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# Analysis of the Combinatory Effect of Uniaxial Electrical and Magnetic Anisotropy on the Input Impedance and Mutual Coupling of a Printed Dipole Antenna

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**ABSTRACT** The main objective of this work is to investigate the combinatory effects of both uniaxial magnetic and electrical anisotropies on the input impedance, resonant length and the mutual coupling between two dipoles printed on an anisotropic grounded substrate. Three different configurations: broadside, collinear and echelon are considered for the coupling investigation. The study is based on the numerical solution of the integral equation using the method of moments through the mathematical derivation of the appropriate Green's functions in the spectral domain. In order to validate the computing method and evaluated Matlab® calculation code, numerical results are compared with available literature treating particular cases of uniaxial electrical anisotropy; good agreements are observed. New results of dipole structures printed on uniaxial magnetic anisotropic substrates are presented and discussed, with the investigation of the combined electrical and magnetic anisotropies effect on the input impedance and mutual coupling for different geometrical configurations. The combined uniaxial (electric and magnetic) anisotropies provide additional degrees of freedom for the input impedance control and coupling reduction.

**INDEX TERMS** Spectral domain analysis, uniaxial anisotropy, input impedance, mutual coupling, dipole antenna, dipole antenna.

## I. INTRODUCTION

With the advancement of telecommunications in recent years, it has become increasingly obvious to use planar antennas

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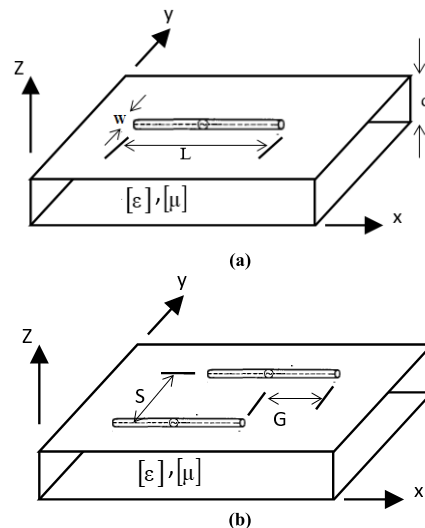
and antenna arrays in many areas. In fact, the technology of printed antennas has greatly benefited from these advances. On the other hand, these antennas have potentially contributed in their turn to the development of these systems. Dipole antennas show specific characteristics and features that make them attractive for modern wireless

communication applications. They continue to play a crucial role in communication technologies for various wireless applications, all with outstanding operating performances. Simple, small, inexpensive, easy to mount and to integrate with microwave monolithic integrated circuits (MMICs), the planar dipole antennas have been specifically designed to be applied in many antenna and antenna arrays technologies. They are widely used in telecommunication applications, among others, we cite mobile phone systems, RFID, ISM systems and wireless sensors [1]–[4]. This has led to deploying further efforts in order to be able to model and properly characterize these microwave components in terms of geometry as well as in terms of materials related to the manufacture of these devices. Recently, as material sciences have greatly advanced, the complex media have significantly arose as promising materials in the field of microwaves and optics [5]–[7].

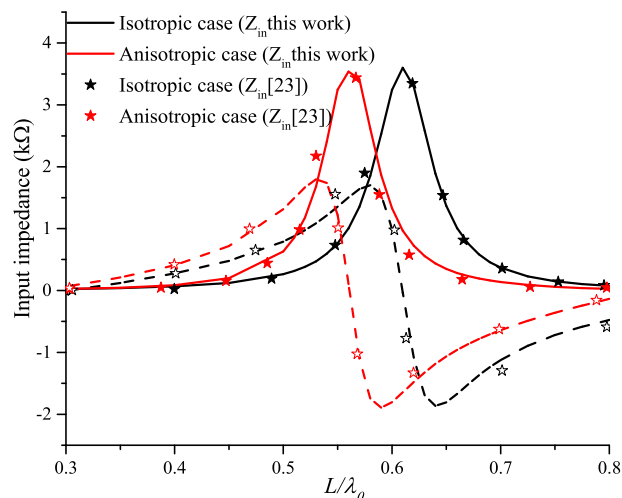
In general, complex media have seen increased interest from scientists and researchers within the frame of artificial media with new and exciting properties due to their extra degree of freedom [6]. Anisotropy is an intrinsic property that is found in crystals, layered structures, composite materials and other natural materials, in addition to artificial ones. The effect of anisotropy is necessary to be taken into consideration and cannot be ignored in predicting properties in engineering design for sensing and antenna applications [8]–[10]. These have attracted a lot of interest and support from researchers and manufacturers as powerful instruments with a promising growth potential in microwave applications [11]. Several studies have been conducted to characterize microwave structures printed on complex media, ferrites, metamaterials, chiral using numerical and analytical methods [10]–[21]. Input impedance and mutual coupling of single and multilayer dipole antennas printed on isotropic, anisotropic and chiral materials have been investigated in [22]–[27]. In [23], [24], and [26], only cases of electrical anisotropy were considered and no discussion of the effect of this component was carried out. In this work, we have characterized a dipole antenna printed on an anisotropic substrate by highlighting, in particular, the effect of uniaxial electrical and magnetic anisotropy on the input impedance, resonant length and mutual coupling of two printed dipoles. Three main configurations are considered: broadside, collinear and echelon. The study is based on a theoretical formulation in the spectral domain and a numerical solution technique using the spectral method of moments.

