Additive Manufacturing of a Uniaxial Anisotropic Dielectric Material for Antenna Applications

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***Abstract* — In this paper, we propose a procedure to design a uniaxial anisotropic dielectric material by additive manufacturing of ceramics. Such materials may find interesting applications in the design of dielectric resonators. As an example, a single-fed circularly polarized dielectric resonator antenna exploiting dielectric anisotropy is detailed. We propose a unit cell that constitutes the required uniaxial anisotropic material. Simulation results based on the antenna performances using an ideal anisotropic material and a periodic structure of several unit cells are also compared, showing a good agreement.**

I. INTRODUCTION

Additive manufacturing (AM) is a 3D printing technology used to build complex structures. It provides a high mechanical accuracy and prevents excessive material wastage with respect to conventional techniques [1]. AM has already been studied for the manufacture of antennas and microwave devices since it provides new degrees of freedom for the shape and properties of materials. It also allows the use of different types of materials such as metals, thermoplastics, or more recently ceramics.

AM of ceramics is particularly interesting for microwave applications since ceramics have high dielectric constant, low dielectric loss, and high temperature stability. The AM process generally consists in the solidification of a ceramic resin by applying an ultraviolet light on a photosensitive liquid polymer contained in a vat [2,3]. After, the resin is exposed in a chemical process to give a defined thickness and polish the desired shape of the dielectric sample.

Recently, a homogeneous and isotropic dielectric resonator antenna (DRA) designed with an additive manufacturing process for ceramics has been proposed with very promising results [4]. However, 3D printing of inhomogeneous and/or anisotropic ceramic materials makes it possible to envisage many other perspectives in the control of DRA properties. Some DRA exploiting anisotropic dielectric materials made of laminated substrates have thus been proposed to enhance the antenna gain [5,6].

In this paper, we present a procedure to design a uniaxial anisotropic dielectric material compatible with the process of AM of ceramics. In addition, we present an example of application exploiting this material, namely a single-fed circularly polarized DRA [7].

This paper is presented as follows. Section II describes the theory used to design a single-fed DRA in circular polarization by using a uniaxial anisotropic dielectric. In section III, a methodology to design a uniaxial anisotropic dielectric material is proposed. Finally, the antenna design is presented and simulation results of the proposed DRA by using an ideal anisotropic dielectric and a 3D printed anisotropic dielectric material are shown in section IV.

II. SINGLE-FED CIRCULARLY POLARIZED DRA USING A UNIAXIAL ANISOTROPIC MATERIAL

The design of the single-fed circularly polarized DRA shown in Fig. 1 has already been detailed in [7]. It relies on the uniaxial anisotropy of a rectangular dielectric resonator to produce two orthogonal degenerated modes, namely TE_{111}^x and TE_{111}^y modes, with same amplitude and 90° out of phase. Thus, circular polarization can be obtained using a single coaxial probe placed near the corner of the dielectric resonator. However, a practical implementation of such an antenna still requires the design of a uniaxial anisotropic dielectric material.

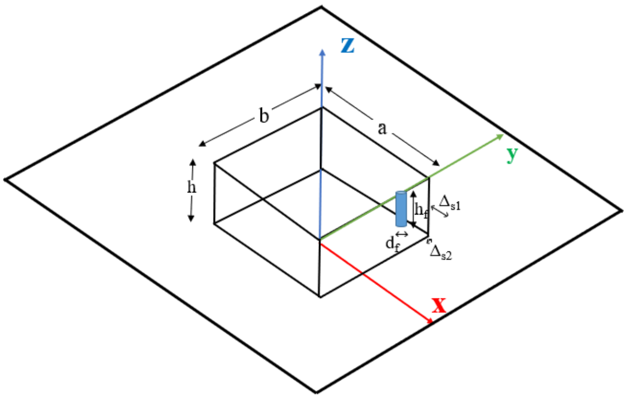


Fig. 1. Proposed DRA using an ideal anisotropic dielectric.

