A Circularly Polarized Circular Antenna Array for Satellite TV Reception

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***Abstract* —This paper proposes a novel design of a wideband compact circularly polarized circular antenna array for satellite TV reception. The circular array is based on a wideband circularly polarized spiral antenna element which has excellent impedance matching (VSWR ≤ 1.5) and axial ratio bandwidths for the satellite-to-ground downlink at Ku-band from 11.7-12.7 GHz. A 16-element circular sub-array is presented with a fixed 23° electronically steered beam upwards which is appropriate for Astra satellite communications in the UK. Furthermore, circular sub-arrays with different numbers of elements (8, 16, 24, 32 and, 40) are also studied. It is shown that the circular antenna array is particularly suitable for satellite TV reception while being vertically mounted on a wall because of its low profile, broadband and electronically steered beam.**

***Keywords* — Circular array, circularly-polarized antenna, electronic steering, satellite communications, spiral antenna**

I. Introduction

Satellite communications are still developing rapidly in both civilian and military applications. It provides many services as navigation, earth imaging, and satellite TV. Generally, dish antennas are used as direct-to-home (DTH) receiving antennas to receive circularly polarized (CP) TV waves from the satellite. Although a dish antenna can have a wide bandwidth (BW), it shows drawbacks as being bulky, heavy, and highly affected by weather conditions fluctuation [1]. It also needs to be mechanically tilted upwards and aligned to achieve a line-of-sight (LOS) communication with the satellite (typically at 23° for Astra satellite in the UK [2]). So, a dish antenna has been widely replaced by planar antenna arrays. Achieving a wideband CP antenna array is a challenging task. Many attempts have been done in the literature using microstrip patches [3], magneto-electric dipoles [4] and helical antennas [5] but the arrays size and thickness are not small enough. The antenna size has been improved in [6] with a low profile at the expense of the antenna impedance BW (11.84-12.42 GHz) and axial ratio (AR) BW (12-12.14 GHz). Later on, in [7], the AR BW has been improved using sequentially rotating excitation method (11.55-12.25 GHz). Although these reported antenna arrays have flat profiles, they cannot be vertically mounted because of their boresight radiation patterns. So, mechanical upward tilting and alignment are still needed.

In this paper, a new Ku-band spiral antenna design is proposed achieving a wide impedance matching BW (11.7-12.7 GHz) with industrial standard (VSWR ≤ 1.5) and AR BW of (11.7-12.7 GHz). The design enjoys stable radiation patterns and high polarization purity (PP) with a low profile and a compact size.

The design is amended to form a flat circular antenna array with a fixed upward electronically steered beam at 23°. This allows the array to achieve a LOS communication with the satellite while being mounted vertically on a wall.

The paper is organized as follows: Section II discusses the antenna structure and the working principles. Section III illustrates the simulated results. Section IV presents the array structure and the paper is concluded in Section V

II. Spiral Antenna Element

A. Antenna Structure

Fig. 1 shows the exploded geometry of the proposed design in addition to the front and rear views while Table 1 presents the dimensional parameters.