**II. ANALYTICAL FORMULATION**

Fig. 1 shows the structure considered in this analysis. The presented configuration will be used to determine the mutual coupling between the printed dipoles and to determine how the input impedance is affected by the uniaxial anisotropic layer. The direction of propagation is directed along the z-axis and it is considered as the optic axis. In this study, the uniaxial electrical and magnetic anisotropic substrates are characterized by the following expressions of the permittivity



**FIGURE 1. (a) Printed dipole (b) Geometry of mutual coupling configurations.**



**FIGURE 2. Comparison of our computed input impedance of printed dipoles on isotropic and anisotropic layer with those in [23], [24].**

and permeability, respectively:

$$[\epsilon] = \epsilon_0 \begin{bmatrix} \epsilon_t & 0 & 0 \\ 0 & \epsilon_t & 0 \\ 0 & 0 & \epsilon_z \end{bmatrix} \tag{1a}$$

$$[\mu] = \mu_0 \begin{bmatrix} \mu_t & 0 & 0 \\ 0 & \mu_t & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \tag{1b}$$

The guided electromagnetic field propagation in the considered anisotropic medium is described in terms of superposition of the decoupled TM and TE modes. The deduced longitudinal components of the electromagnetic field of the TE and TM modes satisfy the following homogeneous second-degree differential wave equation [15]:

$$\frac{\partial^2 \tilde{E}_z}{\partial z^2} - \gamma_e^2 \tilde{E}_z = 0 \tag{2a}$$

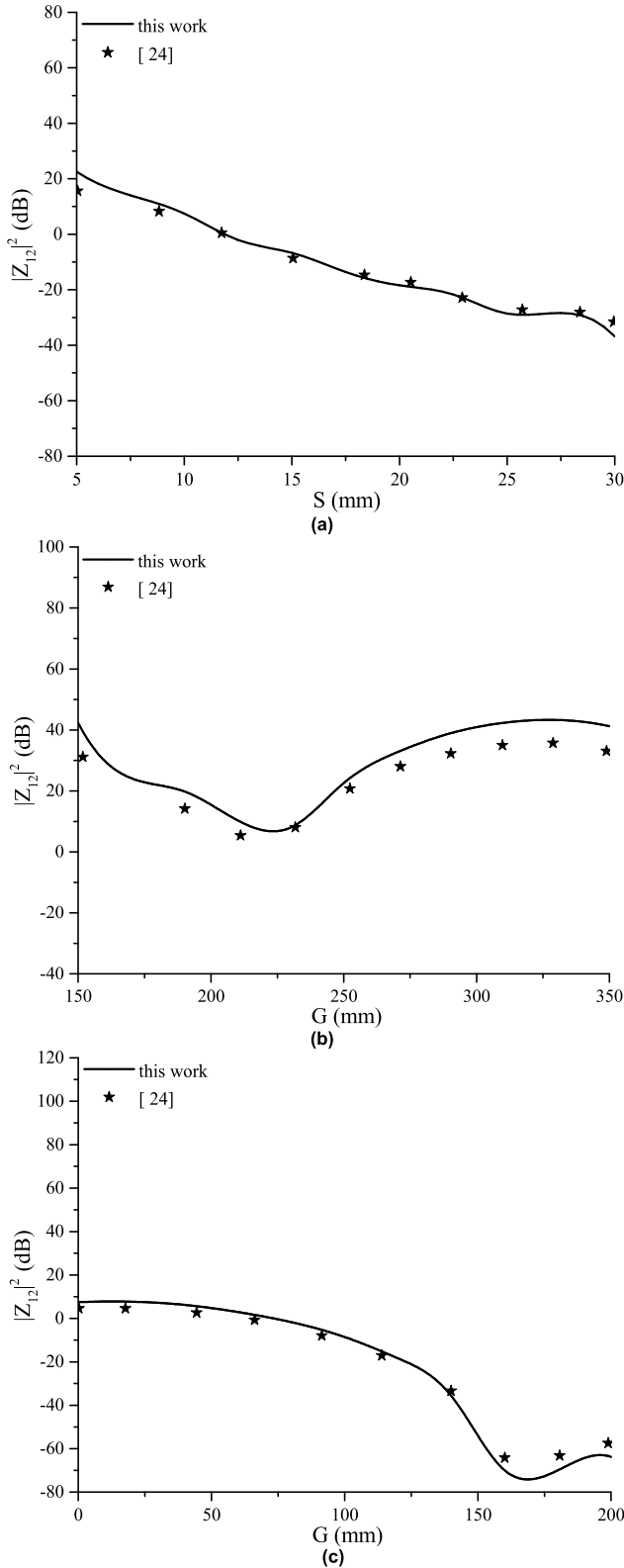


FIGURE 3. Comparison of our computed results of mutual coupling of printed dipoles on isotropic layer with those reported in [24] of (a) broadside (b) collinear and, (c) echelon configurations.

$$\frac{\partial^2 \tilde{H}_z}{\partial z^2} - \gamma_h^2 \tilde{H}_z = 0 \quad (2b)$$

