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RESEARCH PAPER

Analysis of elliptical-disk microstrip patch printed on isotropic or anisotropic substrate materials

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This paper presents a simple approach for accurate determination of the resonant frequency of an elliptical microstrip patch printed on isotropic or anisotropic substrate materials. In this approach, some modifications are made to account for fringe fields, dispersion effects, and losses by calculating effective dimensions, effective permittivity of anisotropy in the layer, and effective loss tangent, respectively. The theoretical resonant frequency results are in very good agreement with the experimental results reported elsewhere. Numerical results show that the change in the resonant frequency of the antenna is due primarily to a small disturbance of the substrate's nature. Then the effect of the uniaxial anisotropic materials is a significant parameter and most essential on the microstrip antenna characterization.

Keywords: Elliptical-disk antenna, Anisotropic substrate, Cavity method, Fringe fields, Circular polarizations

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I. INTRODUCTION

Microstrip antennas are widely used in high-performance aircraft, spacecraft, satellites, and some other applications due to their advantages of low profile, conformable to planar and non-planar surfaces, simple and low cost to manufacture [1–3]. The choice of shape of an antenna opens a whole new aspect of exploration in the field [4]. Extensive work on rectangular and circular geometries can be easily found in available literature. However, these geometries are not suitable for every application [5]. Conventional circular and rectangular microstrip antennas operate at the single-resonant frequency and radiate the linear polarization. In many practical applications, the dual-resonant frequency and circular polarizations (CPs) are required for a number of radar, communication, telecommunication, and navigation systems [6]. Various patch configurations implemented on different types of substrates have been tested and investigated. In practice, it was found that the choice of the substrate material is of a great importance and plays a significant role in achieving the optimum radiation characteristics of the antenna [7, 8].

Some substrate materials used for integrated microwave circuits or printed antennas exhibit dielectric anisotropy. This phenomenon occurs either naturally in the material or is introduced during the manufacturing process [9]. In addition, anisotropic substrates have become popular in the design of microwave integrated circuit components and microstrip antennas [9, 10]. Uniaxial substrates have drawn more attention due to their availability in materials such as sapphire, boron nitride and E-10 ceramic-impregnated Teflon. Previous studies of anisotropic materials used in microwave devices indicate that the effects of anisotropy on the performance of such structures particularly in high frequencies cannot be ignored [9–12]. Furthermore, it has been shown that the performance of directional couplers can be improved using the anisotropic substrates to equalize the even and odd mode phase velocities [9, 10]. Therefore, many investigations have examined the effects of substrate anisotropy in microwave components performance.

The elliptical patch has been analyzed extensively using the cavity model [4, 10–12], generalized transmission line model [13, 14], analysis in the Fourier–Hankel transform domain [5]. The method of moments (MoM) [14], other full-wave analyses [10, 15], and commercial software does not provide closed-form expressions and take a long computational time. So, full-wave analysis and commercial software are not useful for direct synthesis of the patch antenna. The computer-aided design (CAD) oriented cavity model is ideal for design purposes, because it involves fewer mathematical steps than full-wave models; takes less computational times and gives results with accuracy equivalent to that of full-wave models; cost effectiveness, easy to implement, and provides close-form expressions, since the client can use a simple PC for implantation. Another advantage of the proposed model is that it takes into account the uniaxial anisotropy in the substrate.

The cavity model has been chosen as a simple alternative to analyze and predict the behavior of elliptical microstrip antennas (EMAs). Furthermore, some modifications are made to

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account for fringe fields, dispersion effects, and losses by calculating effective dimensions, effective relative permittivity, and effective loss tangent, respectively. However, the effect of uniaxial anisotropy in the substrate on the dual-resonant frequency of elliptical patch microstrip antenna for different structural parameter cases have been not included in the open literature.

However, we are interested in this work to study the effects of anisotropic substrate materials on the resonant frequency of an elliptical patch antenna. Moreover the study of this type of substrates is of interest, many practical substrates have a significant amount of anisotropy that can affect the performance of printed circuits and antennas, and thus accurate characterization and design must account for this effect [8]. It is shown that formulation provides accurate results within lower percentage error values with respect to the previous analyses. Thus, it can be used confidently for the determination of the effect of anisotropic substrate materials on the dual-resonant frequency of an elliptical patch antenna. The proposed model does not require any complicated mathematical functions. This is very simple, efficient, accurate and suitable for CAD applications to design wide bandwidth and high gain antenna for wireless communication.

