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SURFACE WAVES INVESTIGATION OF A BIANISOTROPIC CHIRAL SUBSTRATE RESONATOR

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Abstract—In this paper we studied the effect of a chiral-substrate bianisotropy on the surface waves of the microstrip resonator. The effective technique used to formulate the characteristic equations of the surface waves in a medium equipped with a complex anisotropy is presented and detailed. The equations concerning an evaluation of the cut-off frequencies are given in more detailed forms. A simple approximate formula for estimating the wave number of the surface mode TM_0 and TE_1 are obtained. An estimated maximum value of chiral slab thickness without the excitation of surface waves is given. All of our original results are compared with those published in the literature.

1. INTRODUCTION

In the last few years, a significant interest is directed towards the study of the effect of complex materials, such as: anisotropic dielectrics, magnetized ferrites, chiral materials, etc. on the realization of the MIC (Microwave Integrated Circuits) and of the APC (Antenna Printed Circuits). Certain standard anisotropic media are used as substrates for microwave printed resonators [1]. *Pozar* proved that the substrate anisotropy should always be taken into account when designing planar microstrip resonators; otherwise the structure is likely to operate out of the predicted frequency band [2].

Magnetized ferrites belong to the complex material class which proved to have a potential application as substrates in the field of MIC

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and APC. Measurements have confirmed that the resonant frequencies of the microstrip structures printed on ferrite substrates can be fixed according to a various choice of application. It was enough to adjust the polarization external magnetic field [3]. However ferrites can be employed to reduce the microstrip resonator [4, 5] as well as to design circularly polarized antennas by the application of a simple feed [6].

The possibility of employing chiral materials as substrates for the design of MIC and APC, was reported by *Lindell* [7]. On the other hand, *Pozar* [8] underlined the serious disadvantages of the use of these materials as substrates, because of the losses due to the surface waves excitation and the significant appearance of poles during numerical calculations.

Whereas, Toscano eand Vegni [9] and Zebiri et al. [10, 11] have recently proved that the chiral substrates can advantageously be employed to increase the band-width of the microstrip antennas. This result indicates that more attention must be paid to detailed studies of the surface waves excitation in the microstrip antennas over chiral substrates; which constitutes the aim of this paper.

This study evaluates the cut-off frequencies of TE_0 and TE_1 modes of a resonator printed on an anisotropic medium in order to optimize these structures according to their applications.These resonators appeared during the 1950s and especially were developed during the 1970s [12, 13]. They gather at the same time small size, simplicity, facility of manufacture and practical implementation. Moreover, they are easily matched to plane and non plane surfaces, and they exhibit a great robustness when assembled on rigid surfaces. They are also very effective in terms of resonance, polarization, input impedance and radiation diagram [14–16].

The major disadvantages of the microstrip resonators lie in their low purity of polarization. As regards the cases of the antennas we can consider the reduction of their band-width which is typically a few percent [16].

However, the increase of the substrate thickness and the reduction of the relative permittivity make it possible to improve the resonator efficiency up to 90%, and to increase its bandwidth up to 35%, provided that the surface waves are minimized [17].

2. CHIRAL MEDIA

The idea of using chiral materials as substrates and superstrates in the design of printed antennas, was firstly presented by *Engheta* [18] and the term "*chirostrip*" was then invented. In the literature, it is shown that the power of the surface wave can generally be reduced when a chiral substrate is employed for antennas intended for printed circuitry [19].

2.1. Maxwell's Equations

Chiral compound materials, which highlight the chiral effects at microwaves have been designed in many works, such as: [20, 21]. The chiral medium considered in our work has an inhomogeneous gyrotropic and can be characterized by a set of constitutive relations [22, 23]:

$$\vec{B} = \bar{\bar{\mu}}\vec{H} + \frac{\bar{\bar{\xi}}}{c_0}\vec{E} \tag{1}$$

$$\vec{D} = \bar{\bar{\varepsilon}}\vec{E} + \frac{\bar{\bar{\eta}}}{c_0}\vec{H} \tag{2}$$

c_0 is the speed of the light. Where the permeability and permittivity tensors are of a uniaxial anisotropy and the magnetoelectric elements are respectively given as follows:

$$\bar{\bar{\mu}} = \begin{bmatrix} \mu_t & 0 & 0 \\ 0 & \mu_t & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \tag{3}$$

$$\bar{\bar{\varepsilon}} = \begin{bmatrix} \varepsilon_t & 0 & 0 \\ 0 & \varepsilon_t & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} \tag{4}$$

$$\bar{\bar{\xi}} = \bar{\bar{\eta}} = j\begin{bmatrix} 0 & \xi & 0 \\ -\xi & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{5}$$

