Resonant Frequency of Circular Sectorial Microstrip Antenna Printed On Double-Layered Anisotropic Substrates

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Resonant frequency of circular sectorial microstrip antenna printed on double-layered anisotropic substrates

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Abstract – *In this work, modal characteristics have been rigorously studied which germinate an improved, accurate, and efficient computer-aided design (CAD) formulation to estimate the resonant frequency of sectorial circular microstrip antennas printed on anisotropic suspended and composite substrates. The obtained results demonstrated that the resonant frequencies of the sectorial circular microstrip patch on suspended and composite substrates can be adjusted to obtain the maximum operating frequency of the antenna. The computed results show a fairly good agreement with measured results. Such theoretical validation and results may prove to be more useful for design engineers and further investigation.*

***Keywords* –** *Circular Sector Microstrip Antennas; Modeling & Design; Resonance Frequency; Suspended / Composite structures; Anisotropic Substrates.*

1. Introduction

In the last decades, microstrip patch antennas (MPAs) have been extensively considered by engineering researchers due to their low profile, rugged, lightweight structure, simple fabrication, and their compatibility with microwave integrated circuits, and capability to be easily formed into arrays [1-3]. These advantages make the microstrip patch antennas suitable for handheld wireless communication systems, mobile equipment, radio frequency identification (RFID), and aircraft radomes, missiles, satellites and various radars [4-6]. Nevertheless, the conventional MPAs have the disadvantages of low gain, low profile radiation characteristics, and their narrow impedance bandwidth that is typically a few percent because they are highly resonant structures [2, 7, 8]. Since of this inherent limitation, the MPAs are the main obstacle that restricts extended applications for several domains. To deal with the disabilities mentioned, several techniques have been presented in the literature to boost the characteristics of microstrip antennas, such as adding a parasitic band around the radiant element [1], Making a slot in the ground plane [8], increasing the thickness of the substrate and using stacked configurations [1, 9]. So, one method of designing high-performance antennas is to use antenna printed on anisotropic substrates [10-12]. The anisotropic substrates provide docility, precise design and an additional degree of control over the features of the practical design of printed circuits [13-18]. Consequently, several researchers have been devoted to the characterization of the different geometries of the microstrip antennas printed on anisotropic substrates [11, 13, 16]. In particular, a circular microstrip resonator can be used both as a separate antenna and as a component of oscillators and filters in multilayer microwave and millimeter wave integrated circuits (MWIC) [19]. Circular microstrip antennas (CMPAs) have been studied by several researchers reported in the literature [20-21]. Among them are based on experiences [21] and others are based on numerical methods [18, 20]. By the way, results for the circular microstrip patch printed on uniaxially anisotropic dielectric substrates are available in the literature [14, 16, 17]. So on the other hand, there may be favorable geometric shapes other than the well-known conventional rectangular and circular geometric shapes [22]. Whereas, a circular sectoral microstrip antenna (CSMPA) is very useful where space is the main factor for organizing a patch with conventional geometry [23]. In fact, around 15% and 45% of patch area reduction can be achieved using 60° and 90° sectorial angle respectively for a particular resonant frequency compared to conventional circular patch geometry [24]. For a material with electric anisotropy, the permittivity may be different in different directions. In general, there exist three principal axes. Along each axis the permittivity is characterized by a constant [25]. With the increasing complexity of the geometry and properties of materials, the design of these antennas requires increasingly dedicated and sophisticated computer-aided design (CAD) tools to predict the characteristics [26]. The method of moments via the Galerkin procedure has proven to be one of the most powerful CAD tools for solving this class of problems [26]. Unlike for the case of an isotropic substrate, the Green's function for a generalized anisotropic substrate is not a simple closed form [ant20]. Although, this approach can determine the resonant frequency with reasonable accuracy but at the cost of high computational time and therefore find limited usefulness in integration with standard microwave simulators [21]. The modified cavity model is ideal for design purpose because it involves less mathematical steps, simple, low computation cost and directly applied in CAD programs. The performance of circular sectorial microstrip antennas printed on isotropic substrates has been analysed in [22-24], where the air gap layers are studied [22], but as far as the authors know, the influences of the uniaxial anisotropy substrates on the resonant characteristics of these antennas have been not studied earlier. This paper addresses a simple analysis to study the influence of the anisotropy of the substrate on the resonant characteristics of the circular sectorial microstrip patch antennas. We extended the formulations of the previous work [22, 27], in particular, emphasis is placed on analysing how the resonant characteristics of circular sectorial microstrip patches are modified when the conventional isotropic dielectric substrates are substituted by nonconventional substrates such as anisotropic dielectrics materials.

This paper is organized as follows. In Section II, the analysis uses modified cavity method and discussed some improved and closed-form computer-aided design (CAD) formulas, to the determination of the resonant characteristics of circular sectorial microstrip patch antennas printed on anisotropic substrate. Section III presents discussion concerning the effects of substrate anisotropy on printed antenna properties are studied parametrically to clarify the effects of anisotropic dielectrics materials. Conclusion is given in Section IV.

