A novel circularly polarized slotted substrate integrated waveguide antenna array for satellite applications

Alla M. Eid | Amgad A. Salama | Hassan M. Elkamchouchi

Electrical Engineering Department, Alexandria University, Alexandria, Egypt

Correspondence
Amgad A. Salama, Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt.
Email: am_sadki@ece.concordia.ca

Abstract
In this article, three novel slotted substrate integrated waveguide (SIW) antenna elements are demonstrated with different radiator configurations, namely, two arms Archimedean antenna, single-arm spiral antenna (monofilat), and four concentric circular loops antenna. Additionally, their near, as well as far-field characteristics, have been investigated. The two arms Archimedean spiral antenna has a superior radiation characteristic of 18% return loss bandwidth (RLBW), 12% boresight axial ratio bandwidth (ARBW), and five dBi directivity. Furthermore, a 1 × 10 slotted SIW travelling wave antenna array has been designed, fabricated, and measured. The performance of the proposed antenna array versus the last reported antenna was evaluated and the proposed antenna array performance is superior to that of the others. Moreover, the measurements of the proposed array have a good agreement with the simulation results in which, 35%, 13% RLBW, and ARBW, respectively, have been achieved. The directivity of the proposed antenna array is 14 dBi.

1 | INTRODUCTION

Recently, a lot of research efforts have been carried out in the area of circularly polarized (CP) antennas, especially in satellite applications. CP antennas are preferred due to many reasons such as, there is no restriction in the rotation of the antenna and it works on reducing the losses of the Faraday rotation, and its ability to reject the multi-path echoes [1]. In TV satellite reception application, a lot of research has been carried out to overcome the conventional reflector antenna’s disadvantages such as its bulky structure and heavy weight. In [2], a microstrip truncated corner square patch with a U-shaped slot has been introduced, using three-layers feeding network, a 16 × 16 array has been constructed in order to enhance axial ratio bandwidth (ARBW) and return loss bandwidth (RLBW), yet it suffers from a large profile and complex feeding. A low profile, lightweight antenna array has been designed in [3], by using a 16 × 16 antenna element. However, it has a narrow ARBW, as well as, a complex feeding network. In [4], using a 16 × 1 spiral antenna array, a good ARBW and RLBW have been achieved, and the feeding network is complex. An elliptical array has been reported in [5], using an appropriate profile, wide ARBW and RLBW have been attained, however, the feeding network is based on a multi-layer structure. For millimeter-wave applications, a single layer dual CP series-fed antenna based on sequential rotation has been presented in [6]. The curved transmission line is adopted to be radiated elements, which made the design more compact but only 6.57% ARBW has been achieved.

Due to their superior characteristics, slotted waveguide antennas have attracted a lot of researchers. These structures radiate the incident power to the free space through slots in the rectangular or circular waveguide wall. According to the shape of the wave propagating inside the waveguide, slotted waveguide antennas can be divided into two main categories, standing wave slotted antennas and travelling wave slotted antennas [7, 8]. A standing wave slotted antenna is characterised by a short wall at its end. The slots are allocated in a position to radiate the standing wave from the short wall, so most of the incident power will be radiated, consequently, high efficiency will be obtained. However, it suffers from narrow frequency bandwidth [9, 10]. The travelling wave antenna slots are allocated to radiate the travelling power, each element radiates a fraction of the incident power and the remaining power will be absorbed by a termination at the end of the waveguide. A very low amount of the incident power will back onto the input port, consequently, wide operating bandwidth will be obtained [11]. So, a carefully designed procedure must
be followed to force most of the power to radiate by the slots. Although the waveguide antennas have very good properties, they suffer from factors such as large profile, heavyweight, and high cost.

