Single-fed circularly polarized dielectric resonator antenna using a uniaxial anisotropic material

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SINGLE-FED CIRCULARLY POLARIZED DIELECTRIC RESONATOR ANTENNA USING A UNIAXIAL ANISOTROPIC MATERIAL

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Abstract

A Dielectric Resonator Antenna operating in circular polarization is presented. The proposed antenna is formed by a uniaxial anisotropic dielectric and a ground plane. The optimization of the permittivity tensor and antenna dimensions is performed both theoretically and numerically using an Eigen mode analysis in Ansys HFSS. A good agreement is obtained for the resonant frequencies and quality factors of the different modes. The uniaxial anisotropic DRA radiates two degenerate orthogonal modes, TE_{111}^{x} and TE_{111}^{y}, with equal amplitudes and 90° phase difference in order to achieve circular polarization. An impedance bandwidth of 9.8% is accomplished and a broadside radiation pattern with left-hand circular polarization (LHCP) is achieved in simulation. Furthermore, an Axial Ratio (AR) of 0.06 dB at 2.45 GHz and a 3-dB AR bandwidth of 2.04% are obtained. The maximum simulated directivity is equal to 6.56 dBi.

1 Introduction

Recent advances in Additive Manufacturing (AM) pave the way for new antennas [1]. AM progress allows new capabilities in antenna designs like anisotropic or heterogeneous material manufacturing by controlling the effective permittivity of the dielectric medium. Such properties are particularly interesting for designing new dielectric resonator antennas (DRAs) [2].

DRAs offer a great flexibility in the choice of their frequency band, bandwidth, and radiation patterns due to the numerous degrees of freedom [3]. The number of degrees of freedom depends on the antenna shape, i.e. cylindrical [4], [5] or rectangular configuration [6], [7], [8]. DRAs can also exhibit good performance in circular polarization (CP). That is useful for moderns satellite communications and navigation to mitigate the ionosphere multipath fading and maximize the polarization efficiency [9], [10]. Generally, CP is achieved by using complex feed structures or incorporating symmetric perturbation elements which modify the antenna shape. In this paper, a single-fed DRA using a uniaxial anisotropic dielectric is proposed to obtain CP, maintaining its square dimensions.

In the literature, anisotropic materials mainly have been proposed to achieve CP for microstrip antenna applications. In [11], a dual frequency linear polarization microstrip antenna has been performed. The antenna is composed of a metallic anisotropic Complementary Split Ring Resonator (CSRR) with two concentric slots rings and small gaps. The gaps are used to create a perturbation, allowing the antenna operates in CP. In [10], a CP antenna formed by a metallic anisotropic conductor of parallel thin metal strips has been developed. The wire-mesh conductor is optimized to design a miniaturized CP antenna and its performance is compared with conventional corner-truncated square microstrip antenna.

However, circularly polarized DRAs using anisotropic dielectric materials have not been proposed in the literature. The related DRA designs that have been proposed use the anisotropic properties of dielectric materials to improve the directivity and control the resonant frequency of DRA antennas. For example, in [12], a linearly polarized DRA formed by an anisotropic layered medium with Degenerate Band Edge (DBE) properties has been developed. By using an anisotropic medium alternating barium titanate and aluminium, the coupling of TM_{011}^{y} and TE_{101}^{y} modes is altered for controlling the resonant frequency. In addition, a uniaxial anisotropic DRA has been proposed in [12] for enhancing the boresight directivity. The directivity improvement is based on the higher mode excitation by using an anisotropic dielectric. In [13], a uniaxial anisotropic DRA for operating at 3.5 GHz WIMAX band with linear polarization has been designed. The anisotropic material is employed for improving the directivity and bandwidth of the DRA operating at the fundamental TE_{111}^{y} radiating mode.

In this paper, we want to show how a uniaxial anisotropic material can provide a new degree of freedom in DRA design. We propose a single-fed Circularly Polarized (CP) antenna based on a uniaxial Anisotropic Rectangular DRA (ARDRA). The goal is to design an ARDRA with two orthogonal modes, namely the TE_{111}^{y} and TE_{111}^{x} modes, to achieve CP. A methodology for determining the geometrical dimensions and permittivity tensor of the uniaxial ARDRA is proposed using an Eigen mode analysis in Ansys HFSS. Additionally, a parametric analysis is developed to optimize the antenna performance.