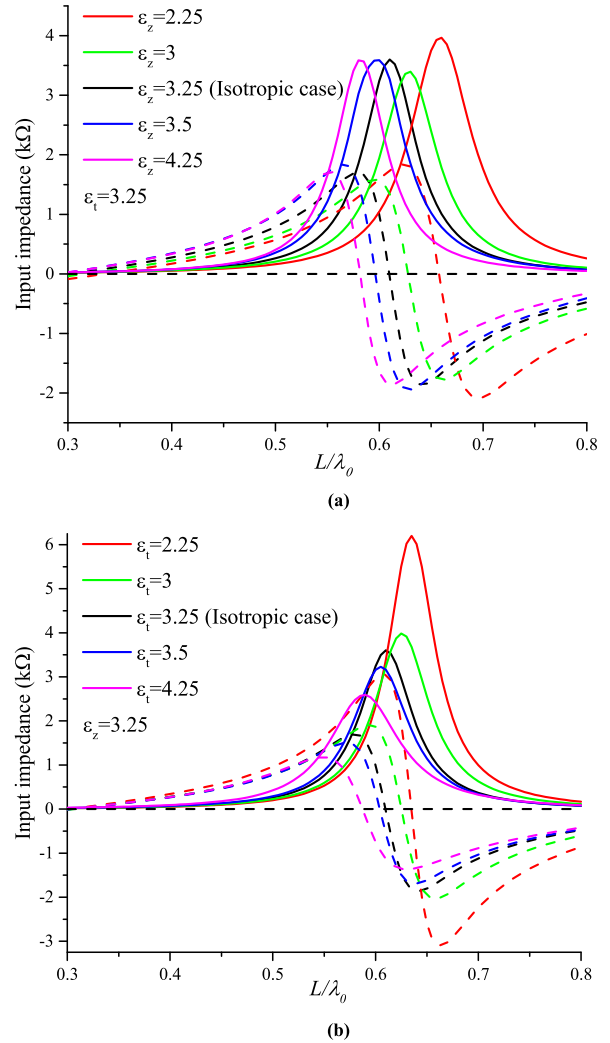


FIGURE 4. Real and imaginary parts of input impedance with uniaxial anisotropic substrate of printed dipole antenna (a) for various values of  $\epsilon_z$ , (b) for various values of  $\epsilon_t$ .

The dispersion relations are found to be as follows:

$$\gamma_e = \sqrt{\left(\frac{\epsilon_t}{\epsilon_z} (\alpha^2 + \beta^2) - \kappa_0^2 \epsilon_t \mu_t\right)} \quad (2c)$$

and

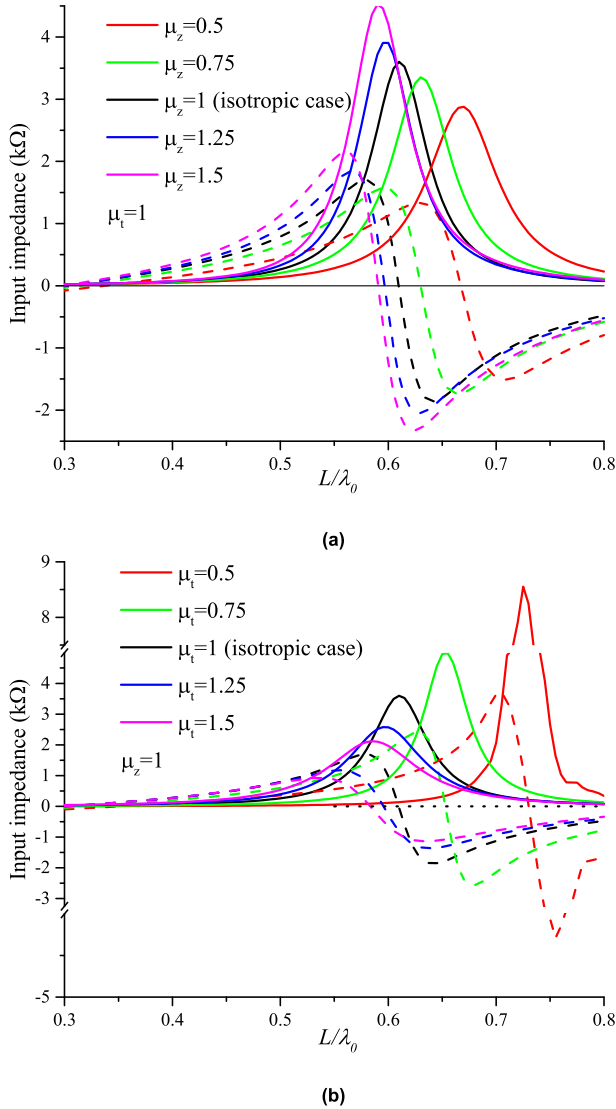
$$\gamma_h = \sqrt{\left(\frac{\mu_t}{\mu_z} (\alpha^2 + \beta^2) - \kappa_0^2 \epsilon_t \mu_t\right)} \quad (2d)$$

$\gamma_e^2$  and  $\gamma_h^2$  represent the propagation constants of the TM and TE transverse modes, respectively.  $\alpha$ ,  $\beta$  are the Fourier variables corresponding to the space domain and  $\kappa_0$  is the free space wavenumber.

### III. METHOD OF SOLUTION

Afterward, let's search solutions for the two differential equations (2a) and (2b). The longitudinal components  $\tilde{E}_z$  and  $\tilde{H}_z$  in the guided region admit the forms given by the following expressions:

$$\tilde{E}_z(\gamma_e, z) = A_e \cosh(\gamma_e z) + B_e \sinh(\gamma_e z) \quad (3a)$$



**FIGURE 5.** Real and imaginary parts of input impedance with uniaxial anisotropic substrate of printed dipole antenna (a) for various values of  $\mu_z$ , (b) for various values of  $\mu_t$ .

$$\tilde{H}_z(\gamma_h, z) = A_h \sinh(\gamma_h z) + B_h \cosh(\gamma_h z) \quad (3b)$$

where  $A_e, B_e, A_h$  and  $B_h$  are complex constants.