II. ANTENNA CONFIGURATION AND DESIGN

The geometrical configuration of EMA for obtaining the dual-resonant frequency (f_{11}^{eo}) and circular polarizations (CPs), consists of a planar slightly elliptical patch with the semi-major axis a and the semi-minor axis b, elliptical patch is parallel to ground plane and separated from ground plane by a dielectric substrate with relative permittivity ε_r and height h as shown in Fig. 1.

The resonant frequency of elliptical waveguide [6] can be modified and simplified for our case to yield

$$f_{11}^{e,o} = \frac{15}{\pi e a}\sqrt{\frac{q_{11}^{e,o}}{\varepsilon_r}}, \tag{1}$$

where f_{11}^{eo} is the dual-resonant frequency of even TM_{11}^{e}, and odd TM_{11}^{o}, mode and a is the physical semi-major axis. Generally, the measured results of the f_{11}^{eo} are lower than the calculated values due to the effective (electrical) semi-major axis a_{ef} ($a_{ef} > a$).

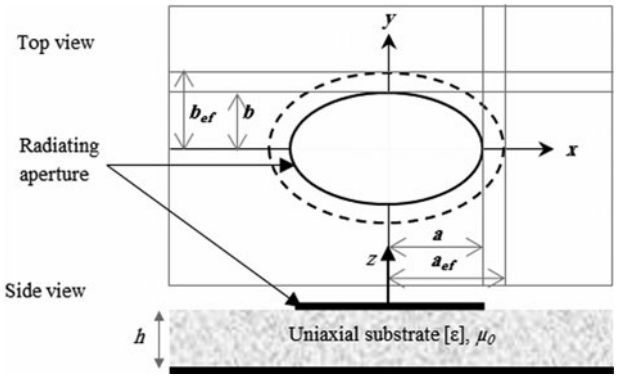


Fig. 1. Geometrical configuration of EMAs for dual-resonant frequency.

The parameter a_{ef} is used to account for the stored energy in the fringing field of elliptical edge. Therefore, f_{11}^{eo} is a closed-form formula determined accurately by replacing the physical semi-major axis a with the effective semi-major axis a_{ef}

$$f_{11}^{e,o} = \frac{15}{\pi e a_{ef}}\sqrt{\frac{q_{11}^{e,o}}{\varepsilon_{ef}}}. \tag{2}$$

Determination of the exact values of Mathieu function q_{mn}^{eo} for the given modes are rather complicated to avoid this complexity, the approximate Mathieu function q_{mn}^{eo} of the dominant TM_{11}^{eo} mode, can be obtained from [5]

$$\begin{aligned} q_{11}^{e} &= -0.0049e + 3.7888e^2 - 0.7278e^3 + 2.2314e^4, \\ q_{11}^{o} &= -0.0063e + 3.8316e^2 - 1.1351e^3 + 5.2229e^4. \end{aligned} \tag{3}$$

The dual-frequency f_{11}^{eo} with eccentricities $e = \sqrt{1-(b/a)^2}$ corresponding to the aspect ratio [6, 16, 17].

The effective semi-major axis should be considered the suggested approach in [15] is applicable to the EMAs. The f_{11}^{eo} of the modified structure for the TM_{11}^{eo} mode is calculated by modifying the equation for a circular microstrip antenna [16] as given below

$$a_{ef} = \left\{ a^2 + \frac{ha}{0.3525\pi\varepsilon_{ref}}\left[\ln\left(\frac{a}{2h}\right) + (1.41\varepsilon_{ref} + 1.77) + \frac{h}{a}(0.268\varepsilon_{ref} + 1.65)\right]\right\}^{1/2}. \tag{4}$$

The effective dielectric permittivity ε_{ef} depends on the relative dielectric permittivity ε_r and the ratio of the aperture dimensions to substrate thickness of the microstrip antenna [13] as

$$\varepsilon_{ef} = \varepsilon_r - \frac{0.7\varepsilon_r}{2}\left(\frac{h}{a} + \frac{h}{b} + \frac{h^2}{ab}\right). \tag{5}$$

It should be pointed out that the correction to the resonant frequency (1) in formula (2) involves both the effective permittivity and the effective semi-major axis, what permits to obtain a good agreement between theory and experiment in the case of the elliptical-disk antenna.

If we want to take the substrate uniaxial anisotropy into account, the relative dielectric permittivity ϵ_r will be replaced with the tensor $\epsilon_r = diag(\epsilon_x, \epsilon_x, \epsilon_z)$ where ϵ_x and ϵ_z are the relative dielectric permittivity along x and z axis, respectively.

