossed slot antennas for planar integration," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 2972–2979, Oct. 2009.

[7] Z.-C. Hao, X. Liu, X. Huo, and K.-K. Fan, "Planar high-gain circularly polarized element antenna for array applications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 5, pp. 1937–1948, May 2015.

[8] S. A. Razavi and M. H. Neshati, "Development of a low-profile circularly polarized cavity-backed antenna using HMSIW technique," *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, pp. 1041–1047, Mar. 2013.

[9] Q. Wu, H. Wang, C. Yu, and W. Hong, "Low-profile circularly polarized cavity-backed antennas using SIW techniques," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2832–2839, Jul. 2016.

[10] E. Y. Jung, J. W. Lee, T. K. Lee, and W. K. Lee, "SIW-based array antennas with sequential feeding for X-band satellite communication," *IEEE Trans. Antennas Propag.*, vol. 60, no. 8, pp. 3632–3639, Aug. 2012.

[11] T. Zhang, W. Hong, Y. Zhang, and K. Wu, "Design and analysis of SIW cavity backed dual-band antennas with a dual-mode triangular-ring slot," *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 5007–5016, Oct. 2014.

[12] H. Gharibi and F. Hodjatkashani, "Design of a compact high-efficiency circularly polarized monopulse cavity-backed substrate integrated waveguide antenna," *IEEE Trans. Antennas Propag.*, vol. 63, no. 9, pp. 4250–4256, Sep. 2015.

[13] D.-Y. Kim, J. W. Lee, T. K. Lee, and C. S. Cho, "Design of SIW cavity-backed circular-polarized antennas using two different feeding transitions," *IEEE Trans. Antennas Propag.*, vol. 59, no. 4, pp. 1398–1403, Apr. 2011.

[14] A. B. Guntupalli and K. Wu, "60-GHz circularly polarized antenna array made in low-cost fabrication process," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 864–867, Apr. 2014.

[15] W. Han, F. Yang, J. Ouyang, and P. Yang, "Low-cost wideband and high-gain slotted cavity antenna using high-order modes for millimeter-wave application," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 4624–4631, Nov. 2015.

[16] M. Asaadi and A. Sebak, "High-gain low-profile circularly polarized slotted SIW cavity antenna for MMW applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 752–755, 2016.

[17] B. Cao, H. Wang, Y. Huang, and J. Zheng, "High-gain L-probe excited substrate integrated cavity antenna array with LTCC-based gap waveguide feeding network for W-band application," *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5465–5474, Dec. 2015.

[18] H. Zhou and W. Hong, "Compact circularly polarized patch array antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 778–781, 2016.

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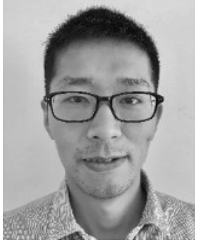

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