Substrate integrated waveguide (SIW) behaves the same way as that of the waveguide but it supports only the TE$_{10}$ modes, that is, because of the low substrate height. Further, the periodic vias prevent the surface current from flowing to the sidewalls. The SIW fabrication process is superior to that of the waveguide (WG) as it is based on printed circuit technology. Hence, accurate implementation with low cost, and intermediate power handling capabilities could be achieved by choosing a proper material. Furthermore, it has the ability to be integrated with other devices on a single board [12, 13]. In [14], a 16-element CP antenna array based on the slotted SIW travelling wave antenna has been presented. Each element consists of two pairs of rectangular slots perpendicular to each other in order to produce a CP field. Using Taylor distribution, a superior side lobe level (SLL) has been obtained, however, the operating bandwidth is narrow. Using the previous pairs of rectangular slots, Liu et al., introduced a leaky-wave antenna based on the corrugated substrate integrated waveguide (CSIW) [15]. The CSIW achieved 0.73 dB AR in boresight direction and 3.6% ARBW, however, the obtained ARBW is narrow. Using a two linear slotted SIW array with a 90° phase shift, a 94 GHz dual-polarized antenna array with low SLL has

**FIGURE 1** The proposed slotted substrate integrated waveguide antennas. (a) Two arm Archimedean antenna, (b) Single arm spiral antenna (monofilar), and (c) Four concentric circular loops

**FIGURE 2** Directivity comparison of the proposed slotted substrate integrated waveguide antennas. (a) directivity at $\phi = 0^\circ$, and (b) directivity at $\phi = 90^\circ$
been reported in [16]. However, it has an ARBW of 1%, by using two layers feeding structure increased the design complexity. In [17], two design examples for 45° linear as well as CP leaky-wave antennas, based on slow-wave SIW structure, have been presented. Using the CP antenna, an operating BW of 9.7% has been achieved. A directional coupler is needed, consequentially, more large size has been added to the total antenna size. In [18], a two layers CP antenna array based on SIW has been presented. The first layer contains 10 rectangular slots allocated using Taylor distribution to feed the second layer. The second layer consists of 10 pairs of loops, which had been loaded by two square patches on the opposite corners in order to produce circular polarization. Using this array, a SLL of −22 dB, further, −29 dB cross-polarization ratio has been achieved. But it has a narrow RLWB as well as ARBW of 3.5% and 2.8%, respectively. In X-band, eight rectangular slots fed by a three-layer SIW corporate feeding network has been introduced in [19]. The proposed array provides a right-hand circular polarized (RHCP) pattern with low SLL because the proposed feeding network eliminates the undesirable surface current of the coaxial connector transition. Although the feeding network provides a superior characteristic, a large profile is introduced along with a narrow ARBW of about 1%.

There are limitations in the operating bandwidth of the slotted waveguide arrays because of the high Q-factor of the slot self admittance, further, the rapid rotation of the phase along the waveguide because of the series-fed nature [20]. A lot of research has been conducted in order to enhance the BW such as [9] which illustrated that the conventional rectangular waveguide (RWG) BW does not exceed 10%. In order to enhance the operating BW, a sub-array technique has been used but it made the design suffer from a large profile. By using SIW, utilising fractal-shaped slots instead of the conventional slot improves the array RLBW to 12.5%, which is about 2.5 times the conventional one [21]. 10 elements SIW standing wave antenna array which is fed by differential feeding has been illustrated in [22], where the large resonating standing wave antenna is electrically divided into wideband

**FIGURE 3** Comparison of the three proposed substrate integrated waveguide antennas. (a) return loss, (b) axial ratio bandwidth, and (c) peak realized gain.
subarrays to obtain a RLBW of 7.8%. In [23], extra slots have been illustrated instead of a single radiator in order to improve the impedance BW, which contributed to achieve 10.3% RLBW.

The novel aspects of the present article are as follows: (1) provide three new slotted SIW antenna configuration which are characterised by a wide operating frequency and a CP behaviour; (2) design, fabrication, and measurement of 1 × 10 travelling wave slotted SIW antenna array; (3) provide controlled beam steering which enables to reduce the ordinary mechanical steering cost; and (4) simplicity, cost and the low design profile where the SIW technique has been used.