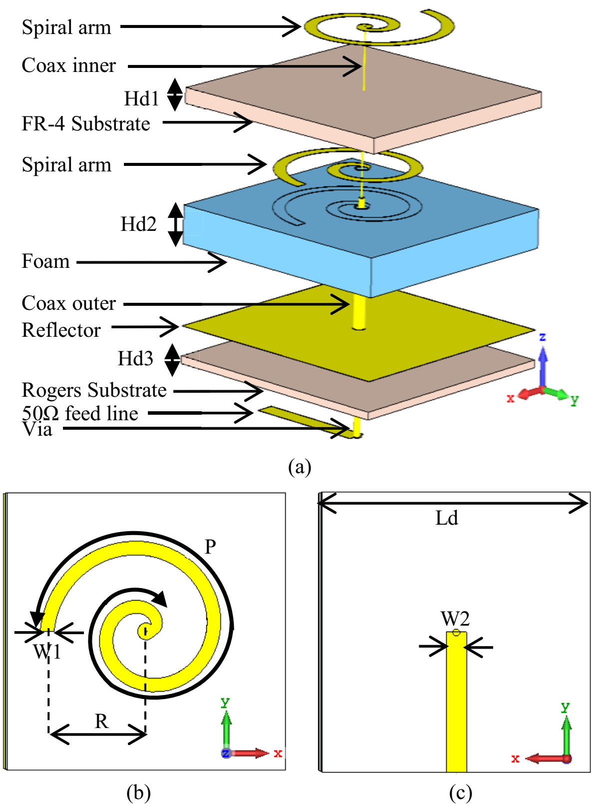

Fig. 1. The proposed antenna (a) exploded geometry (b) front view (c) rear view

Table 1. Parameters of the Proposed Antenna

Parameter	Value (mm)
P	38
R	10.7
W1	1.5
W2	2.3
Ld	30

Generally, the antenna consists of three stacked layers. The first layer (antenna layer) is an FR-4 substrate with thickness Hd1 = 1.6 mm, relative permittivity ε_{r1} = 4.3 and tangential loss of 0.025. Two identical spiral arms are printed on opposite sides of the FR-4 substrate to work as the radiating antenna. One of the spiral arms has a relative rotating angle of 180° around the Z-axis with respect to the other to provide circular polarization. The second layer is a foam layer with thickness Hd2 = 4 mm and relative permittivity $\varepsilon_{r2} \approx 1$. The third layer (feeding network layer) is a Rogers RT5880 substrate with thickness Hd3 = 0.8 mm, relative permittivity ε_{r3} = 2.2 and tangential loss of 0.0009. A metallic reflector is printed on one side of the Rogers substrate while a 50 Ω feeding line is printed on the other side. The function of the metallic reflector is to provide a unidirectional radiation at the Z-axis. A 50 Ω coaxial cable is used to connect the feeding network layer to the antenna layer intersecting the foam layer. The upper spiral arm is connected to the inner of the coaxial cable and hence to the feeding line through a via. The lower spiral arm is connected to the outer of the coaxial cable and hence to the metallic reflector. For practical implementation, a hole should be drilled at the centre of the lower spiral arm to avoid contacting it to the coaxial inner.

B. Antenna Working Principles

To understand the working principles of the proposed antenna, two reference antennas (antenna REF1 and antenna REF2) are used as shown in Fig. 2. Initially, the spiral antenna total length (*2P*) is selected to be $0.5\lambda_0$ (antenna REF1) (where λ_0 is the free space wavelength at the central frequency of the desired band 12.2 GHz). A good impedance matching is observed in this case across the entire BW but the AR is not suitable for circular polarization performance. To improve the AR, two approaches may be used. The first approach is to increase the number of turns of the spiral arm while keeping its length P constant. This can be done by rolling the spiral around Z-axis with a smaller pitch (winding) angle and a thinner spiral width *W1*. Unfortunately, when *W1* decreases, the impedance matching worsens. The second approach is to increase the number of turns by increasing the spiral arm length *P*. To keep good impedance matching, the spiral antenna total length *2P* should maintain equal to odd multiplying of $0.5\lambda_0$ [8]. This approach is used in antenna REF2. In this case, the antenna total length 2P equals to $1.5\lambda_0$. It is observed that the AR is improved but still not sufficient. Further improvement can be achieved in the proposed design by adjusting the antenna total length *2P* to $2.5\lambda_0$. The foam layer thickness is initially selected to provide a separation between the antenna layer and the metallic reflector of $0.25\lambda_0$.

