APPLICATIONS OF
MODELLING AND SIMULATION
http://arqiipubl.com/ams eISSN 2600-8084 VOL 3, NO. 3, 2019, 154-159

A Circularly Polarized Slotted Waveguide Antenna Array

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Received 7 August 2019, Revised 24 August 2019, Accepted 28 August 2019.

Abstract: The design of a novel circularly polarized X–band Slotted Waveguide Antenna Array (SWAA) is proposed in this paper. The CST Microwave Studio (CST MWS) simulation results show that the simulated Axial Ratio (AR) is below 3 dB from 9.497 GHz to 9.676 GHz, or 1.86% relative bandwidth, with a minimum AR is 0.556 dB at 9.6 GHz. The simulated reflection coefficient is below –23 dB within the 3 dB AR bandwidth. The simulated antenna gain is 7.288 dB at 9.6 GHz.

Keywords: Slotted waveguide antenna; Circular polarization; Rectangular waveguide; Antenna array.

1. INTRODUCTION

The Slotted Waveguide Antenna Array (SWAA) features high power handling capacity, high efficiency, low profile, and can be conformed to basically any configuration, thus it has been found many applications especially in radar systems [1-2]. To achieve a circularly polarized SWAA, two orthogonal electric fields with the same magnitude and are quadrature in phase are excited by narrow slots with certain shapes which are located at the proper point in the broad wall of the rectangular waveguide [3].

In [4], two slots (one is longitudinal and another is transversal) are cut perpendicular to each other on the broad wall of a rectangular waveguide to radiate a circularly polarized wave. The position and the size of the slots are numerically optimized to suppress reflection, and to realize a desired polarization in the tilted beam direction. In [5], a circularly polarized SWAA was proposed. This circularly polarized radiator consists of longitudinal slots and a U–shaped slot pair cut on the broad wall of a rectangular waveguide in order to radiate linear polarization perpendicular to each other with 90˚ phase difference. A circularly polarized waveguide antenna was presented by Wu *et al*. [6]. This antenna array was based on using an air cavity above the cross slot with two orthogonal pairs of radiation slot on the top. In [7], a slotted waveguide antenna unit was consisted of one longitudinal slot and two transverse slots. This antenna array unit was optimized to realize the circular polarization.

In this paper, a new configuration of circularly polarized SWAA is introduced. The proposed circularly polarized SWAA is compact, easy to fabricate, and can be used for tough environment applications due to its all–metal structure. The layout of this paper is as follows. In Section 2, the design of the proposed circularly polarized SWAA is presented. In Section 3, the simulation results are described. The conclusions are provided in Section 4.

2. DESIGN OF THE PROPOSED CIRCULARLY POLARIZED SWAA

The longitudinal slots in the broad wall are located at opposite sides to the central line in order to add phase shift of (π) between the neighbouring longitudinal slot fields. As shown in Figure 1, the distance between the neighboring longitudinal slots is one–third guide wavelength $\left(\frac{\lambda_g}{3}\right)$, which results in another addition of $\left(\frac{2\pi}{3}\right)$ phase shift between the neighboring longitudinal slot fields.

The longitudinal slot fields are added together to generate a wave which is directed in the x–direction as follows:

$$E_{slot\#1}\sin(\omega t+\varphi)\,\hat{a}_x + E_{slot\#3}\sin\left(\omega t+\varphi+\frac{2\pi}{3}+\pi\right)\hat{a}_x = -E_L\sin\left(\omega t+\varphi+\frac{5\pi}{6}\right)\hat{a}_x \tag{1}$$

The spacing between the two transversal slots is $\left(\frac{\lambda_g}{3}\right)$ in order to add phase shift of $\left(\frac{2\pi}{3}\right)$ between the neighboring transversal slot fields. The fields of the neighboring transversal slots are added with each other to produce a wave which is directed in the z–axis direction as given by:

$$E_{slot\#2}\sin\left(\omega t+\varphi-\frac{\pi}{3}\right)\hat{a}_z + E_{slot\#4}\sin(\omega t+\varphi-\pi)\,\hat{a}_z = E_T\sin\left(\omega t+\varphi-\frac{2\pi}{3}\right)\hat{a}_z \tag{2}$$