The article is divided into four main sections as follows: In Section 2, three novel different left-hand circular polarized (LHCP) slotted SIW antennas are presented. The performance of the proposed elements has been investigated. In addition to that, a parametric study has been performed on the two arms Archimedean antenna for which the performance is superior to that of the other proposed elements. In Section 3, a travelling wave spiral slotted SIW antenna array is designed, fabricated, and measured. The performance of the proposed array is examined versus other arrays in Section 4. Finally, the work is concluded in Section 5.

2 | SLOTTED SPIRAL ANTENNA ELEMENT DESIGN

The spiral antenna has been classified as a frequency-independent antenna, that is, it has a constant input impedance along with a wide frequency bandwidth [1]. The band theory explains the two arms Archimedean spiral antenna working principle and its radiation mechanism [24]. The input power of one arm with a certain phase shift, at a
certain point of the spiral circumference, becomes in-phase to the other arm, and construction in the radiation pattern will occur. For a one-arm spiral antenna, also known as a monofilar, a circular polarization with a tilted beam is realized by superposing the fields from two active regions [25]. The slotted spiral antenna has a radiation mechanism similar to that of the monofilar spiral, where the spiral slot cuts the travelling wave, consequently, two orthogonal fields are superimposed to each other to generate a circular polarization with a tilted beam.

The Archimedean spiral antenna consists of two arms, each arm have radius \( R_1 \) and \( R_2 \), and the relation between them is given by [26].

\[
R_2 = g_r \theta_w + R_1 \quad (1)
\]

where \( g_r \) is the growth rate, \( \theta_w \) is the winding angle, \( R_1 \) is the minimum radius of the spiral, and \( R_2 \) is the maximum radius. The minimum radius determines the higher operating frequency whereas the lower radius determines the upper-frequency [27].

To produce a CP field, two equal and orthogonal components must exist [1]. The transverse and longitudinal magnetic fields of the dominant mode (TE_{10}) in a RWG are given by [28].

\[
H_x = H_o \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2 \sin \left(\frac{\pi x}{a}\right)} \quad (2)
\]

\[
H_z = -jH_o \frac{\lambda}{2a} \cos \left(\frac{\pi x}{a}\right) \quad (3)
\]

where \( H_x \) is the transverse magnetic-field intensity, \( H_z \) is the longitudinal magnetic-field intensity, \( H_o \) is a constant, \( \lambda \) is the free-space wavelength, \( a \) is the waveguide width, and \( x \) is

**FIGURE 5** Simulation results of the proposed two arm spiral antenna. (a), (b), and (c) illustrate the effect of \( Y_{\text{shift}} \), \( P_{\text{slot}} \), and \( R_1 \) on the axial ratio bandwidth, respectively. \( R_1 \), spiral minimum radius; \( P_{\text{slot}} \), distance between the spiral arms; \( Y_{\text{shift}} \), offset from the centre of substrate integrated waveguide.
the transverse coordinate. Two values of $x$ could be found for which $|H_x| = |H_y|$ and are given by

$$x = \frac{a}{\pi} \cot^{-1} \left( \sqrt[4]{\frac{2a^2}{\lambda}} - 1 \right)$$

Equation (4)

According to Equations (1–4), three different spiral-shaped slot antennas have been designed. The first design contains two arms each with two turns Archimedean spiral SIW slot while the second one is a slotted monofilar spiral SIW antenna with four turns. The third design consists of four concentric circular loops. The three proposed slotted SIW antennas are as shown in Figure 1.