2. Methodology

In order to obtain CP with a single feed, a rectangular DRA can be excited by using a 50 **Ω** probe feed along the diagonal. In such a way, two degenerate modes are excited. These modes must be 90° out of phase and with same magnitude to produce CP. The resonant frequencies ($f_1<f_2$) of both degenerate modes can be expressed as [14]

$$f_1=f_o\left(1-\frac{1}{2Q_1}\right) \quad (1)$$

$$f_2=f_o\left(1+\frac{1}{2Q_2}\right) \quad (2)$$

where f_o is the center frequency, f_1 and Q_1 are the resonant frequency and quality factor of the TE_{111}^{x} mode, f_2 and Q_2 are the resonant frequency and quality factor of the TE_{111}^{y} mode.

CP is generally obtained by changing the antenna dimensions to match (1) and (2). Here, we proposed to optimize the permittivity tensor of an anisotropic DRA, while maintaining its square dimensions to design a DRA in CP.

The electric properties of the anisotropic medium depend on the direction of the applied electric field [15]. For our uniaxial anisotropic material, we consider the following permittivity tensor

$$\bar{\bar{\boldsymbol{\varepsilon}}} = \begin{bmatrix} \boldsymbol{\varepsilon}_{\perp} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\varepsilon}_{||} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{\varepsilon}_{||} \end{bmatrix}$$

The optical axis of the anisotropic medium is here placed along x-direction. The TE_{111}^{x} mode with f_1 and Q_1 remains as with an isotropic dielectric due to the symmetry in $\varepsilon_{||}$ along y and z directions. On the other hand, the TE_{111}^{y} mode with f_2 and Q_2 is altered by the anisotropic properties of the dielectric. Indeed, both permittivities $\varepsilon_{\perp}$ and $\varepsilon_{||}$ have an impact on the TE_{111}^{y} mode.

The methodology to design a uniaxial ARDRA operating in CP relies in the following steps:

1. The height of the antenna $h=\frac{d}{2}$, $\varepsilon_{||}$ and f_o are fixed as initial values of the algorithm.

2. Based on the initial values and the proposed permittivity tensor, the square dimensions of the DRA are computed by using the simplified isotropic Dielectric Waveguide Model (DWM) [3]. In this step, we analyze the TE_{111}^{x} mode that relies only on $\varepsilon_{||}$ to find a and b imposing $a=b$, so that f_1 and Q_1 allow to reach f_o using (1).

3. Eigen mode analysis is performed to determine $\varepsilon_{\perp}$ of the uniaxial material. To accomplish this requirement, an algorithm in MATLAB is implemented. The algorithm analyzes the data provided by HFSS, resonant frequency and quality factor of the TE_{111}^{y} mode, and selects the value for $\varepsilon_{\perp}$ which satisfy (2) to achieve CP.

3 Results

A uniaxial DRA in CP at the center frequency f_o=2.45 GHz is designed by using the methodology proposed in the previous section. The parameters d=23.3mm and $\varepsilon_{||}=20$ are defined as input values. As a result, the square dimension of the DRA is $a=b$=21.4 mm to satisfy (1).

Fig. 1 shows the design of the proposed antenna. It consists of our uniaxial anisotropic DR on a ground plane of size 0.65 λ_o × 0.65 λ_o. The coaxial probe has a diameter d_f=0.9 mm and height h_f=10.5 mm. The probe and finite size ground plane have a small impact on the frequency response of the DRA. Therefore, the square dimensions ($a=b$) of the designed DR using our methodology are slightly modified. The final dimensions are $a=b$=22.3 mm.

Finally, Eigen mode analysis of step 3 gives the permittivity tensor of the proposed ARDRA $\boldsymbol{\varepsilon}_{\perp}$=15 and $\varepsilon_{||}$=20. The electric properties obtained are: f_1=2.38 GHz, f_2=2.53 GHz, Q_1=17.56 and Q_2=15.53, that satisfy (1) and (2).