On the other hand, for the region above the substrate (air), the spectral components are decreasing waves with  $z$ , for which the following solutions are assumed:

$$\tilde{E}_z(\gamma_0, z) = C_e e^{-\gamma_0(z-d)} \quad (4a)$$

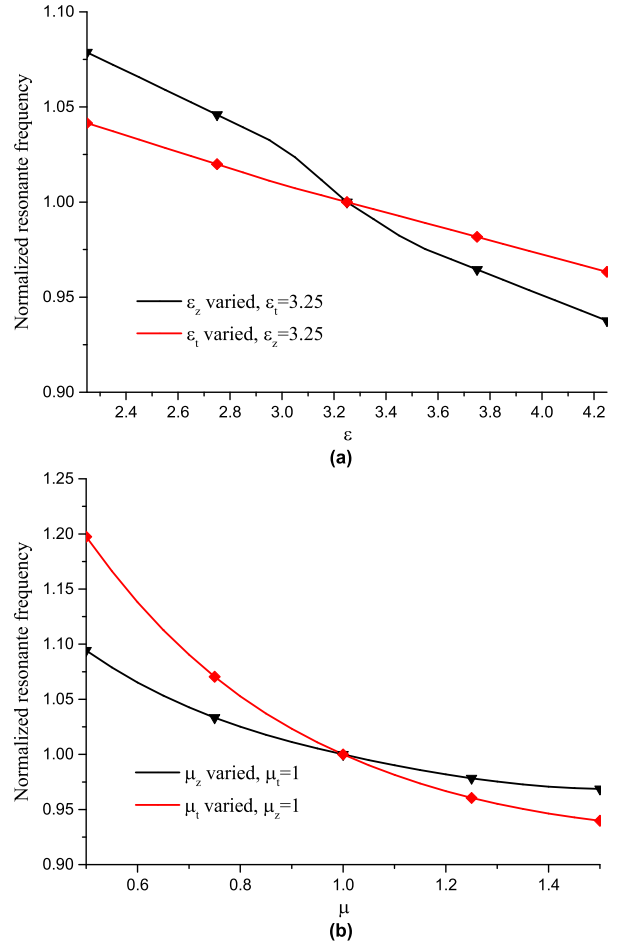
$$\tilde{H}_z(\gamma_0, z) = C_h e^{-\gamma_0(z-d)} \quad (4b)$$

where

$$\gamma_0 = \sqrt{(\alpha^2 + \beta^2) - \kappa_0^2} \quad (4c)$$

and  $C_e$  and  $C_h$  are complex constants.

To determine the complex constants appearing in the expressions of the electromagnetic field components, the following boundary conditions are used at  $z = 0$  and



**FIGURE 6.** Normalized resonant frequency of the dipole with uniaxial anisotropic substrate for various values of (a):  $[\epsilon]$  and (b):  $[\mu]$ .

at  $z = d$ :

$$\tilde{E}_{x1} = \tilde{E}_{y1} = 0 \quad (5a)$$

$$\tilde{E}_{x1} = \tilde{E}_{x2} \quad (5b)$$

$$\tilde{E}_{y1} = \tilde{E}_{y2} \quad (5c)$$

$$\tilde{H}_{y2} - \tilde{H}_{y1} = \tilde{J}_x \quad (5d)$$

$$\tilde{H}_{x1} - \tilde{H}_{x2} = \tilde{J}_y \quad (5e)$$

Detailed algebraic analyses of the resulting mathematical equations lead to the formulation of the estimated electric field at the interface between the two media with respect to current densities  $\tilde{J}_x$  and  $\tilde{J}_y$ . Green's tensor elements are obtained and arranged to satisfy the following system of equations [25], [28].

$$\tilde{E}_x = \tilde{G}_{xx}\tilde{J}_x + \tilde{G}_{xy}\tilde{J}_y \quad (6a)$$

$$\tilde{E}_y = \tilde{G}_{yx}\tilde{J}_x + \tilde{G}_{yy}\tilde{J}_y \quad (6b)$$

where  $\tilde{J}_x$  and  $\tilde{J}_y$  are the Fourier transforms of the current densities. In the analysis of the configuration of narrow dipole structures, the studied case, the cross-current density in the  $y$ -direction is generally neglected, because it is assumed that the width of the strip is very small [25]. Therefore, only the