An investigation has been done to distinguish the differences between the three proposed antenna elements and the results are as shown in Figures 2 and 3. From these figures, it can be seen that the two arm spiral antenna performance is superior to that of both the monofilar and the four concentric
TABLE 1 The optimised parameters of the two arms spiral antenna

| Parameter | Description                  | Value (mm) |
|-----------|------------------------------|------------|
| W_sub     | Substrate width              | 23         |
| L_sub     | Substrate length             | 46.6       |
| W_feed    | Feed width                   | 3.2        |
| L_feed    | Feed length                  | 3.8        |
| W_transition | Transition width             | 4.5        |
| L_transition | Transition length           | 3.8        |
| D_via     | Via diameter                 | 1.4        |
| p         | Via distance                 | 1.7        |
| a_r       | SIW width                    | 12.5       |
| R_1       | Spiral minimum radius       | 1.6        |
| R_2       | Spiral maximum radius       | 4.5        |
| P_slot    | Distance between the spiral | 1.5        |
| W_slot    | Width of spiral arms         | 0.3        |
| Y_shift   | Offset from the centre of SIW| 1.9        |
| \(\theta\) | Rotation                    | 50°        |
| \(d\)    | SIW edge to spiral centre    | 15         |

Abbreviation: SIW, substrate integrated waveguide.

circular loops antenna. The two-arm spiral antenna has the widest operating frequency BW as well as ARBW at the boresight direction.

A comprehensive parametric study has been conducted on the two arm spiral antenna in order to recognise the antenna characteristics versus its parameters. The spiral minimum radius, \(R_1\), offset from the centre of SIW, \(Y_{\text{shift}}\) and the distance between the spiral arms, \(P_{\text{slot}}\) have been used for the parametric study and the results are as illustrated in Figures 4 and 5. It can be seen from Figure 4 that \(Y_{\text{shift}}\), \(P_{\text{slot}}\) and \(R_1\), have a small effect on the antenna return loss. On the other hand, there is a notable effect on the ARBW as it can be seen from Figure 5. Figure 6 illustrates the surface current distribution on the two arms spiral antenna, where it can be noted that the surface current rotates in a clockwise direction, consequently, leading to an LHCP behaviour. The final parameters of the design are given in Table 1.

Figure 7 illustrates the fabricated two-arm Archimedean antenna, while Figure 8 presents the comparison between the measurement and the simulation results. It can be seen that a good agreement, between the measurements as well as the simulations, has been achieved. It can be seen from Figure 8 (a) and (b) that the two arm spiral antenna RLdB is about 18.3% from 11 to 13.2 GHz, and 11.6% boresight ARBW. Furthermore, it achieved a co-to cross-polarization ratio better than −10 dB at the tilting angle direction.

3 | SLOTTED SPIRAL ANTENNA ARRAY

Travelling-wave arrays are characterised by having a higher frequency-bandwidth than that of the standing-wave arrays. For travelling wave arrays, it must be noted that if \(d > \lambda_g/2\), the beam is moved towards the load, on the other hand, it is moved towards the feed if \(d < \lambda_g/2\). According to the following equation [7].

\[
\sin(\theta_d) = \frac{\lambda}{\lambda_g} - \frac{(N - 0.5)\lambda}{d} \quad N = 0, \pm 1, \pm 2, \ldots \tag{5}
\]

\[
\lambda_g = \frac{\lambda}{\sqrt{\epsilon_r}} \tag{6}
\]

where \(\theta_d\) is the angle of beam direction, \(\lambda_g\) is the guided wavelength, \(N\) refers to the grating lobes number, \(d\) is the inter-element spacing and \(\epsilon_r\) is the relative electric permittivity. Each element radiates part of the incident power, delivering the remaining power to the next element, and so on. In order to achieve 100% efficiency, all the incident power must be radiated; yet, part of the incident power absorbed by the termination at the end of the array as follows [29].

\[
P_{\text{total}} = P_{\text{radiated}} + P_{\text{load}} = \sum_{i=1}^{M} P_i + P_{\text{load}} \tag{7}
\]

where \(P_{\text{total}}\) is the total incident power, \(P_{\text{radiated}}\) is the total radiated power from the slots, \(P_{\text{load}}\) is the power going to the load and \(M\) is the number of elements.