- For the case of isotropic substrate, the effective dielectric constant ϵ_{ef} is given in equation (5).
- For the case of uniaxially anisotropic substrate, ϵ_{ef} and h_e given in [18] is used, there resulting values are:

$$\varepsilon_{eq} = \varepsilon_z, \tag{6}$$

$$h_e = h\sqrt{\frac{\varepsilon_x}{\varepsilon_z}}. \tag{7}$$

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Table 1. Comparison of calculated and measured resonant frequencies of EMAs with $h = 0.1575$ cm, $\varepsilon_r = 2.48$, $a = 4$ cm.

e	Measured [17] (GHz)		calculate [6]		Present technique (Ghz)		Absolute error (%)	
	f^e_{11}	f^o_{11}	f^e_{11}	f^o_{11}	f^e_{11}	f^o_{11}	f^e_{11}	f^o_{11}
0.273	1.410	1.385	1.417	1.389	1.415	1.388	0.354	0.216
0.2178	1.400	1.378	1.401	1.385	1.399	1.383	0.071	0.362
0.1836	1.380	1.370	1.394	1.383	1.392	1.381	0.869	0.802
0.0894	1.370	1.370	1.382	1.379	1.380	1.378	0.729	0.583

Absolute error % $= |(f_{theo} - f_{meas})|/f_{meas} \times 100$.

Table 2. Dependence of dual-resonant frequency on relative permittivities with $h = 0.3175$ cm, $\varepsilon_r = 2.48$, $a = 4$ cm, $b = 3.84$ cm.

Uniaxial anisotropy type	Relative permittivity		Anisotropic ratio AR	Resonant frequencies (GHz)		Fractional change $\Delta f_r/f_r$ (%)	
	ϵ_x	ϵ_z	$AR = \epsilon_x/\epsilon_z$	f^e_r	f^o_r		
Isotropic	2.48	2.48	1	1.328	1.354	0	0
Negative	4.96	2.48	2	1.281	1.307	3.54	3.47
Negative	2.48	1.24	2	1.708	1.742	28.61	28.66
Positive	1.24	2.48	0.5	1.362	1.39	2.56	2.66
Positive	2.48	4.96	0.5	0.982	1.002	26.05	26.00

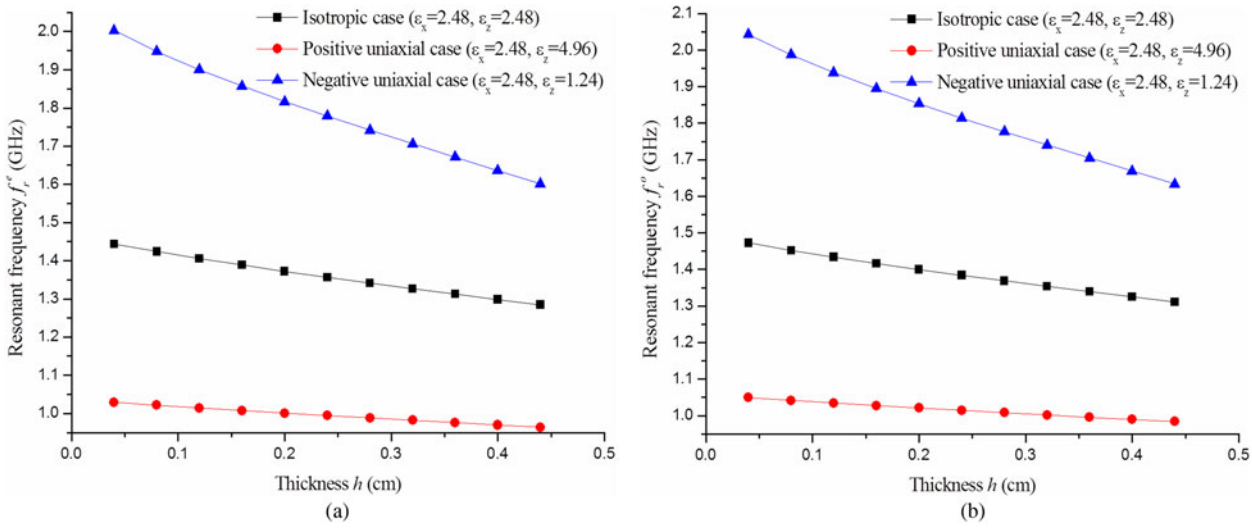


Fig. 2. Variation of resonant frequency with thickness of EMA, (a) even mode, (b) odd mode with; $h = 0.3175$ cm; $a = 4$ cm, where ε_z varied.

III. NUMERICAL RESULTS AND DISCUSSION

In order to examine the computation accuracy of the approach described in the previous section, Table 1 shows the results for the resonant frequencies of elliptical-disk microstrip antenna on isotropic substrate have been compared with previously published results [6, 17].