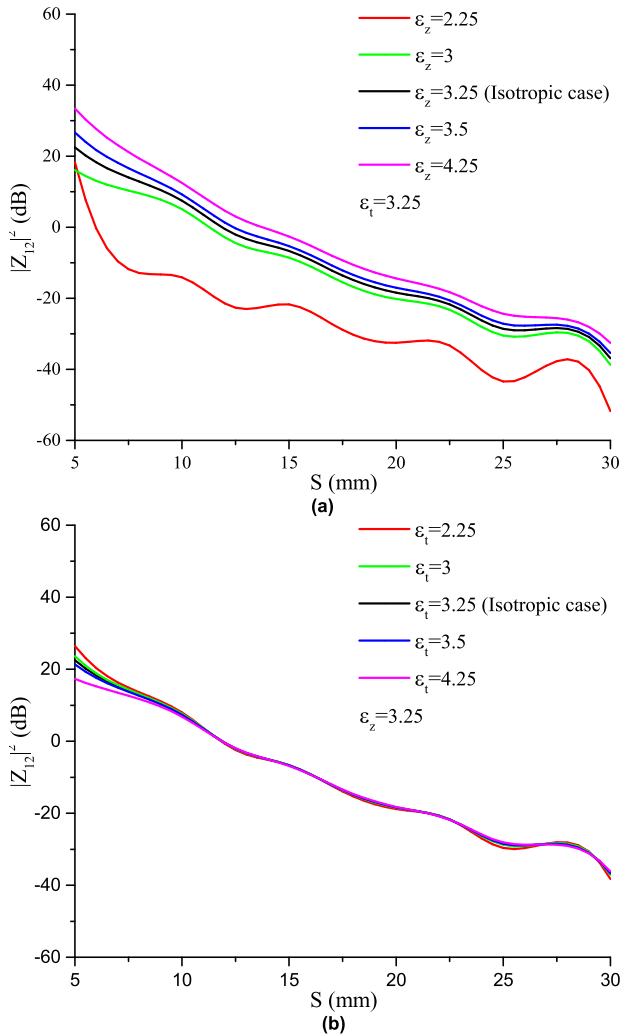


FIGURE 7. Broadside mutual coupling for various values of (a):  $[\epsilon_z]$ , (b):  $[\epsilon_t]$ .

function of the green  $\tilde{G}_{xx}$  is presented, since the others are not involved in the calculations.

$$\tilde{G}_{xx} = \frac{-j}{\omega\epsilon_0(\alpha^2 + \beta^2)} \left( \frac{\alpha^2\gamma_0\gamma_e}{[\gamma_0\epsilon_t \coth(\gamma_e d) + \gamma_e]} - \frac{\beta^2\kappa_0^2\mu_t}{(\gamma_h \coth(\gamma_h d) + \mu_t\gamma_0)} \right) \quad (7)$$

#### IV. NUMERICAL RESULTS

In this work, we are first interested in the input impedance, the resonant length of the dipole and second in the mutual coupling between two printed dipoles arranged in three configurations. Before discussing the results obtained of the uniaxial anisotropy case, a validation of the calculation code elaborated, in Matlab, through a comparison with published literature is essential.

##### A. VALIDATION

In this subsection, we investigate the effect of the substrate anisotropy on the input impedance of the dipole, in addition

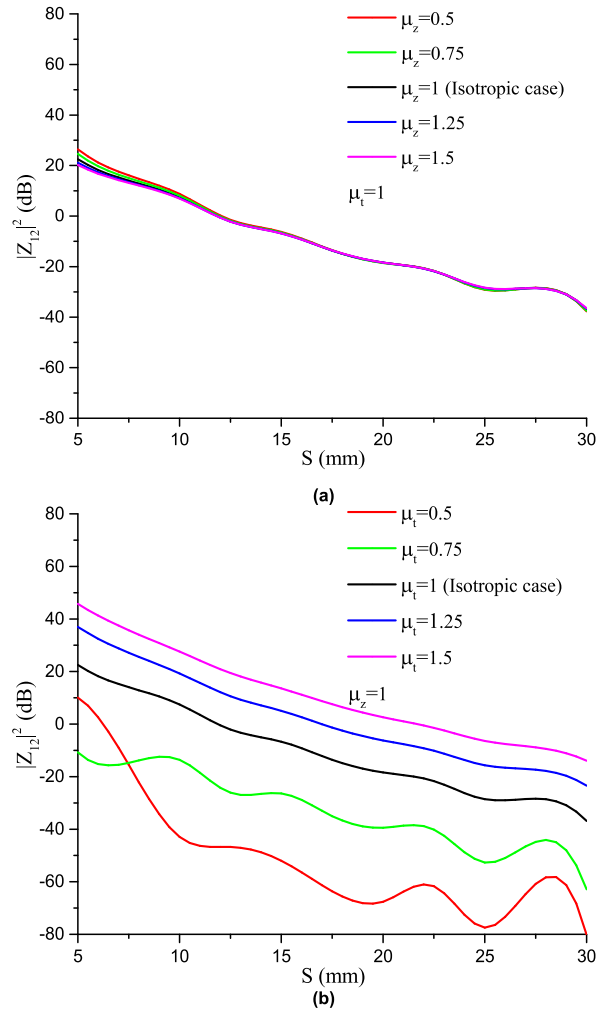


FIGURE 8. Broadside mutual coupling for various values of (a):  $[\mu_z]$  and (b):  $[\mu_t]$ .

to the consideration of the mutual coupling for three cases of geometrical configurations. Extensive computations were performed involving a dipole structure printed on a uniaxial anisotropic structure. The results from these computations were successfully compared to the published results. We have initially considered the isotropic and uniaxial anisotropic cases ( $\epsilon_t = \epsilon_z = 3.25$  and  $\mu_r = \mu_z = 1$ ) and ( $\epsilon_t = 3.14$ ,  $\epsilon_t = 5.12$  and  $\mu_r = \mu_z = 1$ ), respectively.