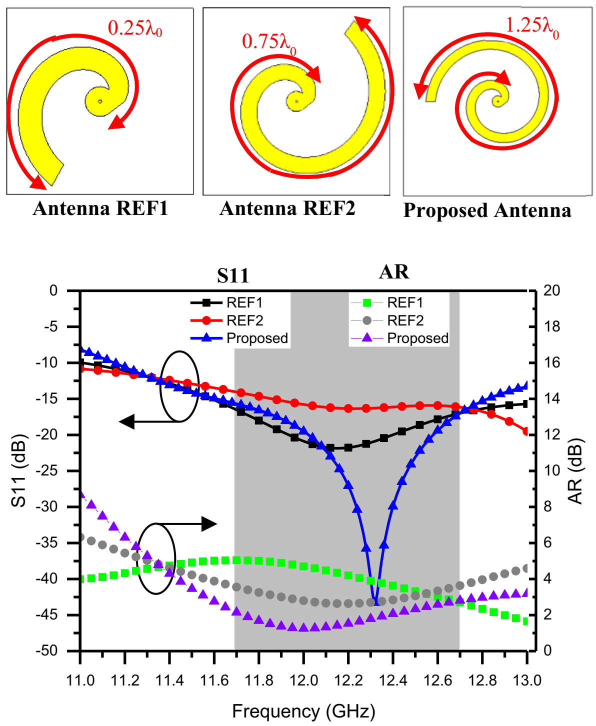

Fig. 2. References and the proposed antenna designs

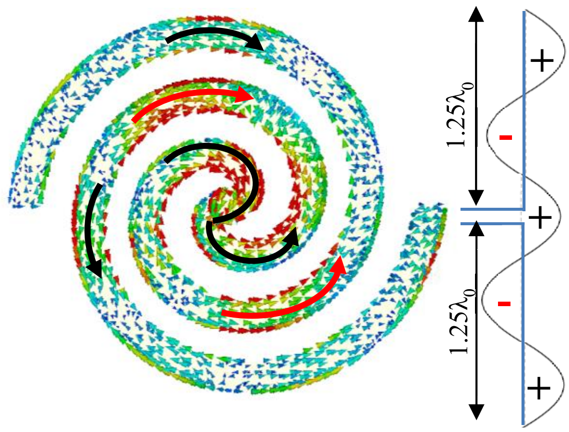

Fig. 3. Current distributions at the central frequency

Fig. 3 presents the current distributions along the spiral antenna at the central frequency. It is noticed that the spiral antenna has five current peaks as a conventional 2.5-wavelength dipole. Positive and negative current peaks are represented in Fig. 3 as black and red arrows respectively.

III. Simulation and Results

The proposed antenna has been designed and simulated using CST MW Studio. Fig. 4 illustrates the AR, VSWR, realized gain and, total efficiency of the proposed design. It is clear that the VSWR is less than 1.5 (industrial standard) and the AR is less than 3dB for the frequency band 11.7-12.7 GHz. The design has a realized gain of 6.25±0.4 dBic and a total efficiency of 85% across the desired frequency band.

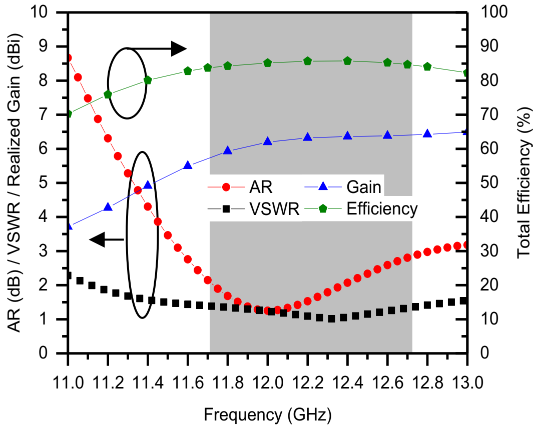

Fig. 4. VSWR, AR, the realized gain and, the total efficiency of the proposed antenna

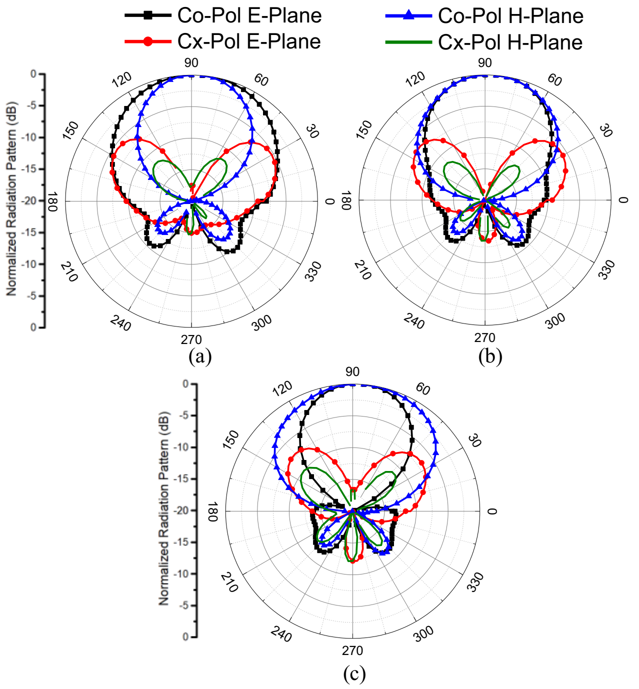

Fig. 5. Co- and cross-polarized radiation patterns in E-plane and H-plane at (a) 11.7 GHz (b) 12.2 GHz (c) 12.7 GHz.