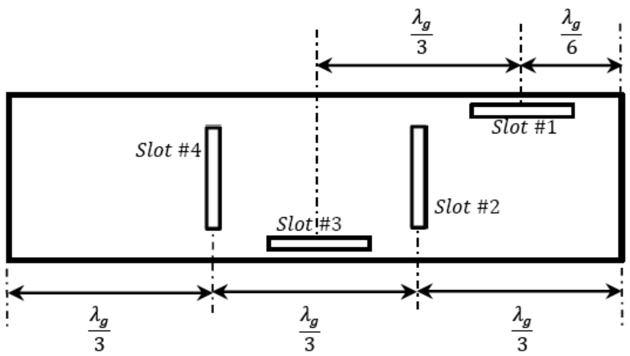


Figure 1. Structure of the resonating circularly polarized SWAA

where $E_{slot\#1}$, $E_{slot\#2}$, $E_{slot\#3}$ and $E_{slot\#4}$ are the magnitudes of the slot fields; and $E_{slot\#1} = E_{slot\#3}$, also $E_{slot\#2} = E_{slot\#4}$. E_L and E_T are magnitudes of the resultant waves from the longitudinal and transversal slot fields, respectively. There is a phase shift of $\left(\frac{\pi}{2}\right)$ between the generated waves from the longitudinal slot fields (directed in x-axis) and the wave produced by the transversal slot fields (directed in z-axis).

The Right Hand Circular Polarization (RHCP) is obtained by optimizing the slot offset from the central longitudinal line in order to change the value of E_L to be equal to the value of E_T. The amount of the radiated power from the longitudinal slots on the broad wall of the slotted waveguide antenna depends on the slot offset from the central line [8], so that the value of the slot offset has been varied in CST Microwave Studio (MWS) in order to control the amount of the radiated electric fields from slots #1 and #3, and obtain circular polarization from the proposed antenna array. For the proposed SWAA, the broad wall width of the rectangular waveguide is selected to make the cut-off frequency of TE_{10} mode is 86.9 % of the operating frequency at 9.6 GHz. The narrow wall width of the rectangular waveguide is selected to be half the broad wall width. The waveguide wavelength (λ_g) is calculated as [8]:

$$\lambda_g = \frac{1}{\sqrt{\frac{1}{\lambda^2} - \frac{1}{{\lambda_c}^2}}} \tag{3}$$

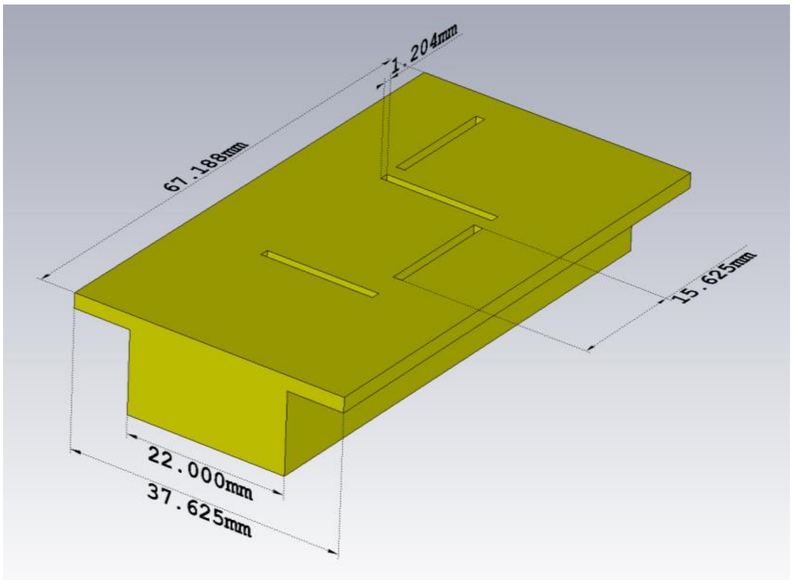
where λ_c is the cutoff wavelength at the operating mode. SEMI-RIGID CABLE .250 is used to feed the rectangular waveguide [9]. Wings are added to the proposed circularly polarized SWAA to reduce the amount of backward energy that may wrap around the back of SWAA. The antenna gain, the reflection coefficient and the purity of the circular polarization will be affected if the slots are arranged in different locations. Also the purity of the circular polarization will be degraded if more slots are added or removed such that the numbers of the longitudinal and the transversal slots are no longer equal to each other.