III. METHODOLOGY TO DESIGN A UNIAXIAL ANISOTROPIC DIELECTRIC MATERIAL

A. Unit cell and simulation setup

As described in [7], the rectangular dielectric resonator shown in Fig. 1 must have the following dielectric permittivity tensor

$$\bar{\bar{\varepsilon}} = \begin{bmatrix} \varepsilon_{\perp} & 0 & 0 \\ 0 & \varepsilon_{||} & 0 \\ 0 & 0 & \varepsilon_{||} \end{bmatrix} \quad (1)$$

with $\varepsilon_{\perp}$=20 and $\varepsilon_{||}$=14.5. Note that the optical axis of the anisotropic medium is here placed along *x*-direction.

In practice, the anisotropy of the 3D printed ceramic material is obtained by periodically printing an anisotropic unit cell. To ensure a homogeneous macroscopic behavior of the final material, the unit cell must remain small with respect to the wavelength.

Fig. 2 illustrates the proposed unit cell. The structure is composed of air and dielectric parts (in red in Fig. 2). The dielectric is Zirconia with a dielectric constant ε_r=32.5. Based on the manufacturing process [8], a maximum thickness of 4 mm for Zirconia is allowed. Then, a cross-shaped hole is placed along *x*-direction to satisfy this manufacturing constraint. Moreover, the symmetry of the cross-shaped hole implies that the permittivity along *y*-direction and *z*-direction are the same, then so called $\boldsymbol{\varepsilon}_{||}$.

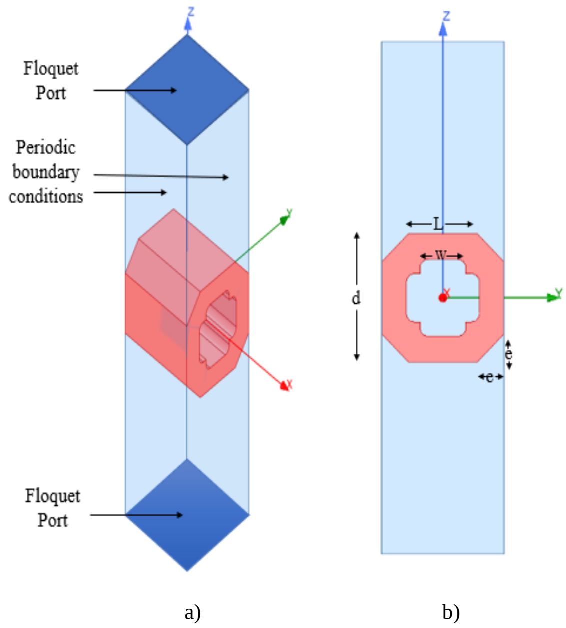


Fig. 2. Unit cell: a) Simulation setup, b) dimensions.

Regarding Ansys HFSS simulations, master-slave boundary conditions are imposed to force periodic boundary conditions in the four side walls at *x*-axis and y-axis [9]. However, the single unit cell is unable to extract the S-parameters in the plane of the unit cell interfaces along *x*-direction and *y*-direction. For that reason, Floquet ports are embedded in the unit cell interfaces in order to measure the S-parameters. These ports provide normal incident waves with capabilities to control the polarization vector.

Given the periodic boundary conditions imposed on the unit cell (see Fig. 2a), the first Floquet mode in *x*-polarization is excited to extract the S_{11} and S_{21} parameters, allowing to retrieve $\varepsilon_{\perp}$. On the other hand, to achieve $\boldsymbol{\varepsilon}_{||}$, the first Floquet mode in *y*-polarization is excited to extract the S-parameters.

