

Wideband Circularly Polarized Square Slot Array Fed by Slotted Waveguide for Satellite Communication

Min Wang*, Lei Hu, Jingjing Chen, Shishan Qi, and Wen Wu

Abstract—A wideband circularly polarized (CP) slot array with high radiation efficiency is proposed. The cavity-backed square slots are designed to achieve wideband CP radiation with a unidirectional pattern. The slotted waveguide is adopted to feed the array with high efficiency. The square slot, cavity and feeding slot in the waveguide can be viewed as a radiating element. A CP slot array can be conveniently designed as traditional waveguide slot arrays, once the element admittance characteristic is determined. A 1-by-8 CP array operating at 12.5 GHz has been developed. Measured impedance bandwidth of 6.9%, axial-ratio (AR) bandwidth of 8.8% and a gain of 15.4 dBi have been achieved. This array can be conveniently expanded to a larger wideband CP array with a higher gain, which is preferred for the specific satellite communication applications.

1. INTRODUCTION

Circular polarization has been extensively used in satellite communications due to its advantage of great flexibility in orientation angle between transmitter and receiver [1, 2]. There are also strong demands for wideband, high gain and low profile planar arrays. Microstrip patch antennas are an attractive choice due to their light weight, low profile with conformability, flexibility of achieving CP radiation [3]. However, large microstrip arrays show low efficiency due to ohmic loss, dielectric loss and parasitic radiation in the feed network [3, 4]. In contrast, waveguide-fed slot arrays can provide high gain along with desirable efficiency and bandwidth [5, 6]. CP waveguide-fed slot antennas could be achieved by caving various slots on the wall of the waveguide or loading polarizers on the slots [7, 8]. However, there are often too complicated to be designed and fabricated. A CP waveguide-fed slot array is proposed in [9], in which a fully metal polarizer is integrated to the broad wall shunt slot and changes the polarization of the radiated fields from vertical to circular polarization. A return loss (less than -10 dB) bandwidth of 5% and an AR (less than 3 dB) bandwidth of 4% are achieved for a 12-element linear array. However, the polarizer is too cumbersome with high profile. In [10], split truncated patches are used to replace the metal polarizers to construct a CP patch array fed by slotted waveguide, which can also provide good circular polarization and efficiency. But the axial ratio 3 dB bandwidth of 3% is too narrow to meet the specific demand of satellite communications for which a wide bandwidth more than 6% is desirable.

In this paper, a CP cavity-backed square slot array fed by slotted waveguide is proposed which can implement wideband CP radiation, high radiation efficiency, and low profile. The cavity-backed square slot is designed to achieve wideband CP radiation with a unidirectional pattern. The slotted waveguide is adopted to feed the slot array with high efficiency. The cavity-backed square slot along with the feeding slot on the broad wall of the waveguide is viewed as an element. Once the admittance characteristic of the element is determined, large CP square slot arrays can be conveniently designed as

Received 6 March 2016, Accepted 19 July 2016, Scheduled 26 July 2016

* Corresponding author: Min Wang (wangmin@mail.njust.edu.cn).

The authors are with the Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing 210094, China.

a traditional waveguide slot array. A waveguide-fed CP element operating at 12.5 GHz is investigated in detail. Then a 1-by-8 CP array has been developed. Measured impedance bandwidth of 6.9%, AR bandwidth of 8.8% have been obtained at 12.5 GHz. The overall height of the antenna is about a half wavelength. It is convenient to expand to the larger wide band CP array with a higher gain, which is preferred for the specific satellite communication applications.

2. DESIGN OF CIRCULARLY POLARIZED ELEMENT

The structure of the proposed CP antenna element is shown in Figure 1. It consists of three parts: a substrate with a slot on its ground plane, a metallic cavity and a feeding waveguide. The upper substrate is Rogers RT/duroid 5880 ($\epsilon_r = 2.2$, $\tan \delta = 0.0009$) with a thickness of $t_1 = 0.508$ mm. It only retains the lower metal layer, on which a square slot with a pair of square perturbations in the diagonal direction is etched to radiate CP EM waves. The edge-lengths of slot and perturbation are l_c and l_p , respectively. Beneath the substrate is a metallic board with a height of h . A square hole with the same edge-length l_c is drilled through the board which served as the metallic side walls of the cavity. Another metal board is placed below to mill the waveguide on it. A thin metal layer of a height of $t_2 = 0.1$ mm is inserted between two boards to act as both the lower wall of the cavity and the upper wall of the feeding waveguide. A longitude feeding slot is etched in the metal layer with an offset of *offset* at x -axis to couple energy from waveguide to the radiating slot. The length and width of the feeding slot are l_s and w_s , respectively.