3. SIMULATION RESULTS

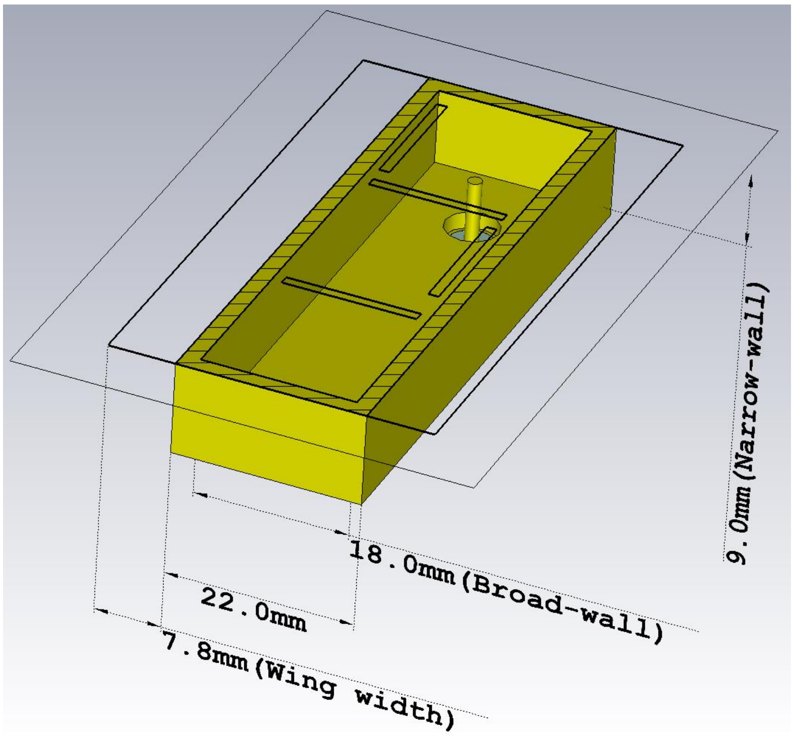
The circularly polarized SWAA was designed on one broad side wall of a rectangular waveguide with a total number of four slots which have the same dimensions (two slots are longitudinal and the other two slots are transversal). The gain of the proposed antenna will be decreased if the selected number of slots is only two (one slot is longitudinal and the other is transversal), while the size of the proposed antenna will be increased if the number of the selected slots is more than four. So the number of the slots is decided to be four in order to compromise between the obtained gain and the size of the antenna. CST MWS software was used to simulate the proposed antenna array at operating frequency of 9.6 GHz. The air-filled substrate is chosen to reduce the fabrication cost. In case of implementing TE_{10} mode excitation, the proposed circularly polarized SWAA dimensions are indicated in Table 1.

Table 1. Proposed circularly polarized SWAA dimensions

Parameter	Circularly Polarized SWAA Dimensions in mm
Wavelength in the waveguide λ_g	63.1875
Broad-wall width of the rectangular waveguide	18
Narrow-wall width of the rectangular waveguide	9
Wavelength λ	31.25
Slot length	15.625
Slot width	1.204
Slot offset from the central longitudinal line	7.447
Wing width	7.8125



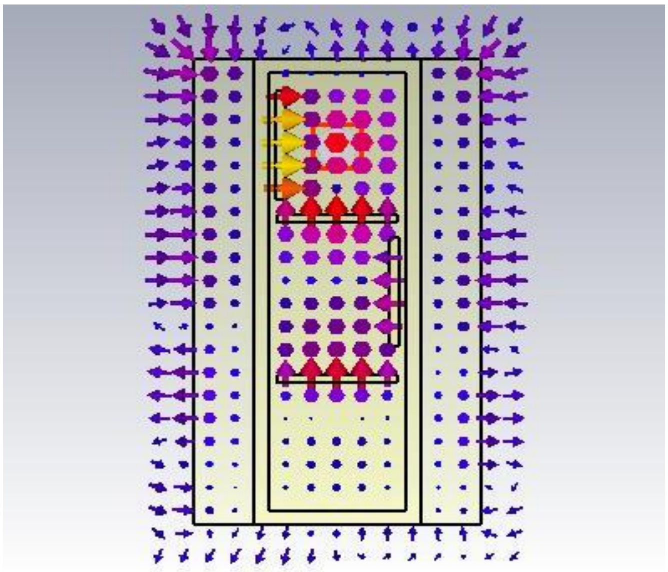
(a)