2. Theoretical Formulation

The geometry of the structure under consideration is shown in Figure 1. The circular sectorial patch of sector angle ϕ has a radius of a, printed on two anisotropic layers, having dielectric constant $\bar{\varepsilon}_{r1}$ of thickness h_1, and $\bar{\varepsilon}_{r2}$ of thickness h_2, respectively. The ambient medium is air with constitutive parameters ε_0 and μ_0. The ground plane is assumed to be infinitely long and perfectly conducting.

The resonant frequency of circular sectorial microstrip antenna can be calculated from the cavity model for conventional circular patch taken into account some restriction of modified conditions. This, in fact, provides a basic estimate of the resonant frequency of circular sectorial microstrip patch antenna printed on double-layered anisotropic substrates.

The resonant frequency of a circular patch antenna, operated in TM*mn* modes based on cavity model analysis may be computed from [22] as

$$f_{rmn} = \frac{\chi'_{mn}}{2\pi a\sqrt{\mu\varepsilon}} = \frac{\upsilon_0\,\chi'_{mn}}{2\pi a\sqrt{\varepsilon_r}} \tag{1}$$

where υ_0 is the velocity of light in free space, and χ'_{mn} is the nth zero of derivative of Bessel function of order m, a is the radius of the patch and ε_r is the permittivity of the substrate.

Now if we take into account the fringing around the patch periphery, the physical dimension a will be replaced by the effective dimension a_{eff} and the dielectric constant ε_r by the effective dielectric constant ε_{reff}.

Thus, the resonant frequency is then given by [22]

$$f_{rmn} = \frac{\upsilon_0\,\chi'_{mn}}{2\pi\, a_{eff}\,\sqrt{\varepsilon_{reff}}} \tag{2}$$

Several expressions for a modified, effective radius (a_{eff}) have been proposed to account for the fringing fields. The most common expression is the one given by [20]

$$a_{eff} = a\sqrt{(1+q)} \tag{3}$$

The term q arises due to the fringing fields at the edge of the disk capacitor and can be obtained from [20].

The effective dielectric constant ε_{reff} can be calculated based on static and dynamic capacitances [22]

$$\varepsilon_{reff} = \frac{4\varepsilon_{re}\,\varepsilon_{rdyn}}{\left(\sqrt{\varepsilon_{re}} + \sqrt{\varepsilon_{rdyn}}\right)^2} \tag{4}$$

where ε_{re} is the equivalent dielectric constant of the two-layered medium below the patch. Thus, can be obtained from [20]

$$\varepsilon_{re} = \frac{h\left(\varepsilon_{r2}\cdot\varepsilon_{r1}\right)}{\left(\varepsilon_{r2}\cdot h_1 + \varepsilon_{r1}\cdot h_2\right)} \tag{5}$$

with, $h = h_1 + h_2$, and ε_{r1}, ε_{r2} are the dielectric permittivities of substrate 1 and 2, respectively.

From Eq. (4) ε_{re} is calculated using (5), and ε_{rdyn} is the dynamic dielectric constant as defined in [20, 22] and can be written as

$$\varepsilon_{rdyn} = \frac{C_{dyn}(\varepsilon = \varepsilon_0 \varepsilon_{re})}{C_{dyn}(\varepsilon = \varepsilon_0)} \tag{6}$$

where C_{dyn} is the total dynamic capacitance, which can be expressed as [20]

$$C_{dyn} = C_{0,dyn} + C_{e,dyn} \tag{7}$$

$C_{0,dyn}$ and $C_{e,dyn}$ are the dynamic main and dynamic fringing capacitances of the different modes determined from the static main and static fringing capacitances $C_{0,stat}$ and $C_{e,stat}$, respectively, as[22]

$$C_{0,dyn} = \gamma_m C_{0,stat} \tag{8}$$

where γ_m is the factor by which the dynamic capacitance and it is strictly depends on the mode number m.

γ_m =1.0 for m=0

γ_m =0.3525 m=1

γ_m =0.2865 m=2

γ_m =0.2450 m=3

The static fringing capacitance $C_{e,stat}$ is defined as [20]

$$C_{e,stat}(\varepsilon) = C_{0,stat}(\varepsilon) \cdot q \tag{9}$$

and

$$C_{0,stat}(\varepsilon) = \varepsilon_0 \varepsilon_{re} \pi \, {a^2}/{h} \tag{10}$$

$C_{e,dyn}$ is the dynamic fringing capacitance that arises from fringing field. From [20], we may write

$$C_{e,dyn} = \frac{1}{\delta} \cdot C_{e,stat} \tag{11}$$

where $\delta = 1$ for $m = 0$ and $\delta = 2$ for $m \neq 0$.

In this subsection, the circular sectorial microstrip patch antenna featuring different sector angles printed on double-layered anisotropic substrates with different characteristics have been thoroughly investigated, categorized, and discussed.