And $\vec{E}$, $\vec{H}$, $\vec{D}$ and $\vec{B}$ are respectively the electric and magnetic fields, and the electric and magnetic flux densities. In these relations, the additional magnetoelectric parameters ξ an η, represent the material chirality.Many fundamental problems using chiral materials were studied and several optical and microwaves circuits were presented [24–27]. From a physical point of view, the chirality presented by the magnetoelectric parameters ξ and η, are a measurement which represents the coupling between the electric and magnetic effects. And from an operational point of view, the additional degrees of freedom granted by ξ and η, allow the setting of the material properties and present a multitude of new phenomena and devices and original components.

2.2. Surface Waves

The surface waves modes are guided by the interface separating two different dielectric media [28]. In the design of the microstrip circuits as well as in their applications, the study of the surface waves is justified by one of the two following reasons: to minimize their effects or to use them in applications [29].

To analyze the characteristics of these waves produced at the interface substrate-conducting plate, by the excitation line. It is initially essential to take into account the proper modes propagation in the chiral layer. We study the propagation of these modes along z axis. For such a propagation, the interface of the structure can be considered as a particular case of *"chirowaveguide"* [24].

In [23] it is proved that in all *chirowaveguides*, the proper modes are hybrid [24], but for the case of the selected chiral the decomposition into TE and TM modes is possible [10, 11, 30, 31].

Their study would be also made during the evaluation of the improper integrals appearing in the formulation of the problem of a microstrip structure by the integral method. It would be also necessary, in certain situations, to determine as a preliminary the surface waves propagating modes, which appear in a microstrip structure. And this if we adopt the spectral method and the tensorial Green's function as an analysing tool. We can mention as an example the case where the integration of the characteristic matrix elements deduced from the Galerkin's method is performed on the wave numbers real axis [32, 33].

Moreover, if we are interested in the fields radiated by a microstrip structure without neglecting the radiation due to the surface waves, the determination of their wave numbers is necessary [34]. However, it is proved that the majority of the studies relating to this subject deal with the problem of the surface waves as being a procedure of two transcendent equations solution for which the expressions appear in the denominators of the Green's function [34–36].

The study in the case of simple structures, made up of one or two dielectric layers, does not present difficulties [37, 38]. However, for the structures that consist of more than two layers, the study becomes increasingly complicated, thus requiring tedious calculations. Thus, the resolution of the resulting characteristic equations and the asymptotic behavior of the solutions for low operating frequencies and low dielectric-layer thicknesses are more complicated. The traditional methods do not lead, in general, on simple expressions unless after providing significant algebraic calculi.

2.2.1. Isotropic Case

The surface waves induce radiations at the non-radiant ends of the structure. Moreover they can lead to the undesirable coupling between the radiant elements in the case of antennas array. The phase velocity of the surface waves strongly depends on the permittivity ε_r and the substrate thickness h. The surface waves excitation in a dielectric layer established on a ground plane was well studied [39]. The dominant mode having the lower frequency is the TM mode, which does not possesses any cut-off frequency ($f_c = 0$). The cut-off frequencies of the higher modes (TM_n and TE_n) are presented as:

$$f_c = \frac{n \cdot c_0}{4 \cdot h \cdot \sqrt{\varepsilon_r - 1}}, \quad n = 0, 1, 2, \ldots, \tag{6}$$

where c_0 is the speed of light, h and ε_r are respectively, the thickness and the permittivity of the substrate.

The cut-off frequencies for the TE_n modes are indicated by odd values of n (1, 3, 5, ...) and the cut-off frequencies for the TM_n modes are indicated by the even values of n.