Fig.2 presents the input impedance (Continuous lines for real impedance parts and Broken lines for imaginary parts) of a planar dipole of width  $W = 0.0004 \lambda_0$  as a function of the normalized length  $L/\lambda_0$ . The dipole is printed on an anisotropic grounded dielectric slab of thickness  $d = 0.1060\lambda_0$ . Fig 3.a, b and c present the mutual coupling between printed dipoles according to the collinear, eche-lon and broadside configurations, respectively, for various values of  $L = 150\text{mm}$ ,  $W = 0.5\text{mm}$ ,  $f = 500\text{MHz}$  and  $d = 1.58\text{mm}$ . All of these dimensions were taken as they are reported in [23] and [24], so that we can validate our results.

The representation shows good agreements with data reported in [23] and [24].

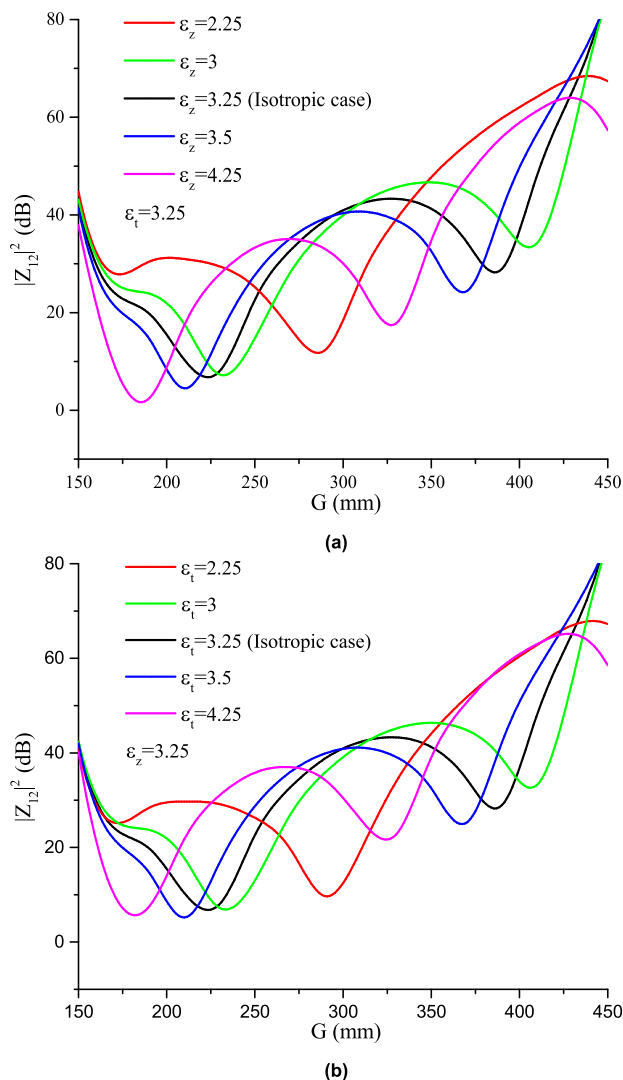


FIGURE 9. Collinear mutual coupling for various values of (a):  $[\epsilon_z]$ , (b):  $[\epsilon_t]$ .

These results represent a validation of the accuracy of the present work computations for both isotropic and anisotropic substrates. A comparison representation of the input impedance and mutual coupling for the configuration of Fig. 1 are presented in Fig. 2 and 3.

In the present analysis, we aimed to highlight the effect of combined uniaxial electrical and magnetic anisotropy that has been less addressed in the literature.

**B. EFFECT OF THE UNIAXIAL ELECTRICAL AND MAGNETIC ANISOTROPY ON THE INPUT IMPEDANCE**

Fig. 4.a shows the effect of  $\epsilon_z$  on the input impedance (continuous lines for real parts and broken lines for imaginary parts).

It consists in shifting the resonant length of the dipole antenna with a slight change in its peak, while  $\epsilon_t$  effects significantly the magnitude of the input impedance with an increase of its peak, where it is doubled, from 3kΩ for  $\epsilon_t = 3.25$  and  $\epsilon_z = 2.25$  to 6kΩ for  $\epsilon_t = 2.25$  and  $\epsilon_z = 3.25$ , all with a slight shift in the resonant length(Fig. 4.b).