2.1. Circular sector patch antenna with sector angle 180° ($\phi = \pi$)

According to Equation 2, the lowest order resonant mode (dominant mode $\chi'_{mn} = \chi'_{11}$) of semi-circular patch becomes TM_{11} and hence its frequency is [22]

$$f_r = \frac{\upsilon_0 \, \chi'_{11}}{2\pi \, a_{eff} \sqrt{\varepsilon_{reff}}} = \frac{1.841 \, \upsilon_0}{2\pi \, a_{eff} \sqrt{\varepsilon_{reff}}} \tag{12}$$

2.2. Circular sector patch antenna with sector angle 90° ($\phi = \pi/2$)

In case of the circular sectorial microstrip patch antenna with sector angle of 90°, the lowest value, $\chi'_{mn} = 3.054$; occurs when $m = 2$ and $n = 1$.

So, the lowest order resonant mode of semi-circular patch becomes TM_{21}(dominant mode $\chi'_{mn} = \chi'_{21}$) and its frequency can be expressed us [22]

$$f_r = \frac{\upsilon_0 \, \chi'_{21}}{2\pi \, a_{eff} \sqrt{\varepsilon_{reff}}} = \frac{3.054 \, \upsilon_0}{2\pi \, a_{eff} \sqrt{\varepsilon_{reff}}} \tag{13}$$

2.3. Circular sector patch antenna with sector angle 60° ($\phi = \pi/3$)

Detailed investigations in [sectorial] show that for circular sectorial microstrip antenna with a sector angle of 60°, the lowest value, $\chi'_{mn} = 3.832$; occurs when $m = 0$ and $n = 1$.

Thus, the lowest order resonant mode of semi-circular patch becomes TM_{01}(dominant mode $\chi'_{mn} = \chi'_{01}$) and its frequency can be expressed us [22]

$$f_r = \frac{\upsilon_0 \, \chi'_{21}}{2\pi \, a_{eff} \sqrt{\varepsilon_{reff}}} = \frac{3.832 \, \upsilon_0}{2\pi \, a_{eff} \sqrt{\varepsilon_{reff}}} \tag{14}$$

In case the i-th layer of the substrate ($i = 1, 2$) is a uniaxial anisotropic, the permittivity tensors is given as follows, where the optical axis is oriented perpendicular to the ground plane, i.e., in the z direction [27]:

$$\bar{\varepsilon}_i = \varepsilon_0 \begin{bmatrix} \varepsilon_{xi} & 0 & 0 \\ 0 & \varepsilon_{xi} & 0 \\ 0 & 0 & \varepsilon_{zi} \end{bmatrix} \qquad , i = 1, 2 \tag{15}$$

For the case of uniaxially anisotropic substrate, by using the electromagnetics knowledge, the thicknesses (h_i) and the relative permittivities (ε_{xi}, ε_{zi}) of each anisotropic substrate are replaced by equivalent parameters using the following equations [11]

$$\bar{\varepsilon}_{eq\ i} = \varepsilon_{z\,i} \qquad , i = 1, 2 \tag{16}$$

$$h_{eq\ i} = h_i \cdot \sqrt{\frac{\varepsilon_{xi}}{\varepsilon_{zi}}} \qquad , i = 1, 2 \tag{17}$$

3. Numerical Results and Discussions

In this subsection, the results obtained by the proposed formulation are compared with the results obtained by simulation, measurement and other theories or formulations available in open literature.

In order to examine the calculation precision of our proposed approach described in previous section, we compare in Table 1 the resonant frequencies calculated for a single-layer circular sector microstrip antenna with previously published theoretical and experimental results [22-24]. The proposed formulation offers a minimum average error percentage of 1.25% compared to the measurement. The results presented in this table (Table 1) reveal a close agreement between the proposed formulation and the measured results.

Now, we study the effect of the patch radius on the resonant frequency of a circular sector microstrip antenna. Figure 2 shows the variation of the resonant frequency as a function of the radius (a) of the circular patch for the case of a isotropic single-layer antenna: $h_1 = 0$, $\varepsilon_{r1} = 1$. The resonant frequency measured by *Ghosh et. al* [22] for different sector angles agrees very well with the values obtained using the modified cavity model for a wide range of the patch radius.

The effects of varying the permittivity of the substrate on the resonant frequency of the single-layer circular sector microstrip antenna are investigated. The circular sector radius is $a = 30\,mm$ and the total dielectric substrate thickness is $h_2 = 1.58\,mm$, as shown if figure 3.

Figure 3 illustrates the variation of the resonant frequencies of a single-layer circular sector microstrip antenna with the variation of the permittivity of the substrate (ε_{r2} ranging from 1.5 to 10.2). The values calculated from the proposed formulation are compared with the results obtained from the measurement [22]. It is observed that the current model presents excellent agreements with the measurements for all values of the dielectric substrate. Comparison of results reveals an excellent agreement between our calculated results and the measured results for two different sector angles.

Besides the dimension parameters of the antenna, other physical parameters also affect the antennas frequencies. Figures 4–6 show the effect of the anisotropic layers on the resonant frequencies of sectorial microstrip antenna using different dimensional parameters.