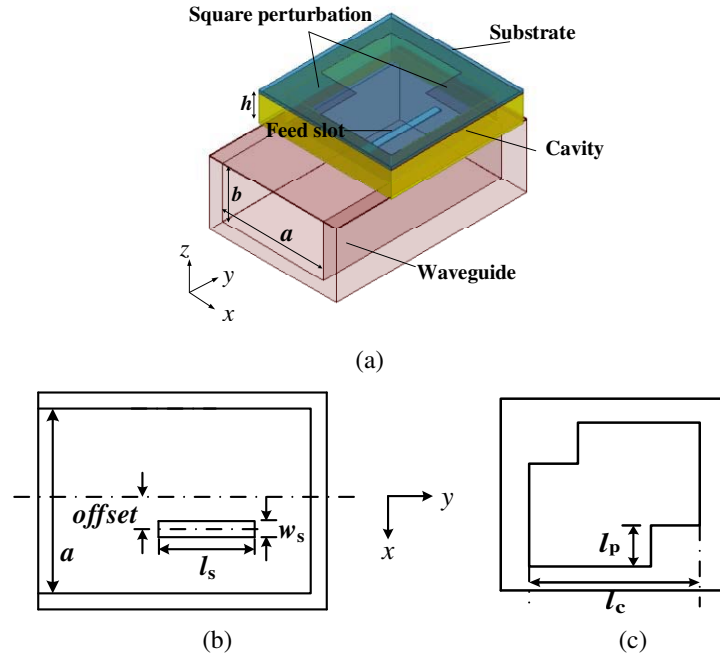


Figure 1. Geometry of CP patch element. (a) Perspective view. (b) Feeding waveguide. (c) Square slot with perturbations.

The CP cavity-backed square slot can be viewed as a circular polarizer loaded on a longitude waveguide-fed slot. The cavity plays a key role in impedance matching and polarization transformation. For the element, desired resonant conductance and circular polarization performance can be achieved by optimally adjusting the dimensions of the radiating slot, feeding slot, cavity and perturbations. The software ANSYS HFSS is used to conduct parametric study to obtain an optimal bandwidth for both return loss and AR performances. The operating frequency of 12.5 GHz is considered.

Firstly, we prescribe the cavity height h , e.g., 4 mm, and determine the dimension of the cavity aperture and the perturbations. As a square waveguide, the cavity edge length $l_c = 16.6$ mm is roughly

determined according to the operating frequency. Meanwhile, as a container, the cavity aperture should be large enough to embrace the feeding slot. However, it must also be smaller than half a guide wavelength when constructing an array. Then, the perturbation length l_p is adjusted to achieve circular polarization radiation. We obtain the amplitude ratios and phase differences between two orthogonal E -field components E_θ and E_φ for $\varphi = 0^\circ, \theta = 0^\circ$ corresponding to different l_p shown in Figure 2. It indicates that good circular polarization can be achieved with an optimal perturbation length $l_p = 5.6$ mm. The E -fields over the slot with orthogonal exciting phases are shown in Figure 3. It illustrates that two resonance modes are excited with two perturbations.

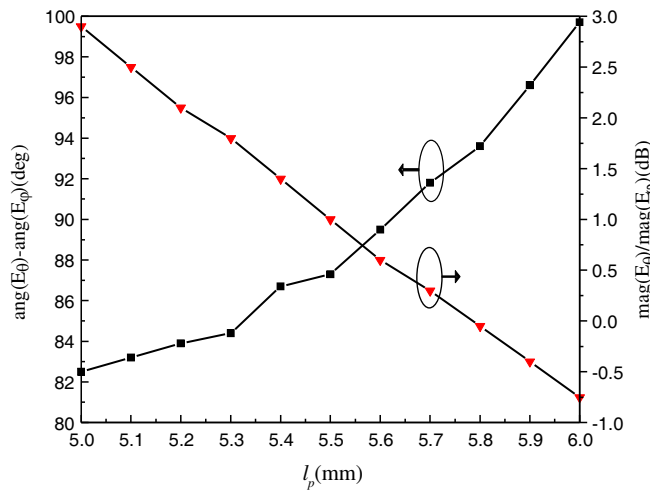


Figure 2. The amplitude ratio and phase difference of the two electric field models versus perturbation edge length l_p .