B. Permittivity tensor extraction

The S-parameters are used to retrieve the permittivity tensor for the uniaxial anisotropic dielectric [9,10]. The S-parameters can be calculated given a normally incident wave propagating between the Floquet ports. Thus,

$$S_{11} = \frac{R_{01}(1 - e^{i2nk_o d})}{1 - R_{01}{}^2 e^{i2nk_o d}} \quad (2)$$

$$S_{21} = \frac{(1 - R_{01}{}^2) e^{i2nk_o d}}{1 - R_{01}{}^2 e^{i2nk_o d}} \quad (3)$$

where $R_{01} = \frac{z-1}{z+1}$, $e^{ink_o d} = \frac{S_{21}}{1 - S_{11}\frac{z-1}{z+1}}$, k_o is the wavenumber, and *d* is the maximum length of the unit cell. The impedance of the unit element *z* and the refractive index *n* are given by

$$z = \pm\sqrt{\frac{(1+S_{11})^2 - S_{21}{}^2}{(1-S_{11})^2 - S_{21}{}^2}} \quad (4)$$

$$n = \frac{1}{k_o d}\cos^{-1}\left[\frac{1}{2S_{21}}(1 - S_{11}{}^2 + S_{21}{}^2)\right] \quad (5)$$

The permittivity is computed based on the refractive index and impedance of the unit cell as follows

$$\varepsilon = \frac{n}{z} \quad (6)$$

In order to obtain the required uniaxial anisotropic dielectric with permittivity tensor $\varepsilon_{\perp}$=20 and $\varepsilon_{||}$=14.5, a parametric analysis is performed using Ansys HFSS. It consists in analyzing the variation of all the dimensions of the unit cell to achieve the required permittivity tensor. Finally, following the proposed methodology and the manufacturing constraints, we find *d*=3 mm, *L*=1.7 mm, *e*=0.65 mm, and *W*=1.13 mm.

IV. ANTENNA DESIGN AND RESULTS

Fig. 3 shows the final DRA design considering the periodic structure of several unit cells. The physical and electric values of the DRA were selected based on the proposed methodology in [7]. As a result, the resonator has square dimensions *a*=*b*=26.3 mm (0.21 λ_0) and a height *h*=11.25 mm (0.09 λ_0). The dielectric resonator is placed above a square ground plane with side dimensions of 0.65 λ_o. Finally, it is fed with a coaxial probe of diameter d_f=0.9 mm and height h_f=10.5 mm.

Fig. 4 depicts the reflecion coefficient for the DRA made of an ideal anisotropic dielectric as in Fig. 1, and for the DRA formed by the periodic structure as in Fig. 3. The simulated reflection coefficients show a good agreement. Both antennas present a similar bandwidth. The proposed DRA composed by several unit cells has an impedance bandwidth of 13.1 % from 2.32 GHz to 2.64 GHz, for a reflection coefficient $|S_{11}| \geq 10$ dB. It has also been observed that we can maximize the coupling of $TE_{111}{}^x$ and $TE_{111}{}^y$ modes by varying the length and position of the coaxial probe along *x*- and *y*-directions. Thus, maximum impedance matching and bandwidth are obtained adjusting the position of the probe with Δ_{s1}=5.45 mm and Δ_{s2}=1.45 mm, as presented in Fig. 1.

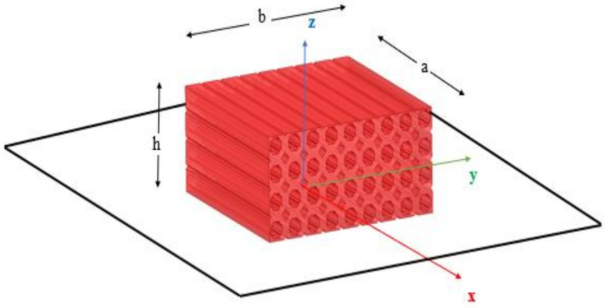


Fig. 3. Proposed DRA using 3D printed anisotropic dielectric material.