For the TE_1 mode the computed values of the ratio $h/\lambda_c^{(1)}$ are: 0.217 for the duroid ($\varepsilon_r = 2.32$), 0.0833 for alumina ($\varepsilon_r = 10$). Using the following equation:

$$\frac{h}{\lambda_c^{(1)}} = \frac{n}{4 \cdot \sqrt{\varepsilon_r - 1}} \tag{7}$$

Thus, the low order mode TE_1 is excited at 41 GHz for a duroid substrate of thickness 1.6 mm, and at approximately 39 GHz for Alumina substrate of thickness 0.635 mm.

The thickness of the substrate is chosen so that the h/λ_0 ratio is lower than the report $h/\lambda_c^{(1)}$ ($\lambda 0$ is the wavelength in open space at the operating frequency), which gives [40]:

$$h < \frac{c}{4 \cdot f_u \sqrt{\varepsilon_r - 1}} \tag{8}$$

where f_u is the highest frequency in the operation band. Note that h should be chosen as high as possible, under the constraint indicated in (8), so that the maximum effectiveness is achieved. Moreover, h must be in conformity with the substrates available in the market. Another practical formula for h is given in [41] by:

$$h < \frac{0.3 \cdot c}{2\pi \cdot f_u \sqrt{\varepsilon_r}} \tag{9}$$

The TM_0 Mode has no cut-off frequency and is always present to a certain extent. The excitation of the surface wave TM_0 mode becomes appreciable when $h/\lambda > 0.09$ ($\varepsilon_r \cong 2.3$) and when $h/\lambda > 0.03$ ($\varepsilon_r \cong 10$). Generally, to eliminate the TM_0 mode, the permittivity should be lower and the substrate size should be smaller. Unfortunately, decreasing ε tends to increase the antenna size. Whereas decreasing h, thus leads to a limitation of the antenna effectiveness, hence the reduction of its band-width.

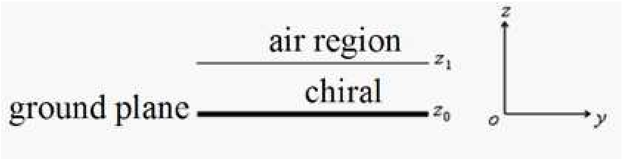

Figure 1. Monolayer chiral substrate configuration.

The reduction of surface waves, for the microstrip antennas printed on ferrites, has been discussed by many researchers [42–46]. Whereas in [47–49], electromagnetic band gap (**EBG**) structures, also known under the name of photonic crystals were carried out to reduce, and in certain cases, to eliminate the surface waves, which lead to an increase in the directivity and the bandwidth. In this context *Yang* [50] was the first who proposed antennas with large gain, which could be carried out with a unique radiant element printed on a photonic band gap (2-D **PBG)** material.

2.2.2. Chiral Case

In this paper, the problem of surface waves, in simple anisotropic monolayer microstrip structures is rigorously formulated and solved. The advantages of the method are highlighted and comparative analyses were carried out between our results and those published in the literature.

We consider in this part, the monolayer structure represented Figure 1. The radiant conducting plate is suppressed in this study, the structure is a chiral layer without excitation source established on a ground plane (Figure 1). The surface waves which occur and propagate in this structure have been studied.

2.2.2.1. Characteristic Equations Formulation (Modal)

In our previous work [10], we calculated the denominators of the Green tensor elements. And we point out here the modal equations of the surface waves:

For the TM modes

$$D^e = \kappa_z^e \kappa_z \varepsilon_t \cos(\kappa_z^e d) + j \left(\kappa_0^2 \varepsilon_t \mu_t - \frac{\varepsilon_t}{\varepsilon_z} \kappa^2 - j \kappa_z \kappa_0 \xi \varepsilon_t \right) \sin(\kappa_z^e d) = 0 \quad (10)$$

For TE modes,

$$D^h = \kappa_z^h \cos\left(\kappa_z^h d\right) + j \left(\kappa_z \mu_t - j \kappa_0 \xi\right) \sin\left(\kappa_z^h d\right) = 0 \quad (11)$$

where the wavenumbers κ_z^e, κ_z^h, κ_z, κ_0^2 and κ^2 are given in [10, 11].