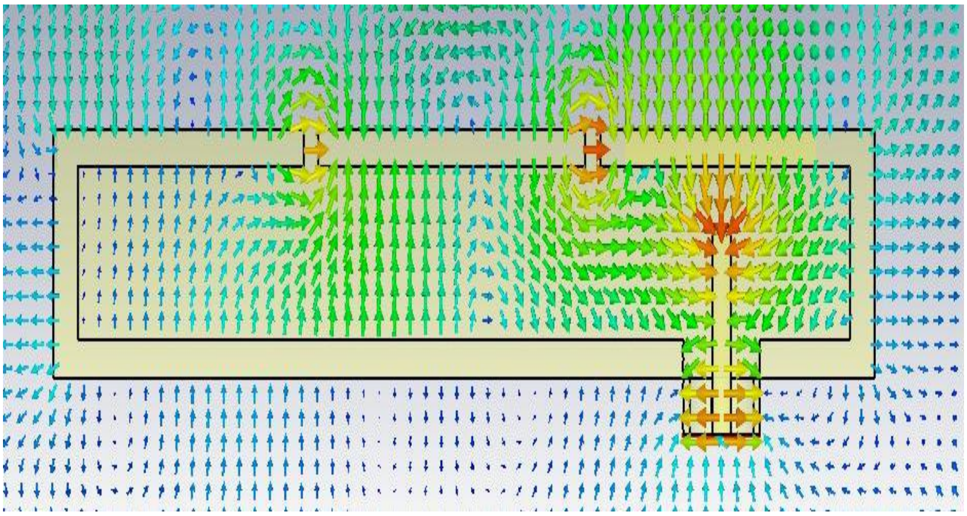
(b)

Figure 2. CST MWS model for the proposed circularly polarized SWAA with 4–slot (a) Perspective view (b) Cutting plane view

The proposed circularly polarized SWAA with four slots is modeled in CST MWS. The perspective and the cutting plane views are shown in Figures 2(a) and 2(b), respectively. The top and the side views of the electric field distribution inside the proposed antenna array are shown in Figures 3(a) and 3(b), respectively. Figure 3(a) indicates that the electric fields at slot #1 and slot #3 have opposite directions, while the electric fields at each of slot #2 and slot #4 are in the same direction. The standing wave is generated inside the rectangular waveguide as shown in Figure 3(b). At the locations of slots #1 and #2, the electric field outside the SWAA is directed down into the top metal surface of the waveguide broad-wall as shown in Figure 3(b), so the generated magnetic field lines are circulated in the clockwise direction, and this magnetic field will produce surface currents which induce electric fields in slots #1 and #2 with directions as shown in Figure 3(a). At the positions of slots #3 and #4, the electric field is directed down to be ended on the top metal surface outside the SWAA broad-wall as shown in Figure 3(b), so the generated magnetic field will be curled in the clockwise direction to produce surface currents which induce an electric field in slots #3 with opposite direction to the electric field in slot #1, and also induce an electric field in slot #4 with the same direction of the electric field in slot #2.



(a)



(b)

Figure 3. Electric field distribution inside the proposed circularly polarized SWAA with 4–slot (a) Top view (b) Side view