In Table 1, the results of our model and those calculated and measured by [6, 17] are shown with corresponding percentage error values. It is observed that the results of this model are better than the results of [17, 6] for isotropic substrate case having smaller percentage error values.

Next, the effect of uniaxial anisotropy on the resonant frequency is analyzed. The anisotropy ratio (AR) is defined as

$$AR = \varepsilon_x/\varepsilon_z. \tag{8}$$

The resonant frequency of an elliptical microstrip patch antenna with dimensions $a = 4$ cm, $b = 3.84$ cm and substrate thickness $h = 0.3175$ cm, for different pairs of relative permittivities (ϵ_x, ϵ_z) is depicted in Table 2.

The change in the dual-resonant frequency relative to the isotropic case ($\epsilon_x = \epsilon_z = 2.48$) is calculated using the

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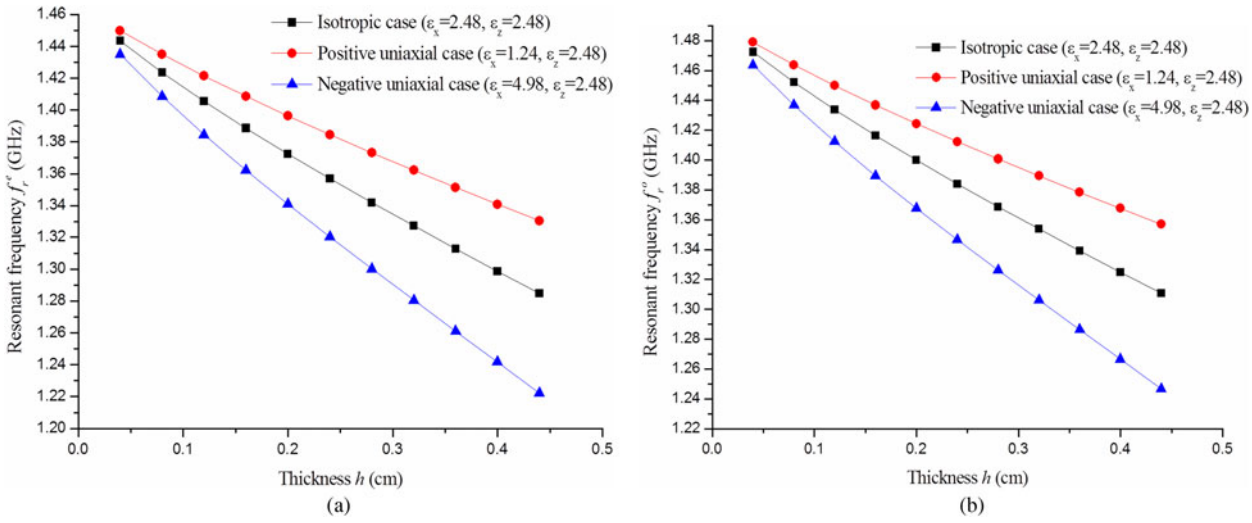


Fig. 3. Variation of resonant frequency with thickness of EMA, (a) even mode, (b) odd mode with; $h = 0.3175$ cm; $a = 4$ cm, where ε_x varied.