Using the same parameters presented in Table 1, based on the proposed two arms spiral antenna, a 1 × 10 array has been designed and fabricated as shown in Figure 9. According to Equation (5), the inter-element spacing, \(d\), has been chosen to be 0.62λ to produce a 7° tilted beam at 12.3 GHz as presented in Figure 10.

Figure 11 represents the far-field simulation results of the 1 × 10 array. From these figures, it can be noted that the array can radiate left-hand CP pattern with stable directivity from 11.2 to 12.8 GHz (BW ≈ 13%) over the tilted beam from −20° to +25°. Further, more than 20 dB co-to cross-polarized ratio has been achieved. However, using low-efficiency material (FR-4) affects the efficiency as shown in Figure 11(b).

The measurements of the proposed 1 × 10 array are illustrated in Figure 12. Figures 12a,b represent the comparison between measured and simulated scattering parameters and boresight AR, respectively. It could be seen that the array has >27% RLBW and <20 dB insertion loss, consequently, very low power will be absorbed by the
load. Moreover, it has 6.57% ARBW in the boresight direction.

Figure 13a represents the measured pattern and it should be noted that a good agreement between simulation and measurement can be observed. At 12.2 GHz, a LHCP and RHCP at $\phi = 0^\circ$, $90^\circ$ are illustrated in Figure 13b,c, respectively. It should be mentioned that $-20$ dB cross-polarization discrimination ratio has been achieved, moreover, SLL is less than $-15$ dB. Furthermore, at $\phi = 90^\circ$ the LHCP to RHCP ratio less than $-10$ dB and the SLL did not exceed $-10$ dB.

**FIGURE 8** Comparison between measurements and simulation results of the two arm spiral antenna. (a) Return loss result, (b) Boresight axial ratio bandwidth, (c) and (d) The realized gain at $\phi = 0^\circ$ and $\phi = 90^\circ$, respectively: LHCP, left-hand circular polarized; RHCP, right-hand circular polarized

**FIGURE 9** The fabricated $1\times10$ antenna array

**FIGURE 10** Directivity at 12.3 GHz for different inter element spacing
FIGURE 11  Simulated far field results of the 1×10 antenna array. (a) The directivity at different frequencies, (b) the peak realized gain and the radiation efficiency, (c) the co- and cross-polarized directivity at 12.3 GHz for (ϕ = 0°, 90°), and (d) the axial ratio at different frequencies. LHCP, left-hand circular polarized; RHCP, right-hand circular polarized.

FIGURE 12  Measurement results of the 1×10 antenna array. (a) Antenna array scattering parameters, and (b) the antenna array axial ratio.
All the proposed designs have been fabricated using FR-4 material with $\epsilon_r = 4.5$, tangent loss ($\delta$) = 0.02 and substrate height $h = 1.6$ mm. The measurements of the scattering parameters have been carried out using the NV991-A vector network analyser. The field measurements are performed using Star Lab. Table 2 concludes the paperwork designs where one is for single spiral two-arm spiral antenna element (Figure 1a), two is for the monofilar (Figure 1(b)), three is for the four concentric circular loops antenna (Figure 1c), and four is for $1 \times 10$ two arms slotted spiral array (Figure 9). S is for simulation result while M is for measurement result.

A comparison of the proposed array to the state-of-the-art CP antenna arrays, as well as the last reported techniques to broaden the operating bandwidth of the conventional slotted waveguide, is summarised in Table 3. First, the proposed design has been compared with linear polarized antenna arrays, where advanced techniques have been used to broaden the RLBW [9, 21–23]. It has been found that the proposed design RLBW is superior to that of the linear polarized antennas. Moreover, it has the smallest profile among them. Secondly, comparison of the proposed design and CP antenna arrays [2–6] was carried out. It
has been noticed that the proposed design structure is the simplest, in addition to that, it has the widest RLBW and ARBW. Finally, on investigating the SIW slotted waveguide antenna [14–19], it is obviously clear that the proposed design has the widest RLBW and ARBW. Furthermore, it is based on a single layer structure which inherently reduces the proposed design profile.