Table 2. HPBW and PP of The Proposed Antenna

Frequency		**11.7 GHz**	**12.2 GHz**	**12.7 GHz**
HPBW (º)	E-Plane	130	70	60
	H-Plane	60	80	95
PP (dB)		17.5	20	16.6

The co- and cross-polarized radiation patterns are shown in Fig. 5 at the start, central and end frequencies at two perpendicular planes: E-plane (XZ-plane) and H-plane (YZ-plane). The half power beam width (HPBW) and the PP values are given in Table 2 at each simulated case. Table 3 compares the proposed design to the state-of-the-art Ku-band circularly polarized antenna in the literature. The proposed antenna has a wider BW in terms of both the impedance matching (with VSWR ≤ 1.5) and AR with a smaller size.

Table. 3. Comparison of the Proposed Antenna to the State-of-the-Art Ku-Band Circular Polarized Antenna

Ref		**[7]**	**Proposed Antenna**
Fractional BW (%)	Impedance Matching	8.2 (VSWR ≤ 2)	8.2 (VSWR ≤ 1.5)
	AR	6.16	8.2
Size (mm^3)		40×40×1.4	30×30×6.5

IV. Array Structure

To improve the antenna received SNR, DTH antennas should provide a high gain. So, they are likely to be arranged into arrays. Maintaining the AR below 3 dB for an array is a challenge. So, in this section, unlike the arrays introduced in the literature, a circular polarized circular antenna array is proposed. Detailed illustrations of the circular array structure and results are introduced as follows.

A. Circular Sub-array Structure and Results

In this section, 16 equal-spaced elements are arranged on the circumference of a circle with a 100 mm diameter ($4\lambda_0$) to form a circular sub-array. The maximum dimensions of the sub-array are 130×130×6.5 (mm^3). For boresight radiation, all the elements are fed simultaneously with signals of equal magnitudes and phases. The radiation pattern at the central frequency and the AR are shown in Fig. 6. The maximum gain is 18.4 dBic at boresight with front-to-back lobe ratio (FBR) and PP better than 27 dB and 22.5 dB respectively. The AR is less than 3dB across the entire BW. By adjusting the feeding signal phases, the beam can be steered by 23° upward. The up-tilted beam pattern and the AR at the main lobe direction are presented in Fig. 7. It is clear that the AR is less than 3 dB along the direction of the main lobe throughout the BW.

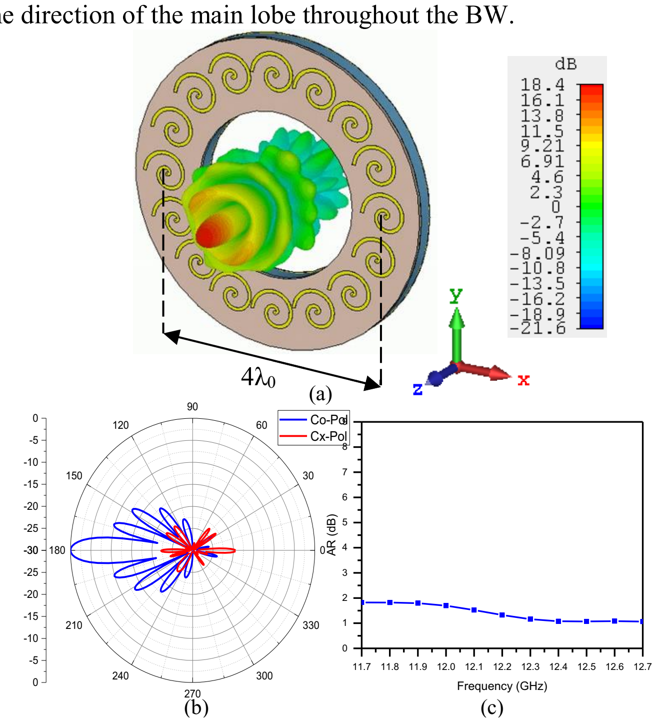

Fig. 6. 16-element circular sub-array (a) 3D radiation pattern (b) 2D radiation pattern (c) axial ratio (boresight radiation).