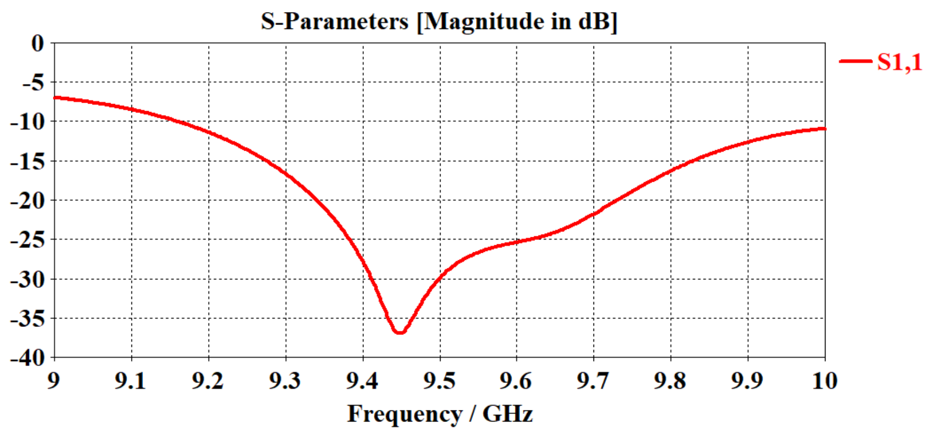


Figure 4. Simulated S–parameters for the proposed SWAA

The simulated S-parameters are below –23 dB in the frequency range from 9.497 GHz to 9.676 GHz as shown in Figure 4. The phase shifts between the electric fields in the slots result in changing the main lobe direction to be at 21˚, the angular 3-dB beamwidth for the proposed SWAA equals 110.2˚ as shown in Figure 5. An antenna gain of 7.288 dB, a radiation efficiency (the ratio of the radiated power to the total power supplied to the SWAA) of 95.52% and a total efficiency (the radiation efficiency multiplied by the input reflection coefficient) of 95.24% are obtained at 9.6 GHz as shown in Figure 6.