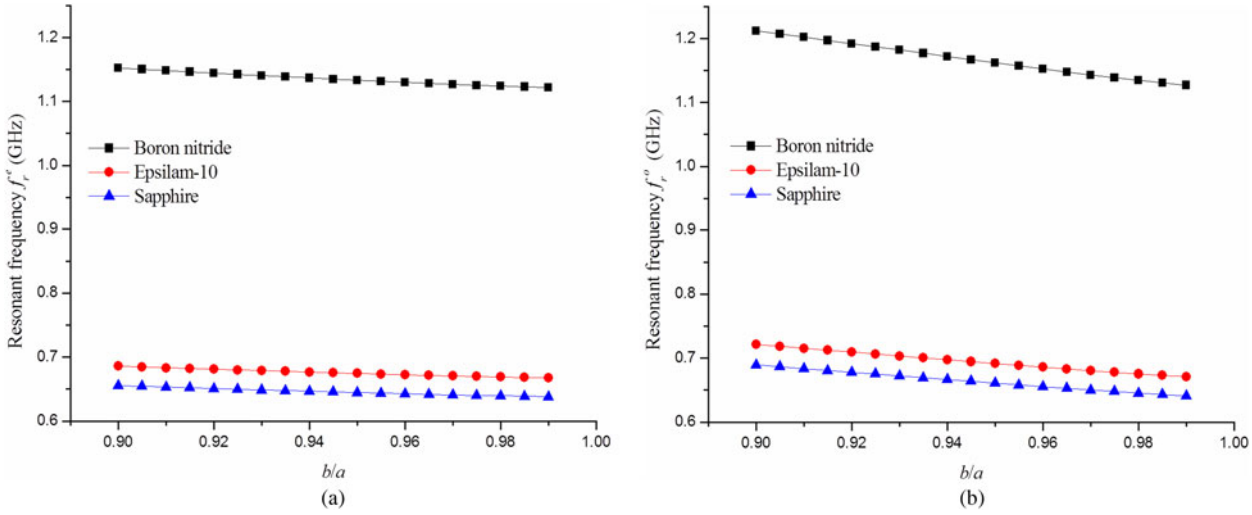


Fig. 4. Dual-resonant frequencies of elliptical microstrip patch antenna versus b/a ratio for different anisotropic dielectric substrates; (a) even mode, (b) odd mode, with $h = 0.3175$ cm, $a = 4$ cm, and $\varepsilon_r = 2.48$.

following expression:

$$\frac{\Delta f_r}{f_r} = \left|1 - \frac{f_{ra}}{f_{ri}}\right|, \tag{9}$$

Where f_{ri} and f_{ra} are, respectively, the resonant frequencies of the antenna for the isotropic and uniaxial anisotropic cases. We observe that, for negative uniaxial anisotropy with AR = 2, the resonant frequency f_{ri}, can shift to a lower value of $(f_r^e, f_r^o) = (1.281, 1.307)$GHz or higher frequency of (1.708, 1.742). A similar remark can be made for the positive uniaxial anisotropy case with AR = 0.5; the corresponding values of lower and higher frequencies are, respectively, (0.982, 1.002) and (1.362, 1.390). Consequently, the AR parameter alone is not sufficient to enhance a decision about whether there is an increase or decrease in resonant frequency to be made.

The resonant frequencies of the elliptical patch against the substrate thickness are shown in Figs 1 and 2, where isotropic ($\epsilon_x = \epsilon_z = 2.48$), negative ($\epsilon_x > \epsilon_z$) uniaxial anisotropic and positive ($\epsilon_x < \epsilon_z$) uniaxial anisotropic substrates are considered.

In Fig. 2, the anisotropy is obtained by changing ϵ_z while keeping ϵ_x constant. The effect of the permittivity along the optical axis persists for low as well as for high substrate thicknesses. When ϵ_x is changed and ϵ_z remains constant, the influence of the resonant frequency decreases with reductions in substrate thickness as shown in Fig. 3. This influence tends to be neglected for lower substrate thickness. These behaviors agree very well with those reported for a various shapes patch antenna, by [7–8, 10–11]. We can conclude that the permittivity ϵ_z along the optical axis is the significant and most important factor in determination of the dual-resonant frequency.

Figure 4 depict the influence of the aspect ratio (b/a) on the resonant frequencies (even and odd mode) of an elliptical microstrip patch antenna for three anisotropic dielectric substrate: boron nitride ($\epsilon_x = 5.12$, $\epsilon_z = 3.4$), epsilam-10 ($\epsilon_x = 13$, $\epsilon_z = 10.3$), and sapphire ($\epsilon_x = 9.4$, $\epsilon_z = 11.6$). The substrate has thickness $h = 0.3175$ cm with varying the aspect ratios (b/a).

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As it can be seen, the dual-resonant frequency (f_r^e, f_r^o) reduces considerably when the dielectric substrate changes from boron nitride to epsilam-10, and this is in constant to happens when the medium changes from epsilam-10 to sapphire. Also it is observed that the resonant frequency decreases with increases of aspect ratios (b/a).

IV. CONCLUSION

This paper presents the expression for predicting the dual-resonant frequencies of an elliptical patch microstrip printed on isotropic or anisotropic substrate. This model is suitable for CAD and is directly applicable for the investigation of microstrip antenna in portable wireless equipment. The theoretical results are in very good agreement with experimental results. The obtained results confirm that to predict the dual-resonant frequencies variations with anisotropic substrate permittivity, it is necessary to consider both the variation of ϵ_x and ϵ_z, not only the ratio ϵ_x/ϵ_z. Other obtained results show that the dependence of the resonant frequency on ϵ_x decreases with decreasing substrate thickness; for the thin substrates, the permittivity ϵ_z along the optical axis is the most important factor in determining the resonant frequency. The analysis presented here can be extended to study other parameters characterizing the elliptical patch antennas with various structures.

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