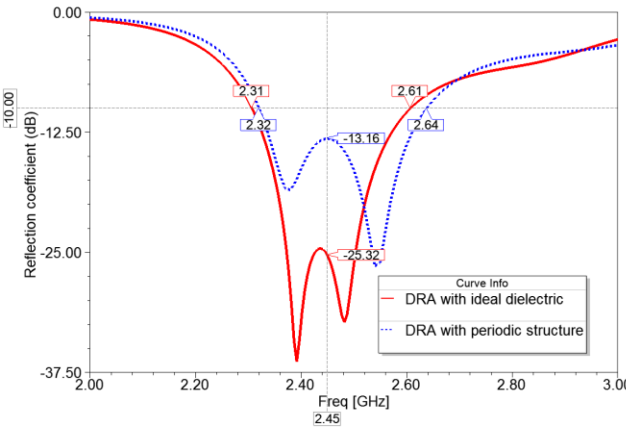


Fig. 4. Simulated reflection coefficient of the DRA using an ideal anisotropic dielectric and periodic structure.

Fig. 5 illustrates the simulated input impedance in the Smith chart for both simulated DRAs. Note that the coupling between the TE_{111}^{x} and TE_{111}^{y} modes is slightly modified. However, it remains consistent with CP when using the anisotropic dielectric formed by a periodic structure.

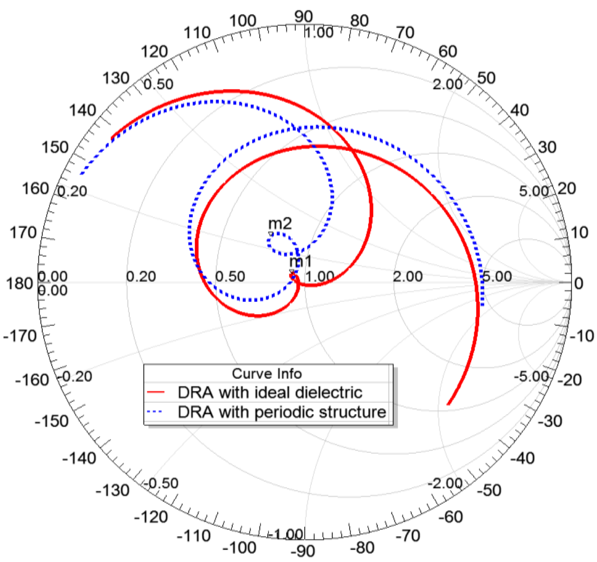


Fig. 5. Simulated input impedance in the Smith chart for the DRA using an ideal anisotropic dielectric and periodic structure.

The axial ratio of the DRA is also compared by using both dielectric materials, as shown in Fig. 6. The proposed 3D printed DRA has a simulated axial ratio (AR) of 1.4 dB at 2.45 GHz, considering ϕ=0° and θ=0°. The circularly polarized DRA has a 3-dB AR bandwidth of about 2.5 % from 2.43 GHz to 2.49 GHz. Fig. 7 depicts the simulated axial ratio as a function of θ, considering f_0=2.45 GHz and ϕ=0°. The AR of the proposed 3D printed DRA is below 3 dB for -65.6° ≤ θ ≤ 50.6°.

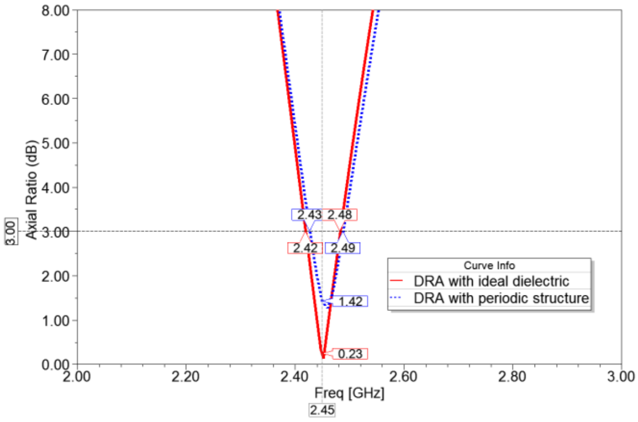


Fig. 6. Simulated axial ratio of the DRA using an ideal anisotropic dielectric and periodic structure vs. frequency.