2.2.2.2. Cut-off Frequencies of the Surface Waves

We develop asymptotic limits at low frequencies for TM_0 modes, where the cut-off frequencies of the surface waves are characterized by $\kappa_s = \kappa$. In the borderline of low frequencies $\kappa \to 0$. And by taking into account the preceding Equations (10) and (11), the asymptotic limits at low frequencies for the surface waves are obtained as follows:

For TM_0 mode, and at low frequencies, by letting $\lim\limits_{\kappa_0 \to 0} \kappa_s^2 = \kappa_0^2$, and according to [10], κ_z^e becomes:

$$\lim_{\kappa_0 \to 0} \kappa_z^{e2} = \kappa_0^2 \left(\varepsilon_t \mu_t - \xi^2 - \tfrac{\varepsilon_t}{\varepsilon_z} \right) \tag{12}$$

Knowing that in this case $\lambda \to \lambda_0$ since $\kappa_s \to \kappa_0$, by substituting (12) into (10), we find

$$\kappa_z = -j\kappa_0^2 \frac{(\varepsilon_z \mu_t - 1)}{\varepsilon_z (1 + \kappa_0 \xi d)} d \tag{13}$$

For the isotropic case the equation (13) is reduced to [38]:

$$\kappa_z = -j\kappa_0^2 d \frac{(\varepsilon_z - 1)}{\varepsilon_z} \tag{14}$$

For TM_1 mode, at low frequencies, where $\kappa_0^2 \to 0$ and $\lim\limits_{\kappa_0 \to 0} \kappa_s^2 = \kappa_0^2$, and according to [10], κ_z^h becomes:

$$\lim_{\kappa_0 \to 0} \kappa_z^{h2} = \kappa_0^2 \left(\varepsilon_t \mu_t - \xi^2 - \tfrac{\mu_t}{\mu_z} \right) \tag{15}$$

Knowing that in this case $\lambda \to \lambda_0$ since $\kappa_s \to \kappa_0$, by substituting (15) into (11), we find

$$\kappa_z = (1 - \kappa_0 \xi d) \frac{1}{\mu_t d} \tag{16}$$

The wavenumber Equations (13) and (16) are general formulas for the anisotropic case with chiral, they can be reduced to equal those obtained by Peixeiro et al. [38].

We evaluate the development of an approximate formula for the wavenumbers of TM_0 and TE_1 modes,

for TM mode

$$\kappa_z = -j\kappa_0^2 \mu_t \frac{1}{(1 + \kappa_0 \xi d)} \left(1 - \frac{1}{\varepsilon_z \mu_t} \right) d \tag{17}$$

And for TE_1 mode

$$\kappa_z = (1 - \kappa_0 \xi d) \frac{1}{\mu_t d} \tag{18}$$

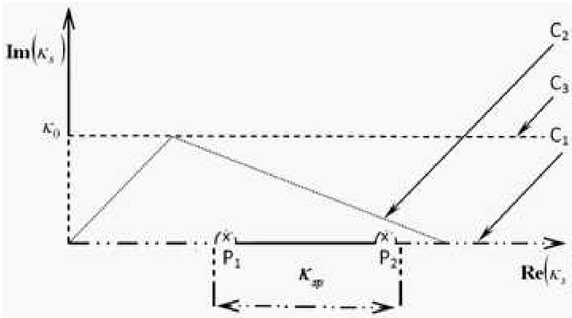

Figure 2. Surface waves approximate wavenumber in the integration path.

The chirality effect on the two wavenumbers is similar, for the case of very thin layers, while bringing the ratio $\frac{1}{1+\kappa_0\xi d}$ closer to $1-\kappa_0\xi d$.

According to the equation $\kappa_z^2 = \kappa_0^2 - \kappa_s^2$, by replacing κ_z in the Equation (12), we find the approximate expression:

$$\kappa_{sp}^2 = \kappa_0^2\left(1+\frac{\kappa_0^2 d^2}{\varepsilon_z^2}\frac{(\varepsilon_z\mu_t-1)^2}{(1+\kappa_0\xi d)^2}\right) \tag{19}$$

$$\lambda_{TM_0} = \kappa_0\left(1+\frac{\kappa_0^2 d^2}{\varepsilon_z^2}\frac{1}{(1+\kappa_0\xi d)^2}(\varepsilon_z\mu_t-1)^2\right)^{1/2} \tag{20}$$

And for TE_1 mode we have:

$$\kappa_{sp}^2 = \kappa_0^2\left(1-\left(\frac{(1-\kappa_0\xi d)}{\kappa_0\mu_t d}\right)^2\right) \tag{21}$$

$$\lambda_{TE_1} = \kappa_0\left(1-\left(\frac{(1-\kappa_0\xi d)}{\kappa_0\mu_t d}\right)^2\right)^{1/2} \tag{22}$$

The last two Equations (20) and (22) are useful as a good initial estimate for the pole location, in a standard routine, to seek the true solution, as shown in the Figure 2.