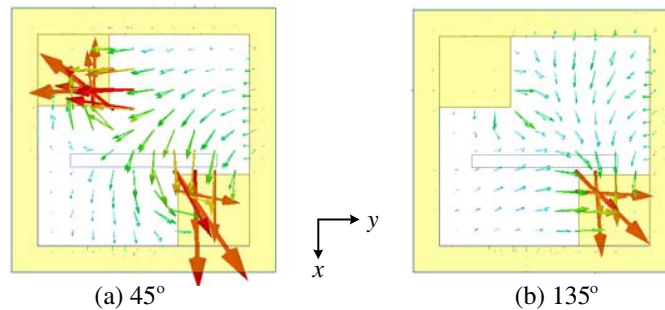


Figure 3. The E -fields over the slot with orthogonal exciting phases.

Once the parameters of the polarizer are determined, the feeding slot is optimized to provide appropriate excitation. The slot length and offset are adjusted to make the whole element resonant and the corresponding resonant conductance is calculated. Simulated results in Figure 4 shows that the element has similar conductance property as a longitude slot cut on the broad wall. Further study has been conducted to investigate the effect of the offset of feeding slot on AR performance [10], which shows that the parameters of the slot have little influence on AR. It is indicated that CP radiation and prescribed excitation can be realized by adjusting perturbations and the feeding slot, independently.

Finally, the effects of the cavity height h on the admittance and circular polarization performance are emphatically discussed. For a specified h , the dimensions of the cavity and perturbations are firstly adjusted to obtain circular polarization performance. Then the length and offset of the feeding slot are tuned to make the resonant conductance g approximately be constant. We take $g = 0.25$. Varying the cavity height h , we obtain different normalized susceptance and axis ratio (AR) curves versus frequency

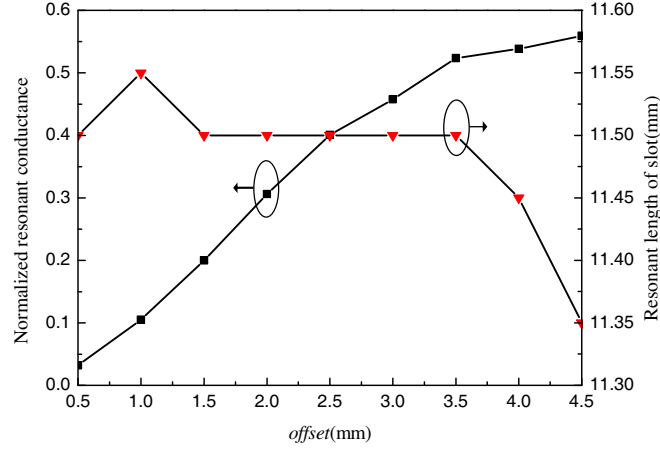


Figure 4. Normalized resonant conductance and resonant slot length versus offset.

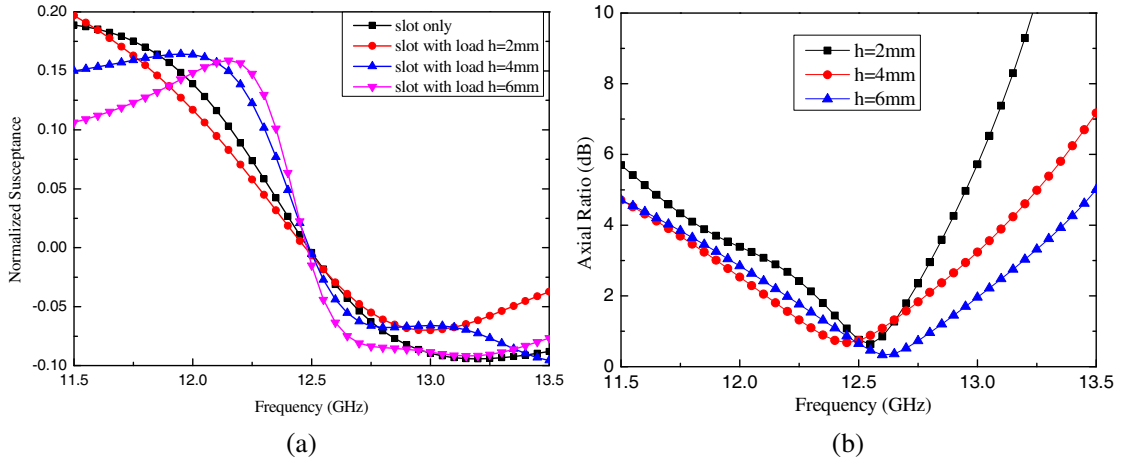


Figure 5. (a) Normalized susceptance of the element versus frequency for different h . (b) Axial Ratio versus frequency for different h .