Figure 4 visualized the variation of the resonant frequencies as function of the patch radius of the sectorial circular patches on a double-layered isotropic or anisotropic substrates in such a way that the material of both substrates always coincides. In this figure, the results obtained for two patches of sector angles of 60° and 90°, each patch printed on two anisotropic dielectric layers are compared with the results that would be obtained if the dielectric anisotropy of the layers were neglected and the layers were assumed to be isotropic. Based on the above figure, we notice that the resonance frequency decreases with increasing the patch radius of the patches, and this is for both sector angles of 60° and 90°. The differences between the results obtained considering dielectric anisotropy in the substrate and the results obtained neglecting dielectric anisotropy in the substrate reach 6.3 % for both sectors of the patch.

In Figure 5, we consider the effect of the thickness of the second layer h_2 on the resonant frequency of the circular patch printed on double-layered anisotropic substrates, for two different sector angles. Here the thickness of the composite and suspended substrate is varying. The resonant frequency decreases with the increase of the thickness of the second layer h_2 for composite substrate. So, the frequency tunability is achieved with the change of the thickness of the composite layer without altering the antenna parameters. Here, the double-layer anisotropic layer may be roughly regarded as one anisotropic substrate. The obtained results treat two cases of the substrate; isotropic and anisotropic substrates. The differences between the results obtained considering dielectric anisotropy, and the results obtained neglecting dielectric anisotropy reach 5.9%, for both sectors of the patch.

The resonant frequency tuning effect brought by the first layer is shown in Figure 6. This study indicates that the resonant frequencies of the both sectors of the patch decreases for composite anisotropic substrate with the increase of the height of the first anisotropic substrate, the decrease of the resonant frequencies reported in this figure is justified by the increase of the thickness of the equivalent relative permittivity of the two-layer substrate (composite substrate).

4. Conclusion

The work presented in this paper focuses on developing and improving the performance of circular sectorial microstrip antenna printed on double-layered anisotropic substrates. Our numerical results obtained via cavity model in conjunction with electromagnetic knowledge for the resonant frequencies and for different values of constitute parameters have been compared with experimental results. The accuracy of this model is satisfactory, and is believed to be comparable to that of those sophisticated time-consuming methods. For a circular sectorial microstrip structure, it is demonstrated that the resonant frequency increases with increasing of the total thickness for suspended substrate. Also, it is seen that the resonant frequencies of these structures decreases monotonically with increasing thickness of composite anisotropic substrate, the rate of decreases being greater for high permittivity of the anisotropic substrate layer. Likewise, the resonant frequencies of the circular sectorial antenna are more sensitive to the permittivity variations along the optical axis. The applications of this approach to the calculation of the resonant characteristics of circular sectorial patch antennas printed on multi-layered anisotropic materials can be expected soon.