### TABLE 2 Conclusion results of this work

| Type | RLBW (%) | ARBW (%) | Gain (%) | Size $\times \lambda_o$ |
|------|----------|----------|----------|-------------------|
| S    | M        | S        | M        |                     |
| 1    | 28.3     | 11.67    | -2       | 0.6 $\times$ 0.8 $\times$ 0.06 |
| 2    | 21.67    | 11.6     | -4       | 0.6 $\times$ 0.8 $\times$ 0.06 |
| 3    | 21.67    | 11.6     | -4       | 0.6 $\times$ 0.8 $\times$ 0.06 |
| 4    | 27       | 6.67     | 8.5      | 7.2 $\times$ 0.8 $\times$ 0.06 |

Abbreviations: ARBW, axial ratio bandwidth; M, measurement result; RLBW, return loss bandwidth; S, simulation result.

### TABLE 3 Design comparisons with other reported designs array

| Ref. | Polarisations | Profile ($\lambda_o$) | RLBW (%) | ARBW (%) | Layers |
|------|---------------|-----------------------|----------|----------|--------|
| [9]  | Linear        | 1.4                   | 15       | -        | Single |
| [21] | Linear        | 0.5                   | 12.5     | -        | Single |
| [22] | Linear        | 0.86                  | 7.8      | -        | Single |
| [23] | Linear        | 0.34                  | 10.3     | -        | Single |
| [2]  | Circular      | 1.12                  | 10.5     | 12       | Three  |
| [3]  | Circular      | 0.05                  | 6.16     | 8.2      | Three  |
| [4]  | Circular      | 0.26                  | 8.2      | 8.2      | Two    |
| [5]  | Circular      | 0.26                  | 22       | 13       | Three  |
| [6]  | Circular      | 0.05                  | 6.6      | 6.57     | Single |
| [14] | Circular      | 0.08                  | 12.5     | 2.5      | Single |
| [15] | Circular      | 0.08                  | 4.8      | 3.6      | Single |
| [16] | Circular      | 0.3                   | 10       | 1        | Two    |
| [17] | Circular      | 0.02                  | 14.5     | 9.7      | Single |
| [18] | Circular      | 0.067                 | 2.8      | 1.6      | Two    |
| [19] | Circular      | 0.08                  | 12.2     | 1        | Three  |
| Proposed design | circular | 0.06               | 35       | 13       | Single |

Abbreviations: ARBW, axial ratio bandwidth; RLBW, return loss bandwidth.

has been noticed that the proposed design structure is the simplest, in addition to that, it has the widest RLBW and ARBW. Finally, on investigating the SIW slotted waveguide antenna [14–19], it is obviously clear that the proposed design has the widest RLBW and ARBW. Furthermore, it is based on a single layer structure which inherently reduces the proposed design profile.

### 5 CONCLUSION

Novel three different slotted SIW antenna elements have been proposed, namely, two-arm archimedean spiral, monofilar spiral, and four concentrated loops. The proposed design has superior characteristics over the conventional slotted antenna array in terms of the operating the bandwidth and the ARBW. A comparison among the three proposed antenna elements has been carried out. The two arms slot antenna performance is superior to that of the monofilar spiral as well as the four concentrated loops. A $1 \times 10$ slotted SIW array antenna, based on the two arms slotted spiral element, has been designed, simulated, and fabricated with a wide ARBW and RLBW with low profile. Furthermore, the proposed antenna array has low SLL and high co-to cross-polarized ratio. Finally, it can be concluded that the spiral-shaped slot antenna enables to broaden the operating bandwidth. In addition to that, using the SIW made the design more simple and suitable to be integrated with other systems.

### ORCID

Amgad A. Salama [https://orcid.org/0000-0001-6951-1288](https://orcid.org/0000-0001-6951-1288)

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