Table 1. Optimized parameters of an element (unit: mm).

| Parameters | a | b | l_s | w_s | $offset$ | l_p | l_c | h |
|------------|------|-----|-------|-------|----------|-------|-------|-----|
| Values | 15.8 | 7.9 | 11.5 | 1 | 1 | 5.6 | 16.6 | 4 |

shown in Figure 5. It is seen from Figure 5(a) that the slope of the normalized susceptance increases as the height of cavity increases, which agrees with the impedance property to that of the convention cavity-backed slot antennas [11]. It has been found that the impedance becomes more highly resonant as the cavity height is increased. It can attribute to the long-line effect of the cavity, because the cavity itself performs rather a transmission line than a resonator, which shunt the radiating slot to the feeding slot to implement the mode- (or polarization) and impedance transformation. Thus, the shorter cavity leads to wider potential array bandwidth.

On the other hand, Figure 5(b) shows that the wider AR bandwidth is obtained for the thicker cavity. It can be well understood that longer cavity provides better polarization transformation. Therefore, the optimized cavity height of 4 mm is chosen to obtain optimal bandwidth for both return loss and AR performances.

Parametric optimization is conducted step by step. Optimized results are shown in Table 1, and

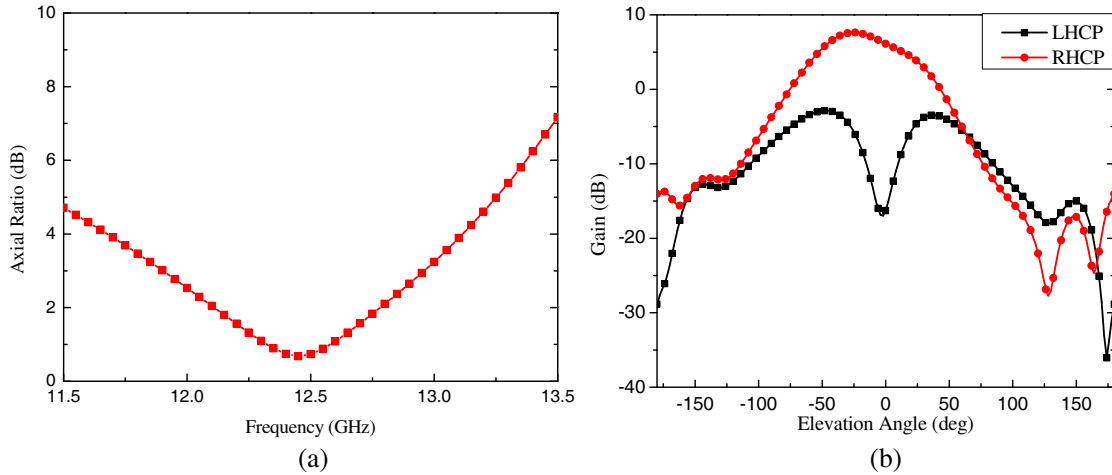


Figure 6. (a) Optimized axial ratio curve of the element. (b) Radiation pattern of the element ($\varphi = 90^\circ$).

the corresponding optimal AR and pattern are shown in Figure 6. It is seen that right-hand circular polarization (RHCP) has been achieved successfully with a circular-polarization bandwidth of 8.4% and a gain of 7.6 dBi.

3. DESIGN OF 1-BY-8 LINEAR ARRAY

Utilizing above element with a normalized conductance $g = 0.25$, a uniform 1-by-8 CP array shown in Figure 7 is developed to demonstrate the efficient design method and desirable array performance. For the feeding slot, square slot and perturbations, the same dimension variables are adopted as those shown in Figure 1. Other variables are shown in Figures 7(a) and (b) in detail.