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Figures

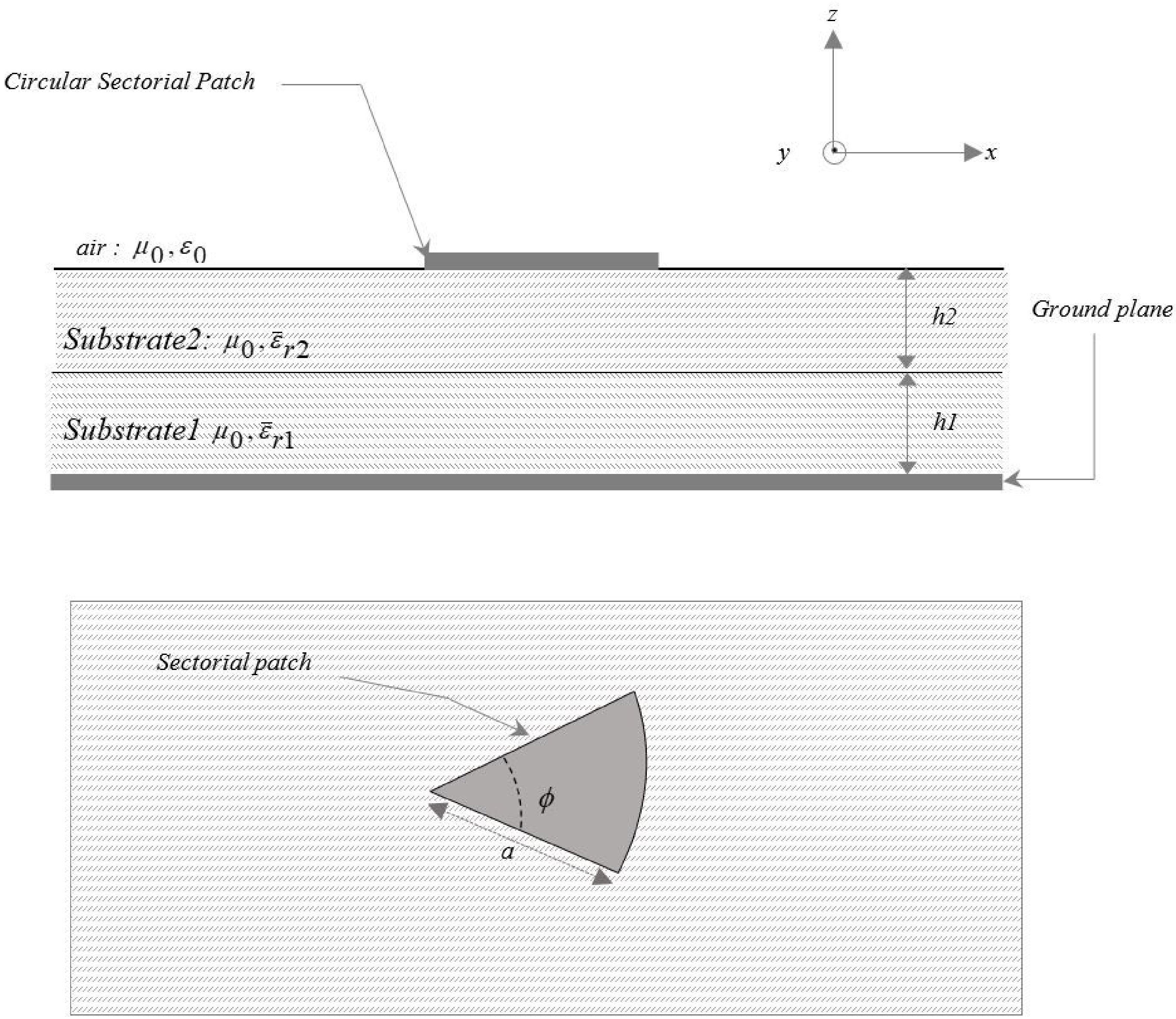

Figure 1

Side and top views of a circular sectorial microstrip patch antenna.

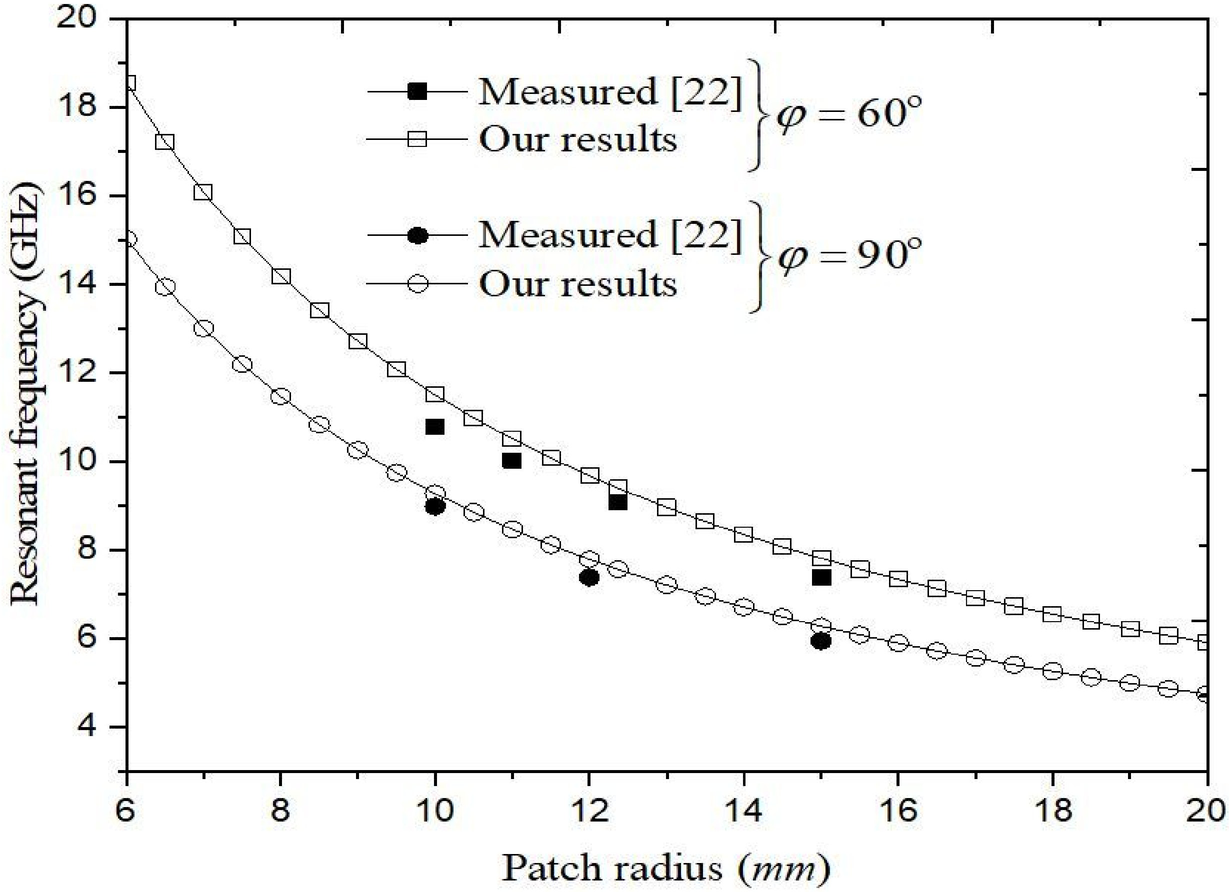

Figure 2

Resonant frequency as a function of the radius of the circular patch printed on isotropic single-layer; h1 = 0, εr1 = 1, h2 = 0.787 mm, εr2 = 2.2.