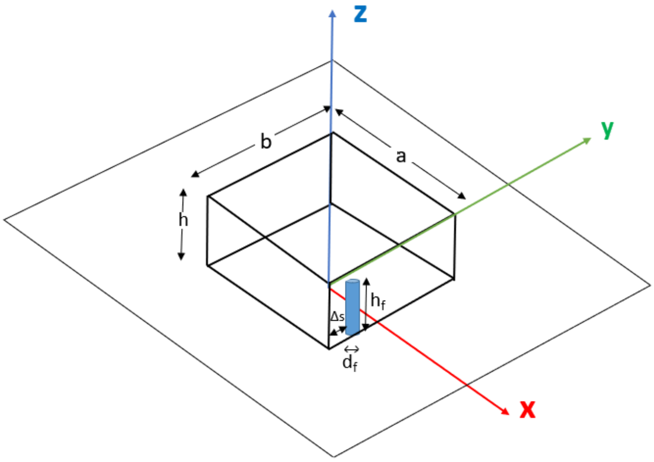

Fig. 1 Configuration of the ARDRA.

Once the DRA is optimized with our methodology, TE_{111}^{x} and TE_{111}^{y} modes are excited using a probe feed placed near the corner of the uniaxial ARDRA. The coupling between the probe and the DR can be controlled by varying the length and position of the probe along y-direction. Thus, a parametric analysis in HFSS is performed to optimize the feed position and maximize the coupling. Fig. 2 depicts the return loss of the ARDRA with a variation of the probe feed position from the corner of the ARDRA along y $\left(\text{coordinate } \frac{d_f}{2}, \Delta s + \frac{d_f}{2}\right)$. Maximum coupling is obtained at Δs=4 mm, where both degenerate modes present an identical reflection coefficient.

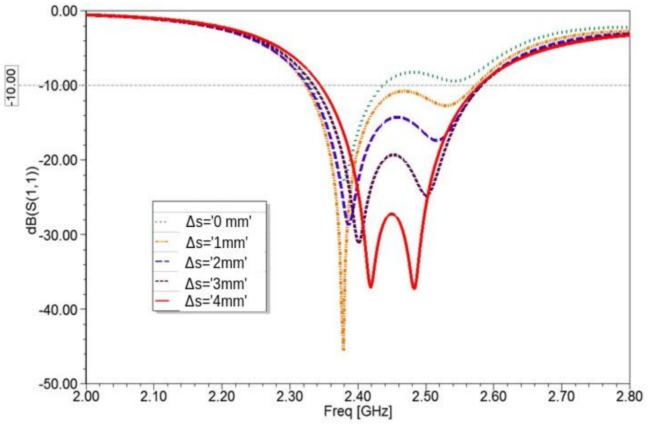

Fig. 2 Simulated S_{11} of the ARDRA by varying the position of the probe.

Fig. 3 depicts the simulated return loss of the final ARDRA. Good coupling between the probe feed and DR is achieved. The antenna has an impedance bandwidth (BW for $|S_{11}|$ >10 dB) of 9.8% covering the frequency band 2.34 GHz - 2.58 GHz.

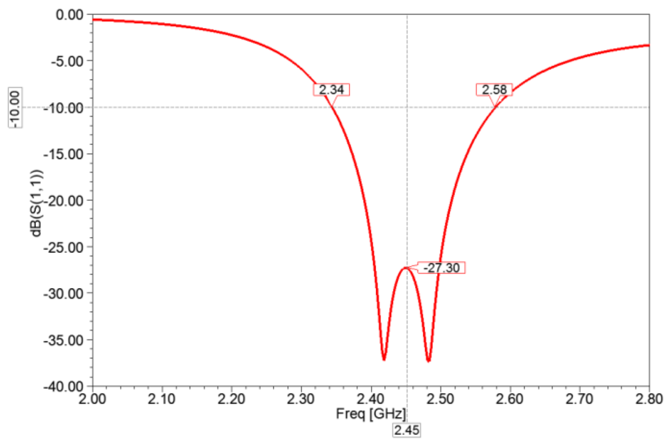

Fig. 3 Simulated S_{11} of the proposed ARDRA.

Fig. 4 illustrates the simulated Smith chart of the proposed antenna. Note that it achieves a perfect matching at the center frequency f_o=2.45 GHz.