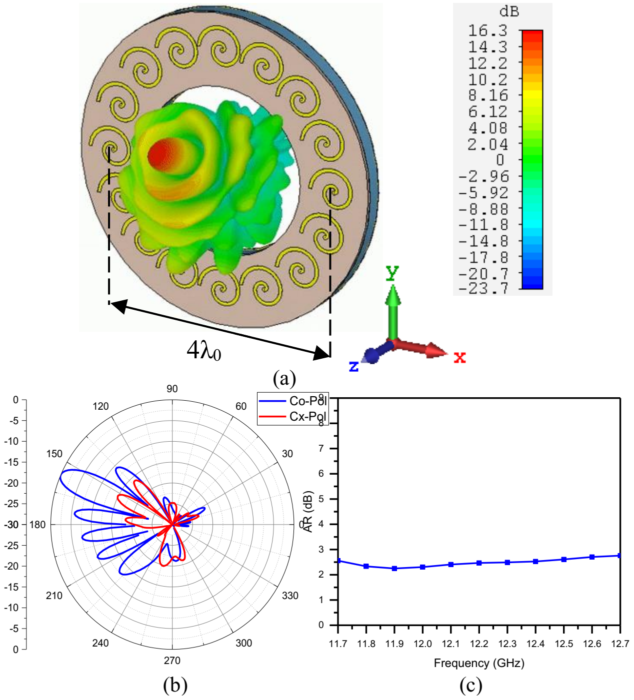

Fig. 7. 16-element circular sub-array (a) 3D radiation pattern (b) 2D radiation pattern (c) axial ratio (steered beam)

B. *Circular Array Structure and Results*

Following the steps illustrated in the previous section, five concentric circular sub-arrays with different numbers of elements and diameters can be constructed to form a higher gain circular antenna array as shown in Fig. 8. Each sub-array is designed individually with an electronically steered beam by 23° upwards. The number of elements in each sub-array (N_i) and its diameter are presented in Fig. 8 where i is the order of the sub-array from 1-5 ranging from inside to outside. The maximum dimensions of the array are 310×310×6.5 (mm^3).

Fig. 9 shows the 3D radiation pattern of the proposed circular antenna array with an electronically steered beam by 23° upwards and maximum gain of 24.4 dBic.

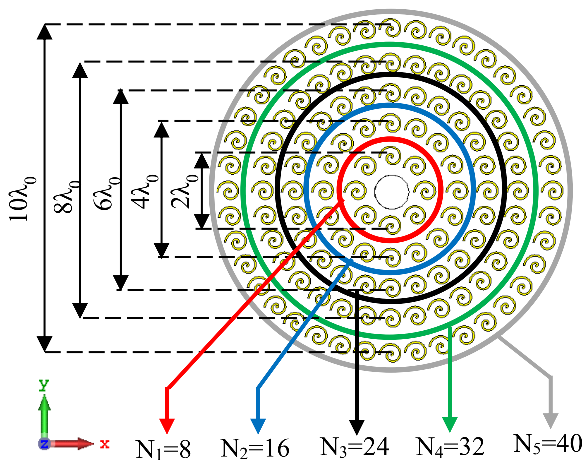

Fig. 8. Structure of the circular polarized circular antenna array.

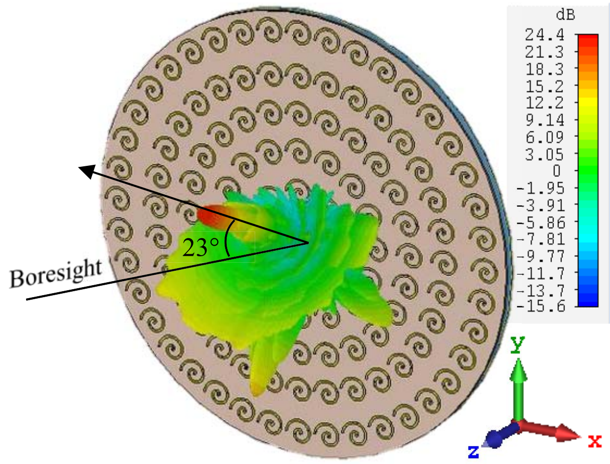

Fig. 9. The 3D radiation pattern of the proposed circular polarized circular antenna array with the steered beam.

V. Conclusions

A circularly polarized circular antenna array has been designed with a fixed vertical electronically steered beam for the satellite TV signal reception. The array covers the frequency band from 11.7 GHz to12.7 GHz in terms of the impedance matching (with industrial standard VSWR ≤ 1.5) and AR. The low profile array with the steered beam allows the array to be vertically mounted on a wall for satellite communications, such as a LOS communication with Astra satellite in the UK

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