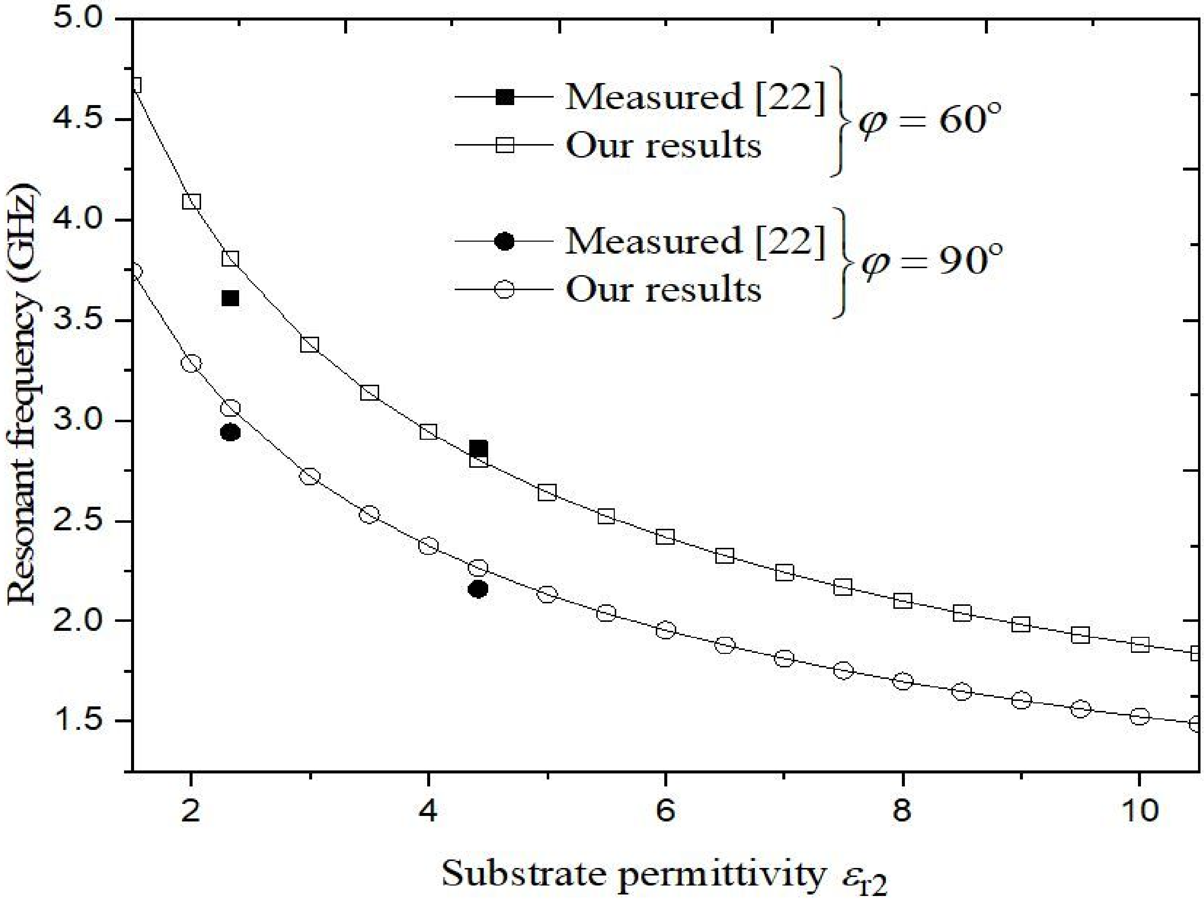

Figure 3

Variation of the resonant frequency as a function of the substrate permittivity of the circular patch printed on isotropic single-layer, for two different sector angles (φ=60° et φ=90°); h1 = 0, εr1 = 1, a = 30 mm, h2 = 1.58 mm.