Given the anisotropic properties of the DRA, by placing the probe near the diagonal and adjusting the permittivity tensor of uniaxial anisotropic dielectric, -90° phase difference and same magnitudes between both degenerate modes can be achieved in order to obtain left hand CP. The proposed ARDRA has a simulated 3-dB Axial Ratio (AR) of 0.06 dB at 2.45 GHz, ϕ=0 and θ=0°, as shown in Fig. 5. Moreover, the circularly polarized antenna has a 3-dB AR bandwidth of about 2.04%, corresponding to the frequency band of 2.43 GHz - 2.48 GHz.

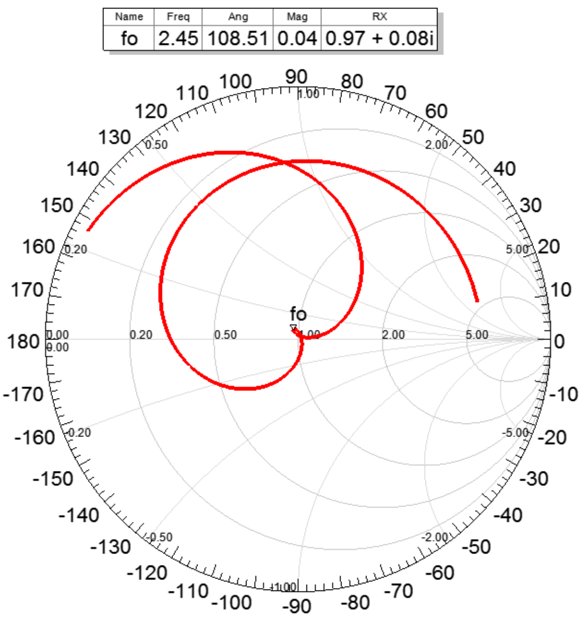

Fig. 4 Simulated Smith chart of the proposed ARDRA.

In addition, Fig. 6 shows the simulated axial ratio versus theta for the proposed ARDRA for ϕ=0. The axial ratio is below 3 dB at 2.45 GHz, when θ covers from -63° to +48°.

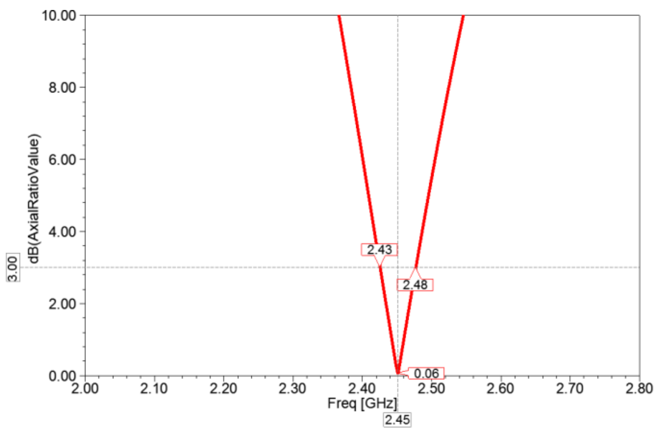

Fig. 5 Simulated axial ratio vs frequency of the proposed ARDRA at θ=0° and ϕ=0°.

Fig. 7 depicts the simulated radiation patterns of the ARDRA, showing good LHCP radiation. Fig. 8 illustrates the simulated 3D radiation pattern of the ARDRA. The antenna patterns have a broadside radiation θ=0° and the maximum directivity is 6.56 dBi at 2.45 GHz.

Finally, the results obtained in this work are compared with similar projects using anisotropic materials to obtain CP, as shown in Table 1. In [10], a metallic anisotropic conductor is used to generate two orthogonal modes for achieving CP in a microstrip antenna at 2.5 GHz. Despite the antenna operates in CP, it presents a reduced impedance and AR bandwidths. Secondly, a microstrip antenna with a metallic square-shaped

CSRR-perpendicular provides anisotropic properties in order to achieve CP at 4.2 GHz [11]. For obtaining CP, the resonant frequencies of the antenna are altered by adjusting the position and size of the CSRR. However, note that the antenna presents a reduced AR bandwidth due to the small size. In contrast with [10] and [11], our proposed antenna is based on a uniaxial anisotropic dielectric material. Observe that using an inhomogeneous dielectric, there is an increase of the number of degrees of freedom and an improvement of the antenna bandwidth based on simulations.