The approximation of the pole location in the integration path is harmful for the effective numerical evaluations of the integrals, it is advantageous to subtract the pole singularity and to reinstate it thereafter analytically.

In the case of a thick substrate, several poles may exist, and the analytical evaluation of the integrals around the half-circles becomes quite complex if two or several poles are very close to each other [51].

The total number of the poles is determined by the operating frequency and the dimensional parameters of the substrate [34, 51]. In the isotropic case it is possible to predict the number of poles, such as in [52], if we have $\kappa_0 d\sqrt{\varepsilon_r - 1} < \frac{\pi}{2}$ then the denominator of $G^h(\kappa_s)$ does not have any zero, while that of $G^e(\kappa_s)$ has only one.

In the case of a structure having only one isotropic dielectric layer i.e., $\varepsilon_z = \varepsilon_t = \varepsilon_r$, $\mu_z = \mu_t = 1$ and $\xi = 0$ the equality (21) is reduced to the simple expression given by [53, 54]:

$$\kappa_{sp}^2 = \kappa_0^2 \left(1 + \kappa_0^2 d^2 \frac{(\varepsilon_r - 1)^2}{\varepsilon_r^2}\right) \tag{23}$$

By replacing (12) in (10), we obtain the TM_0 mode cut-off frequency as follows:

$$\kappa^2 = \kappa_0^2 \frac{\kappa_0 \xi d}{(1 + \kappa_0 \xi d)} \tag{24}$$

It is sufficient to put $\kappa_z = 0$ in Equations (10) and (11), to deduce the cut-off frequencies of TE and TM modes; we find

for TM modes

$$f_c^{TM} = \frac{n \cdot c}{4 \cdot d} \frac{1}{\sqrt{\left(\varepsilon_t \mu_t - \frac{\varepsilon_z}{\varepsilon_t} - \xi^2\right)}}, \quad n \text{ is even.} \tag{25}$$

for TE modes

$$f_c^{TE} = \frac{c}{d} \frac{1}{\sqrt{\left(\varepsilon_t \mu_t - \xi^2 - \frac{\mu_t}{\mu_z}\right)}} \left(\frac{n}{2} - \frac{1}{2\pi} \arctan \frac{\sqrt{\left(\varepsilon_t \mu_t - \xi^2 - \frac{\mu_t}{\mu_z}\right)}}{\xi}\right),$$

$$n \text{ is odd.} \tag{26}$$

In the absence of the chirality, the Equations (25) and (26) become:

$$f_c^{TM} = \frac{n \cdot c}{4 \cdot d} \frac{1}{\sqrt{\left(\varepsilon_t \mu_t - \frac{\varepsilon_z}{\varepsilon_t}\right)}} \tag{27}$$

$$f_c^{TE} = \frac{2n + 1}{4} \frac{c}{d} \frac{1}{\sqrt{\left(\varepsilon_t \mu_t - \frac{\mu_t}{\mu_z}\right)}} \tag{28}$$

And in the case of nonmagnetic anisotropic dielectrics, Equations (27) and (28) become:

$$f_c^{TM} = \frac{n \cdot c}{4 \cdot d} \frac{1}{\sqrt{\left(\varepsilon_t - \frac{\varepsilon_z}{\varepsilon_t}\right)}} \tag{29}$$

$$f_c^{TE} = \frac{2n+1}{4} \frac{c}{d} \frac{1}{\sqrt{(\varepsilon_t - 1)}} \tag{30}$$

And in the case of isotropic dielectrics, Equations (29) and (30) become:

$$f_c^{TM} = \frac{n \cdot c}{4 \cdot d} \frac{1}{\sqrt{(\varepsilon_r - 1)}} \tag{31}$$

$$f_c^{TE} = \frac{2n+1}{4} \frac{c}{d} \frac{1}{\sqrt{(\varepsilon_r - 1)}} \tag{32}$$

The previous equations have the same forms of those developed in [38, 40].