The 1-by-8 array is center-fed by a coaxial probe with a diameter of $d = 0.6$ mm intruding from the back of waveguide. Both ends of the waveguide are short-circuited. The element spacing is $\lambda_g/2$,

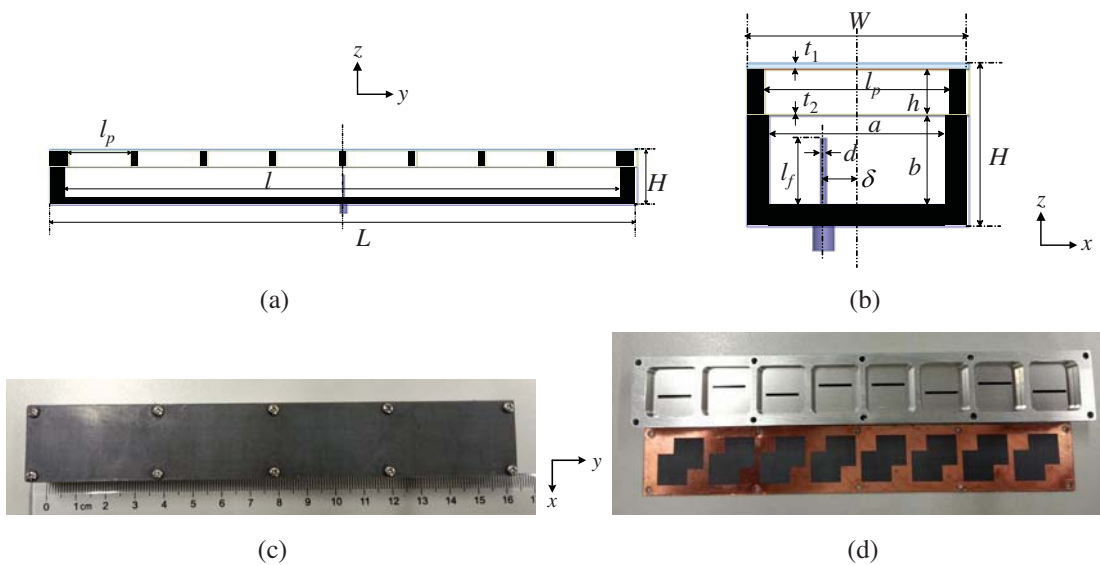


Figure 7. Geometry and photo of the 1-by-8 linear array. (a) Front view. (b) Side view. (c) Top-view. (d) Internal-view.

and the two elements at the end are spaced $\lambda_g/4$ from the short wall, where $\lambda_g = 36.9$ mm is the guided wavelength at 12.5 GHz for the dominant TE_{10} mode. To compensate the alternation in phase of mode voltage and obtain equal exciting phases, the feeding slots are placed with an alternation in direction of the offset.

The dimensions of the perturbations and feeding slot are slightly modified to compensate the mutual coupling effects among elements. By changing the height of the coaxial probe l_f and the offset δ along X -axis, good impedance matching can be achieved. The optimized parameters are obtained as shown in Table 2. The size of array aperture is 149.6 mm \times 19.8 mm.

Table 2. Optimized parameters of the 1-by-8 array (unit: mm).

| | | | | | | | | | |
|------------|-------|-----|----------|-------|----------|-------|--------|-------|-------|
| Parameters | a | b | l_s | w_s | $offset$ | l_p | l_c | h | t_1 |
| Values | 15.8 | 7.9 | 11.5 | 1 | 1 | 5.6 | 16.6 | 4 | 0.508 |
| Parameters | t_2 | d | δ | l_f | L | W | H | l | |
| Values | 0.1 | 0.6 | 3.1 | 5.9 | 149.6 | 19.8 | 14.508 | 145.6 | |