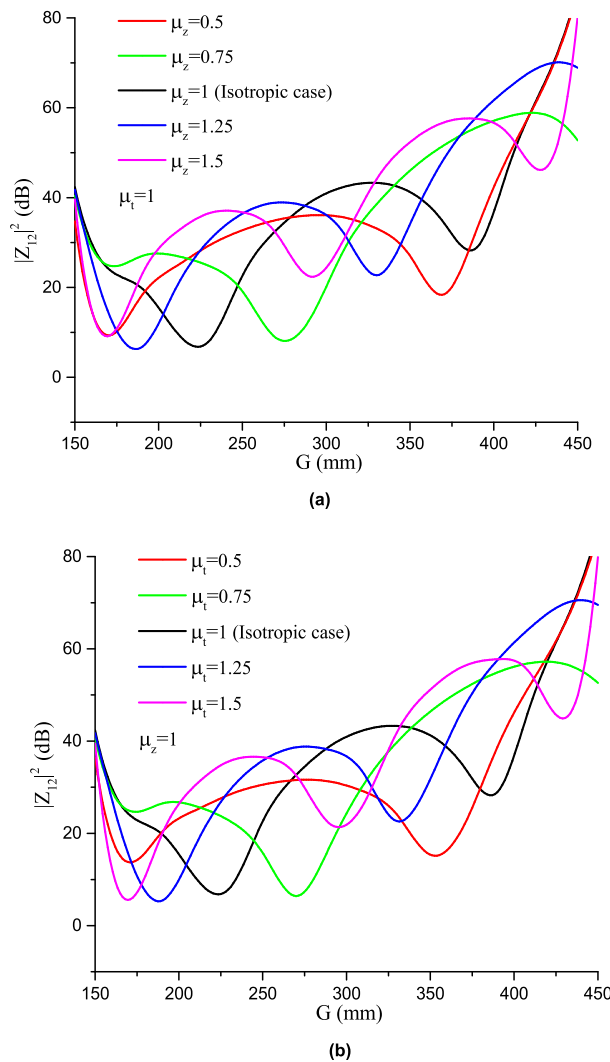


FIGURE 10. Collinear mutual coupling for various values of (a):  $[\mu_z]$  and (b):  $[\mu_t]$ .

In Figs. 5.a and b, the effect of the two components of permeability  $\mu_z$  and  $\mu_t$  does not resemble to that of the permittivity components  $\epsilon_z$  and  $\epsilon_t$ . An increase in  $\mu_z$  results in an increase in the input impedance peak, with a decrease in the resonance frequency.

The effect of the permeability component  $\mu_t$  is reversed in this case, where an increase in the  $\mu_t$  component leads to a significant increase in the resonance frequency with a decrease in the peak value of the input impedance. The boundary conditions imposed by the structure, the choice of uniaxial anisotropy along a given optical axis and the dimensions of the dipole mean that the Green’s tensor (which connects the electric field and the current density) is asymmetrically related to the four constituent parameters ( $\epsilon_t, \epsilon_z, \mu_t$  and  $\mu_z$ ). This may explain the difference registered between the effects of these components compared to each other.

**C. EFFECT OF THE UNIAXIAL ELECTRICAL AND MAGNETIC ANISOTROPY ON THE RESONANT FREQUENCY**

Figs 6.a and 6.b present the effect of the four elements of the uniaxial electrical and magnetic anisotropy on the resonant

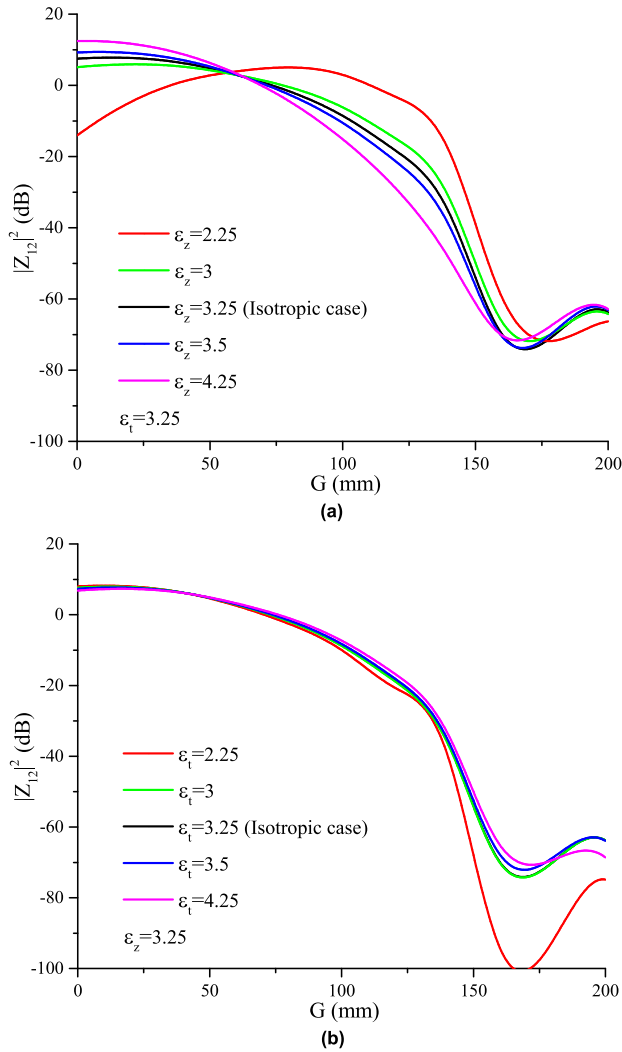


FIGURE 11. Echelon mutual coupling for various values of (a):  $\epsilon_z$ , (b):  $\epsilon_t$ .

frequency. The values of this latter have been obtained from the input impedance by varying  $\epsilon$  and  $\mu$ , respectively and calculating the corresponding resonance frequency which corresponds to the zero crossing of the reactance curve (imaginary part) [29], [30].

It is shown in Figs.6 that the resonant frequency decreases significantly as the value of the permittivity  $\epsilon_z$  and  $\mu_t$  are increased. In particular, the resonant frequency is mainly affected by the  $z$ -component of the permittivity and perpendicular permeability component  $\mu_t$ . This is because the dominant mode is present, which has a field component in the substrate in the  $z$ -direction [13], [26].

**D. EFFECT OF THE UNIAXIAL ELECTRICAL AND MAGNETIC ANISOTROPY ON THE MUTUAL COUPLING**

Mutual impedance computations between two printed dipoles have been performed in three main configurations: 1) broadside, 2) collinear and 3) echelon. In these cases, the dipoles in Fig. 1.b have a length of 15 cm, a width of 0.5 mm with a source frequency of 500 MHz.