The mode of low order TM_1 is excited at 40.77 GHz in a Duroid ($\varepsilon_r = 2.32$) substrate of thickness 1.6 mm, without the effect of the chirality [40]. On the other hand, with the same substrate with the consideration of a positive ($\xi = +1$)/negative ($\xi = -1$) coefficient of chirality, the TE_1 mode for the same structure is excited at 138.4/192.75 GHz. And at approximately 39.33 GHz for an isotropic 0.635 mm thick alumina ($\varepsilon_r = 10$) substrate [40], moreover at 50.75/116.16 GHz with the presence of a positive ($\xi = +1$)/negative ($\xi = -1$) chirality coefficient.

Moreover, the practical expression of d is no more that given by (8), but rather that given by (33), and we can in this case increase the thickness of the substrate without exciting the surface waves [17]:

$$d < \frac{c}{f} \frac{1}{\sqrt{\left(\varepsilon_t \mu_t - \xi^2 - \frac{\mu_t}{\mu_z}\right)}} \left(\frac{n}{2} - \frac{1}{2\pi} \arctan \frac{\sqrt{\left(\varepsilon_t \mu_t - \xi^2 - \frac{\mu_t}{\mu_z}\right)}}{\xi} \right) \tag{33}$$

3. NUMERICAL RESULTS AND DISCUSSION

According to the obtained results represented by the different expressions of the surface modes cut-off frequencies illustrated in Figures 3 and 4, the chirality moves the surface waves away from the operating frequency of the structure, which constitutes an apparent advantage for the antennas. However, for filter structures it is

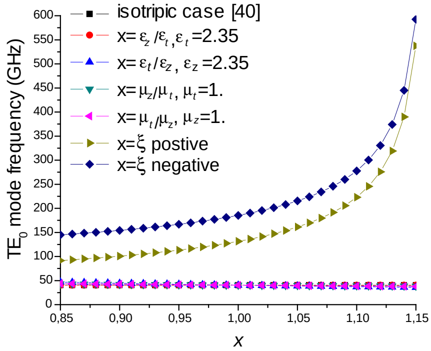

Figure 3. Effect of the chiral constitutive parameters on the TE_0 mode cut-off frequency versus different ratios. TE_0 is excited at 40.77 GHz in a Duroid ($\varepsilon_r = 2.32$) substrate of thickness 1.6 mm [40].

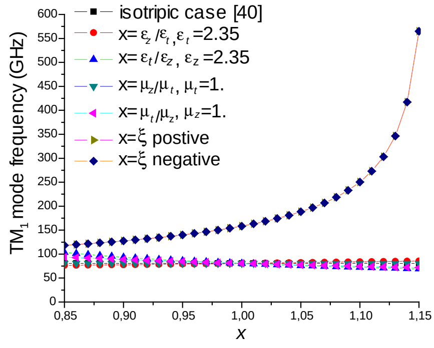

Figure 4. Effect of the chiral constitutive parameters on the TM_1 mode cut-off frequency versus different ratios, in Duroid ($\varepsilon_r = 2.32$) substrate of thickness 1.6 mm [40].

preferable to use the pure imaginary form, of the magnetoelectric elements, formulated from more complex expressions.

This case of study of TM and TE surface waves cut-off frequencies according to the medium constitutive parameters, ended in results which show clearly that the thicker the dielectric is, the more favored the surface waves excitation is.

4. CONCLUSION

The adopted approach in this paper can be employed during the analysis of the microstrip to predict the surface waves which appear in such structures. It can also be used for locating the integrands singularities that can be encountered in the solution by the method of moments via the Galerkin procedure The introduction of chiral leads to a diversity of applications. Its appreciable effect, which is the capacity of miniaturization of the structures, facilitates the electronic components integration [10, 11]. The chirality also moves away the surface waves from the operating frequency of the structure, which is an advantage for antennas. Whereas, for the filters, it is preferable to use the pure imaginary shape of the magnetoelectric elements of the chiral.This case of study of the TM or TE surface waves cut-off frequencies, with respect to the constitutive parameters of the medium, ended in results which show clearly that the possibility of excitation of the surface waves is more favored when the dielectric become increasingly thick, compared to components with traditional dielectrics.

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