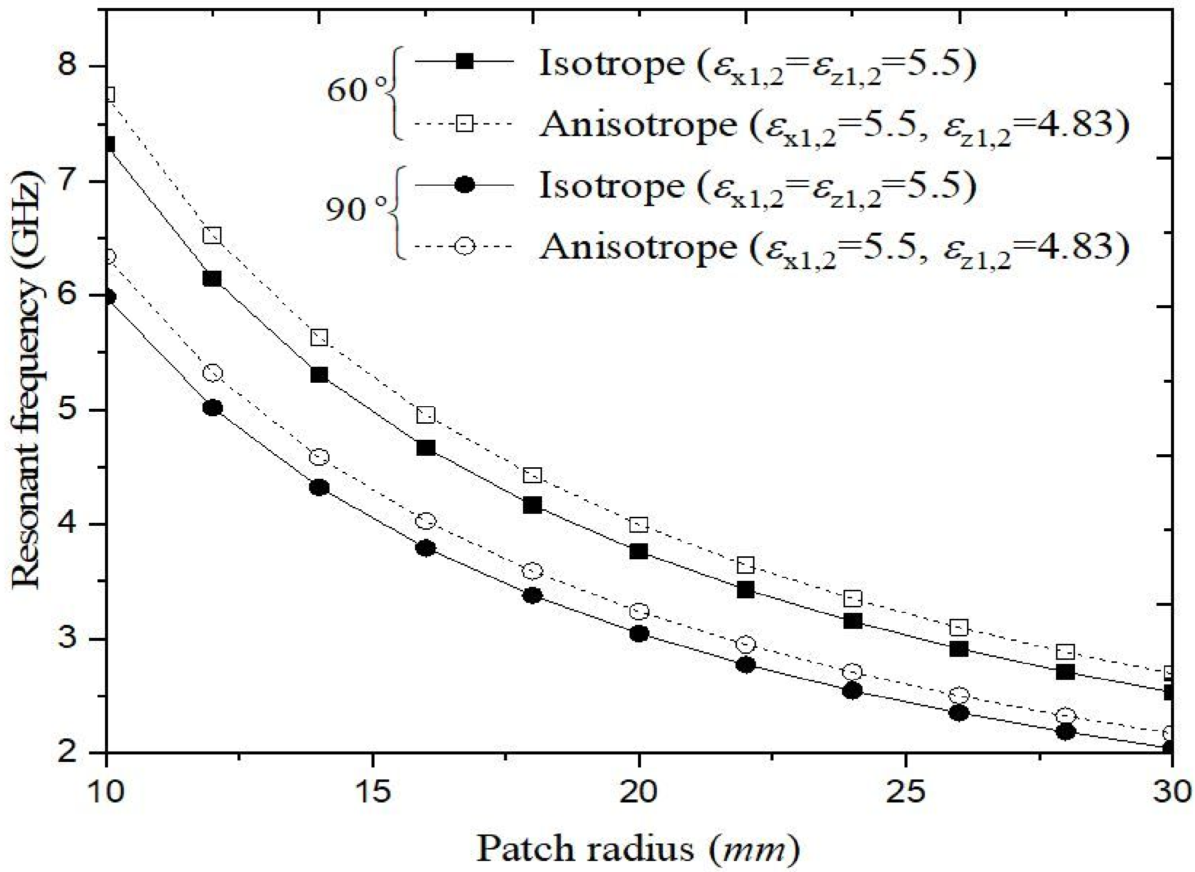

Figure 4

Variation of the resonant frequency as a function of the patch radius of the sectorial circular antenna printed on a double-layered anisotropic substrate, for two different sector angles (φ=60° et φ=90°); h1 = h2 = 0.635 mm.