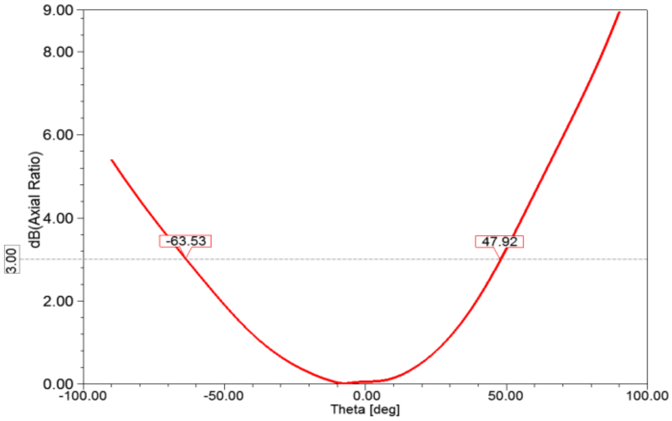

Fig. 6 Simulated axial ratio vs theta of the proposed ARDRA at f_o=2.45 GHz and ϕ=0°.

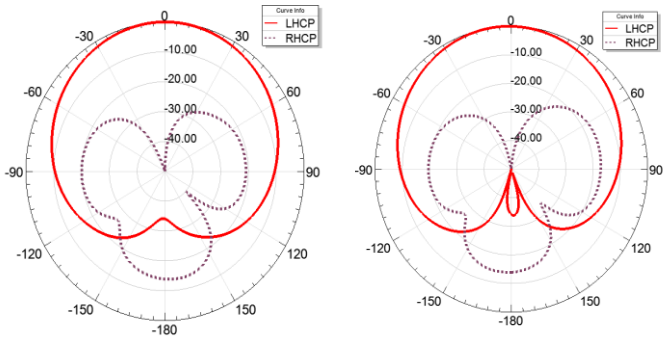

Fig. 7 Simulated normalized directivity of the ARDRA for LHCP and RHCP at f_o=2.45 GHz and ϕ=0°.

Table 1 CP antenna performances using anisotropic materials.

Topology	Size	Impedance BW	AR BW	Gain
Wire-mesh microstrip antenna [10]	$0.16\lambda_o \times 0.16\lambda_o$	1%	0.7%	5 dBi
Microstrip antenna with CSRR [11]	$0.28\lambda_o \times 0.28\lambda_o$	4.2%	0.04%	6.2 dBi
Proposed DRA	$0.65\lambda_o \times 0.65\lambda_o$	9.8%	2.04%	6.6 dBi

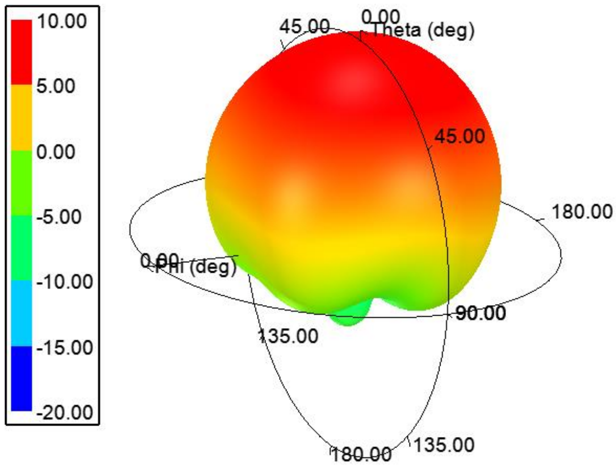

Fig. 8 Simulated 3D total directivity of the proposed ARDRA at f_o=2.45 GHz.

5 Conclusion

An anisotropic dielectric resonator antenna has been designed to achieve circular polarization at 2.45 GHz. The location of the optical axis at x-direction allows the independent control of the TE_{111}^{y} mode in order to accomplish the proper phase shift and magnitude with respect to the TE_{111}^{x} mode.

The methodology applied in this research by combining the DWM and Eigen modes showed satisfactory results to design a uniaxial anisotropic DRA operating in circular polarization. In addition, the use of anisotropic dielectrics for DRA design offer new possibilities for obtaining better bandwidth and gain.

The use of uniaxial anisotropic dielectric materials allows to increase the number of degrees of freedom and control the polarization for designing new DRAs with exotic properties.

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