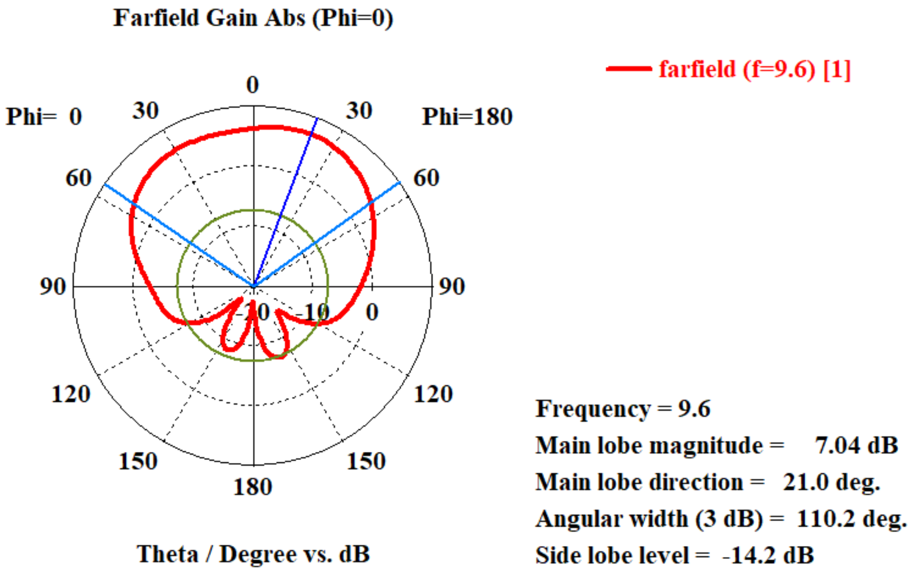


Figure 5. YZ–plane pattern for the proposed SWAA

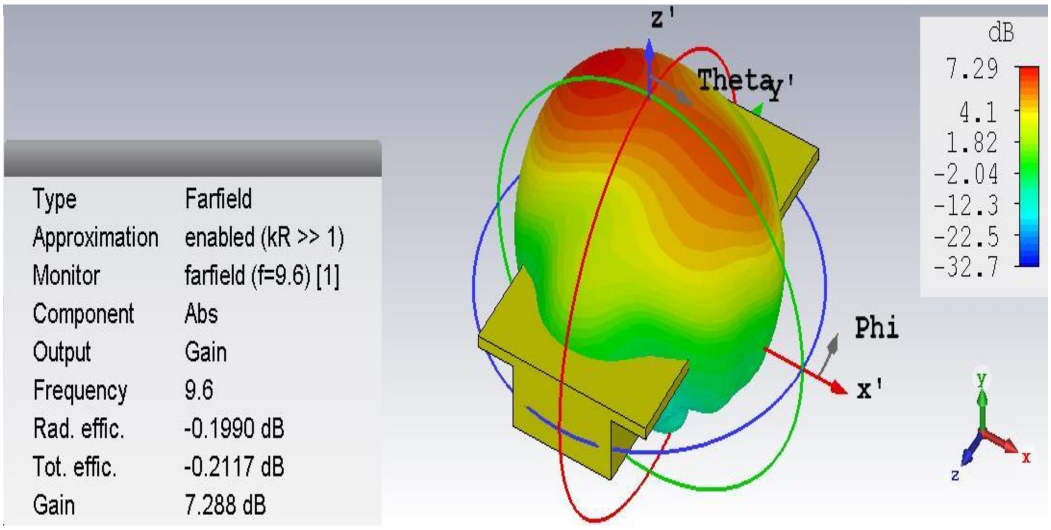


Figure 6. Three–dimensional radiation pattern for the proposed SWAA

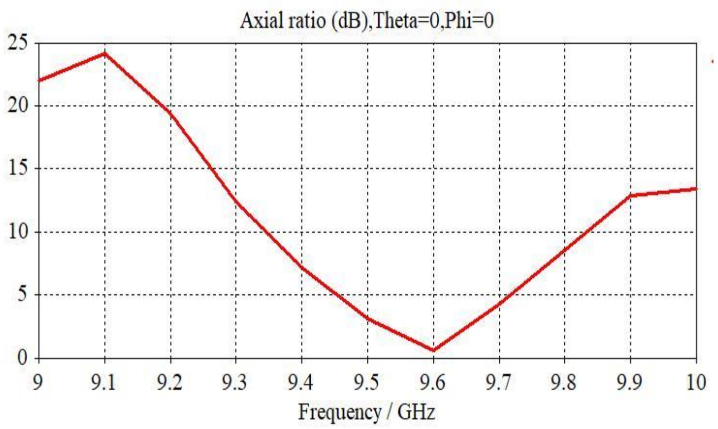


Figure 7. Simulated axial ratio versus frequency for the proposed SWAA

Figure 7 shows that the axial ratio is lower than 3 dB in the frequency band from 9.497 GHz to 9.676 GHz. The simulated antenna gain is 7.288 dB at 9.6 GHz as shown in Figure 8. Figures 4, 7 and 8 demonstrate that the useful bandwidth is approximately 180 MHz. The length of the largest dimension for the proposed circularly polarized SWAA is λ_g, while the length of largest dimension is about $2\lambda_g$ for SWAA with 4-slot as in [5] or SWAA with 6-slot as in [7]. So that the proposed antenna array in this paper provides more than 50% reduction in the antenna array size as a comparison with similar designs in [5] and [7].

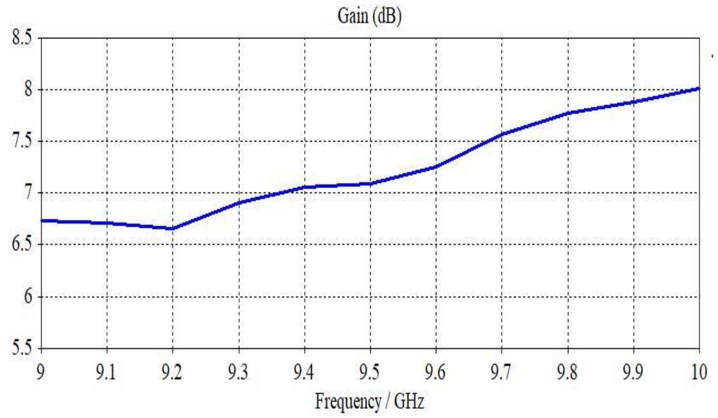


Figure 8. Simulated antenna gain versus frequency for the proposed SWAA

4. CONCLUSIONS

In this paper, a novel circularly polarized SWAA was introduced. The proposed circularly polarized SWAA with 4-slot was modeled in CST MWS software. The proposed antenna array provides RHCP, small size, bandwidth of about 180 MHz, a gain of 7.288 dB at 9.6 GHz, high power handling capacity, and structure robustness.

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