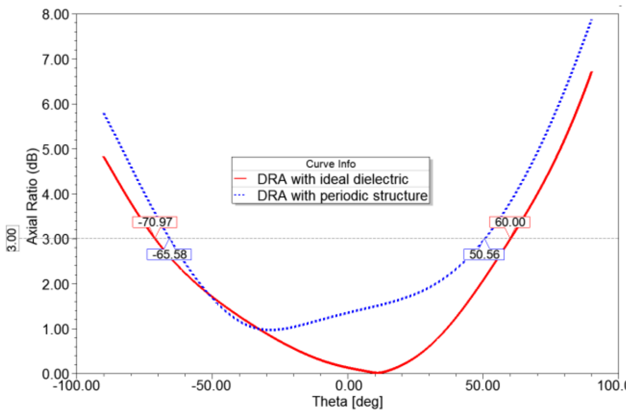
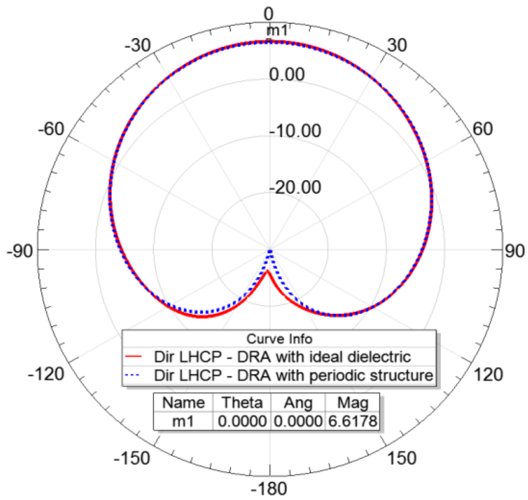
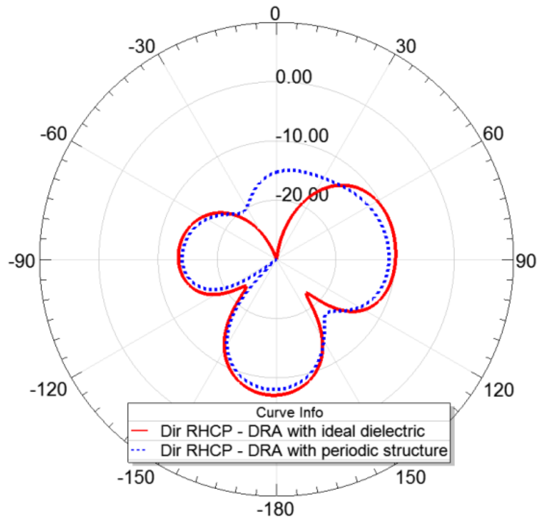


Fig. 7. Simulated axial ratio of the DRA using an ideal anisotropic dielectric and periodic structure vs. θ.

Finally, the simulated radiation patterns are compared in Fig. 8. As observed, both DRAs have similar performances in far-field. The proposed DRA shows a good left-hand circular polarization (LHCP) with a broadside radiation pattern and a maximum directivity of 6.6 dBi at 2.45 GHz.



(a)



(b)

Fig. 8. Simulated (a) left-hand and (b) right-hand CP directivity (dBi) of the DRA using an ideal anisotropic dielectric and periodic structure at f_0=2.45 GHz and ϕ=0°.

V. CONCLUSION

A uniaxial anisotropic dielectric has been designed using a periodic structure made of several unit cells. The methodology to design the unit cell shows satisfactory results using the proposed simulation setup in HFSS based on master-slave boundary conditions and Floquet ports.

This anisotropic material has been used to design a circularly polarized dielectric resonator antenna at 2.45 GHz. The antenna radiates in left-hand circular polarization with an impedance bandwidth of 13.1 % and an axial ratio bandwidth of 2.5 %. The maximum antenna directivity is 6.6 dBi at the center frequency of 2.45 GHz.

A good agreement of simulation results between the antenna performances using the ideal anisotropic dielectric and periodic structure has been obtained.

The proposed periodic structure of several unit cells that constitutes the anisotropic material is compatible with the process of additive manufacturing.

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