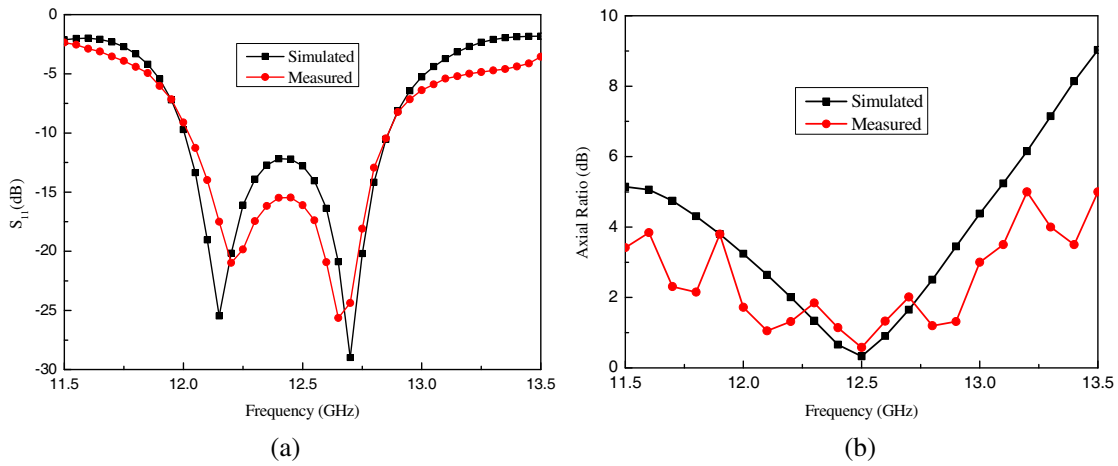


Figure 8. (a) Reflection coefficient of the linear array. (b) Axial ratio versus frequency.

Measured reflection coefficient and axial ratio curves versus frequency are shown in Figure 8, which agree with the simulated ones very well. A measured impedance bandwidth of 6.9% (12~12.86 GHz) is obtained for 10-dB return loss. The measured 3-dB AR bandwidth is 8.8% (11.9~13 GHz). The H -plane axial ratio variation versus the elevation angle is shown in Figure 9(a). It is seen that good circular polarization performance has been achieved within the main lobe. The simulated and measured radiation patterns at $\varphi = 90^\circ$ are shown in Figure 9(b). Cross-polarization level is lower than -25 dB. Measured gain is appropriately 15.4 dBi, which matches the simulated result of 15.7 dBi well. The overall aperture efficiency is 53.7%, which seems to be fairly low. This attributes to the low aperture taper efficiency for the narrow aperture.

Usually a high gain more than 20 dBi, even up to 40 dBi, would be required for communication systems. It is convenient to expand the designed 1-by-8 wideband CP array to construct a larger array to achieve a specific high gain. Furthermore, the higher aperture taper efficiency can be achieved for the larger planar array due to more uniform field distribution. Meanwhile, the feeding waveguide provides high radiation efficiency e_r . For the designed copper waveguide, the conductivity loss for the TE_{10} mode is calculated as 0.21 dB/m. The radiation efficiency will only decrease slightly for a larger array. Therefore, a higher overall aperture efficiency ε_{ap} can be expected for an 8-by-8 planar array, or even a larger one.

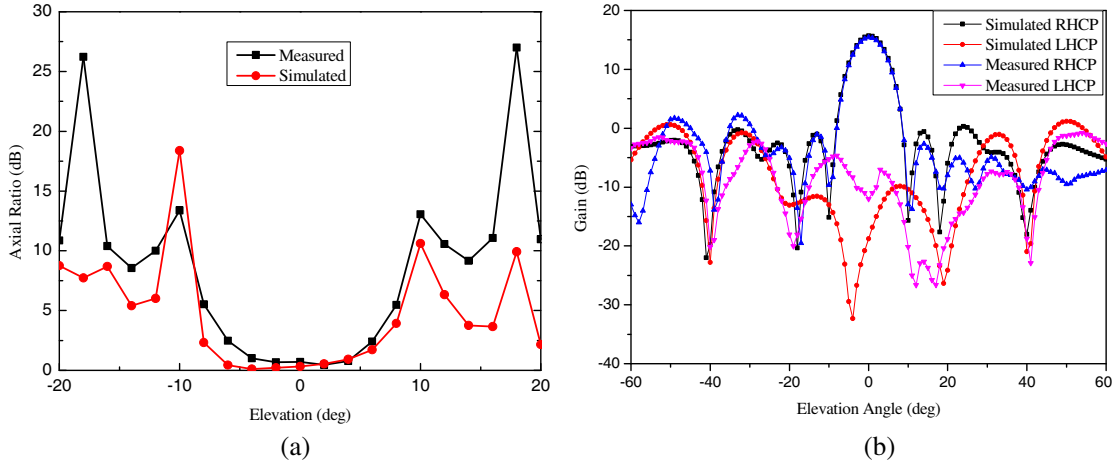


Figure 9. (a) Axial ratio versus at 12.5 GHz ($\varphi = 90^\circ$), (b) Radiation pattern of the linear array at 12.5 GHz ($\varphi = 90^\circ$).