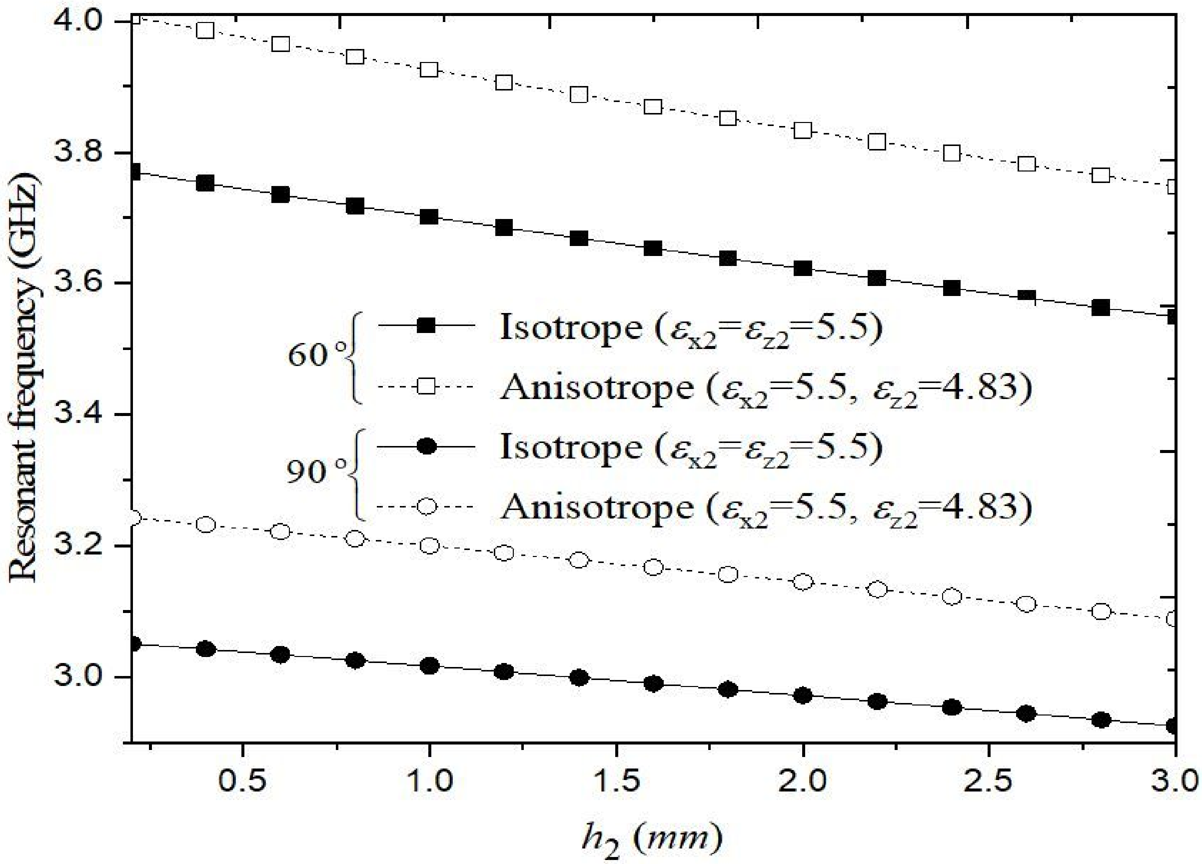

Figure 5

Variation of the resonant frequency as a function of the substrate permittivity of the circular patch printed on anisotropic double-layer, for two different sector angles (φ=60° et φ=90°); h1 = 1 mm, (εx1 = 5.12 , εz1 = 3.4, a = 20 mm.

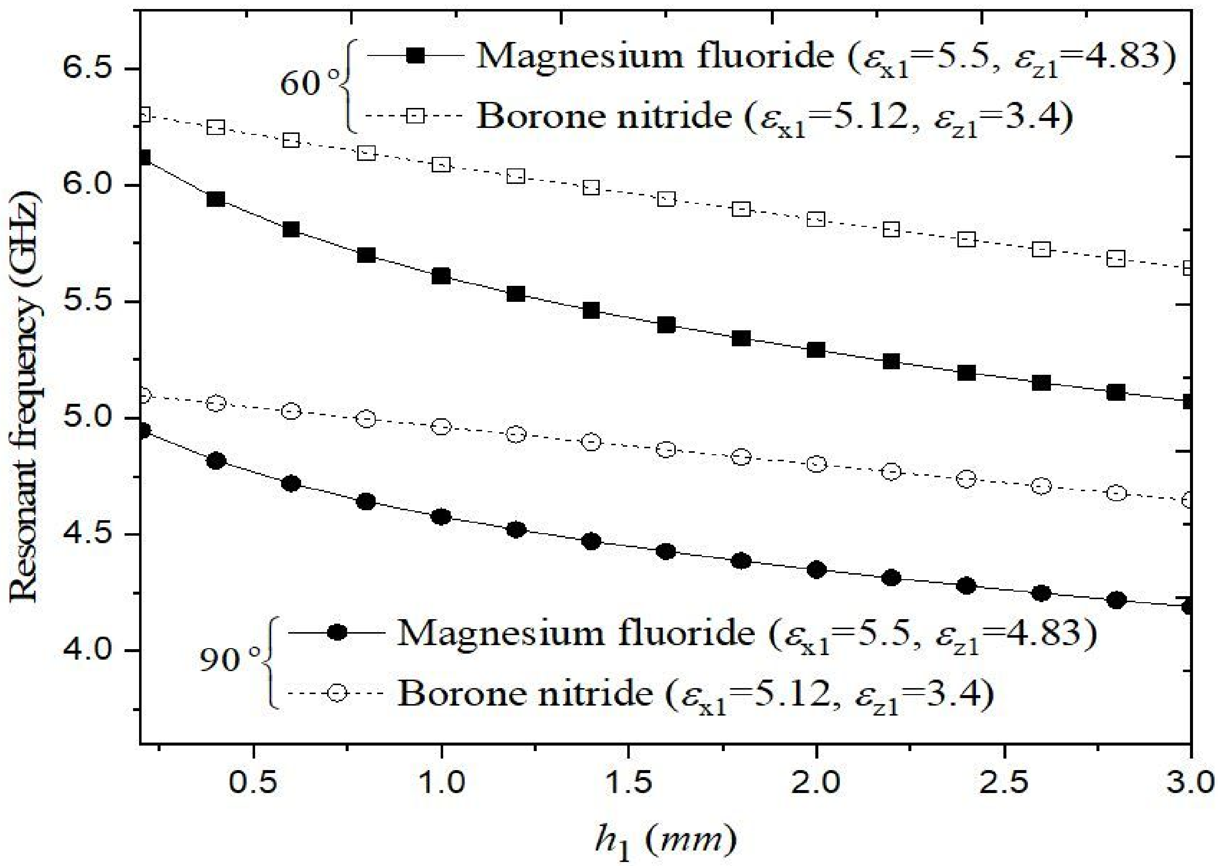

Figure 6

Resonant frequency as a function of the thickness of the lower substrate of the circular patch printed on double-layered anisotropic substrates, for two different sector angles (φ=60° et φ=90°); εx2 = 5.12 , εz2 = 3.4, a = 15 mm, h2 = 0.635 mm.

Supplementary Files

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- Table1.jpg