Table 3. Calculated efficiency for arrays of different sizes.

| Array size | A_p (mm ²) | Gain (dBi) | AR (dB) | ϵ_{ap} |
|------------|--------------------------|------------|---------|-----------------|
| 1-by-8 | 19.8×149.6 | 15.7 | 0.33 | 57.5% |
| 2-by-8 | 37.6×149.6 | 18.7 | 1.24 | 60.4% |
| 4-by-8 | 73.2×149.6 | 22.1 | 0.88 | 67.8% |
| 8-by-8 | 144.4×149.6 | 25.3 | 0.64 | 71.9% |
| 16-by-8 | 186.8×149.6 | 28.3 | 0.53 | 72.8% |

To investigate the efficiency of larger arrays, we construct 2-by-8, 4-by-8, 8-by-8, and 16-by-8 arrays with the designed 1-by-8 array. The spacing is 17.8 mm, i.e., there are metal-walls with a width of 2 mm between two feeding waveguides. The widths of the outmost walls are also 2 mm. All sub-arrays are uniformly excited in phase. Full-wave simulation for the radiation performance is performed with the software HFSS. Results of gain, AR, and calculated ϵ_{ap} at the 12.5 GHz are shown in Table 3. It can be seen that a higher aperture efficiency ϵ_{ap} more than 70% can be obtained for an 8-by-8 planar array, or even a larger one. However, a wideband and high-efficient feeding network, in parallel or/and series form, should be adopted to keep wide bandwidth and high efficiency of a large array.

4. CONCLUSION

In this letter, a wideband circularly polarized cavity-backed square slot array fed by a slotted waveguide is proposed for satellite communication applications. Good AR bandwidth attributes to the radiating square slots. Meanwhile, the desired impedance bandwidth and efficiency are achieved due to the feeding waveguide. A 1-by-8 circularly polarized array has been developed with an impedance bandwidth of 6.9%, AR bandwidth of 7.6% and overall aperture efficiency of 53.7%, which demonstrate superior performance to traditional circularly polarized antenna fed by waveguide.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China under Grant 61301018.

REFERENCES

1. Ferrero, F., C. Luxey, G. Jacquemod, and R. Staraj, "Dual-band circularly polarized microstrip antenna for satellite applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 4, 13–15, 2005.
2. Legay, H. and L. Shafai, "A new stacked microstrip antenna with large bandwidth and high gain," *IEEE AP-S Int. Symp. Digest*, 948–951, 1993.
3. Mailloux, R.-J., J.-F. McIIVenna, and N.-P. Kernweis, "Microstrip array technology," *IEEE Trans. Antennas Propag*, Vol. 29, No. 1, 25–37, 1981.
4. Zhang, Y.-J., A.-X. Chen, S.-F. Cao, and D.-L. Su, "Design of a circularly polarized 8×8 patch antenna array using a new series-parallel feed," *2009 3rd IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, 411–414, 2009.
5. Ando, M. and J. Hirokawa, "High gain and high efficiency single-layer slotted waveguide arrays in 60 GHz band," *Proc. 10th Int. Conf. Antennas Propag*, Vol. 1, No. 436, 464–468, 1997.
6. Wang, W., S.-S. Zhong, Y.-M. Zhang, and X.-L. Liang, "A broadband slotted ridge waveguide antenna array," *IEEE Transactions on Antennas and Propagation*, Vol. 54, No. 8, 2416–2420, 2006.
7. Salari, M. and M. Movahhedi, "A new configuration for circularly polarized waveguide slot antenna," *Proc. APMC*, 606–609, 2011.
8. Miura, Y., J. Hirokawa, M. Ando, and K. Igarashi, "A circularly-polarized aperture array antenna with a corporate-feed hollow-waveguide circuit in the 60 GHz-band," *Proc. 2011 Intl. Symp. Antenna Propag. (APSURSI)*, 3029–3032, Jul. 2011.
9. Dogan, D. and C.-B. Top, "Circularly polarized Ka-band waveguide slot array with low sidelobes," *Proc. 6th Eur. Conf. Antennas Propag.*, 1105–1109, 2011.
10. Xu, J.-K., M. Wang, H.-K. Huang, and W. Wu, "Circularly polarized patch array fed by slotted waveguide," *IEEE Antennas Wireless Propagation. Lett*, Vol. 14, 8–11, 2015.
11. Long, S. A., "A mathematical model for the impedance of the cavity-backed slot antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 25, No. 6, 829–833, 1977.