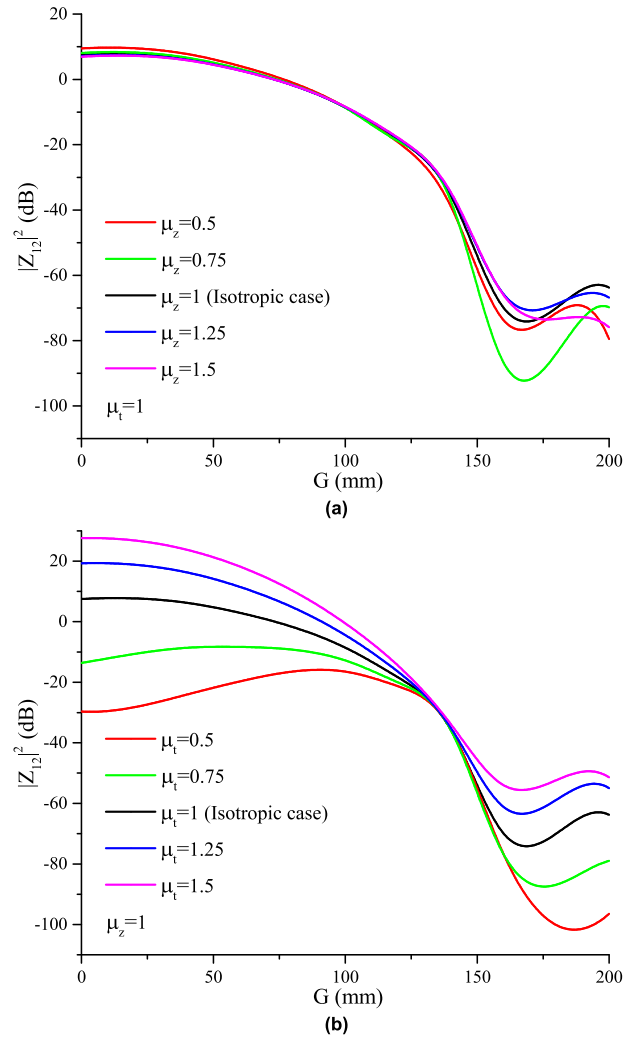
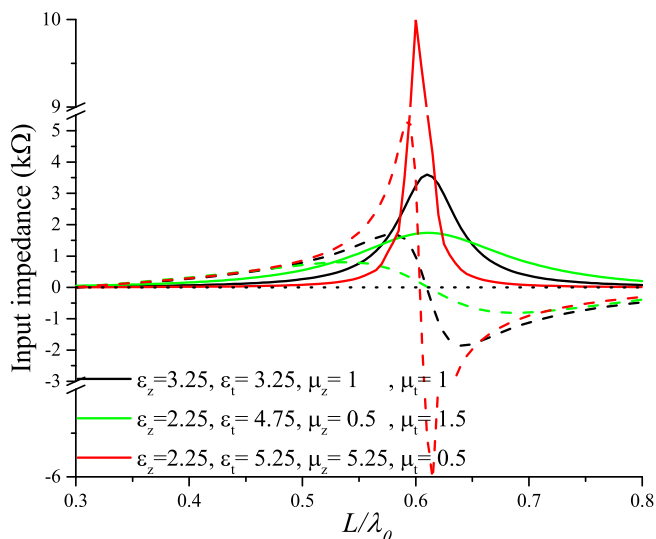


FIGURE 12. Echelon mutual coupling for various values of (a):  $\mu_z$  and (b):  $\mu_t$ .

The mutual coupling between the two printed dipoles in broadside case ( $G = 0$ ), has been calculated, illustrated and compared with literature (Figs. 7.a and 7.b), for various values of the anisotropic permittivity elements  $\epsilon_t$  and  $\epsilon_z$  by varying one element at a time. It is shown that the uniaxial anisotropy results agree well with those published in [23], [24].

The mutual coupling is the largest for the anisotropic values of  $\epsilon_t = 3.25$  and  $\epsilon_z = 5.12$ , and smallest for  $\epsilon_t = 3.25$  and  $\epsilon_z = 2.25$ , while as for the  $\epsilon_t$  component, it has no significant effect. The effect of the two components of the uniaxial magnetic anisotropy  $\mu_z$  and  $\mu_t$  is reversed in this case compared to the uniaxial electrical anisotropy; this is well illustrated in Fig 8.a and b.

The optimal case of mutual decoupling is reached for the permeability  $\mu_t = 0.5$ . This is because the dominant mode TM0 is along the  $z$ -direction *i.e.* the optical axis and is in direct relation with  $\epsilon_z$  and  $\mu_t$  [25]. In the case of a reduced mutual coupling a quasi-oscillation corresponding to lengths 7 and 5mm is noticed for  $\epsilon_z = 2.25$  (1<sup>st</sup> case)



**FIGURE 13.** Optimal combined uniaxial electrical and magnetic anisotropy elements effect on the input impedance of the dipole printed antenna.

and  $\mu_t = 0.5$  (2<sup>nd</sup> case), respectively. The corresponding frequencies of these lengths are 28.57 and 47.06 GHz respectively (Fig.7). Using the explicit cut-off-frequency expressions given in [31], close values are obtained: 29.68 GHz (TM1 mode) for the first case and 44.754 GHz (TE1 mode) for the second case.

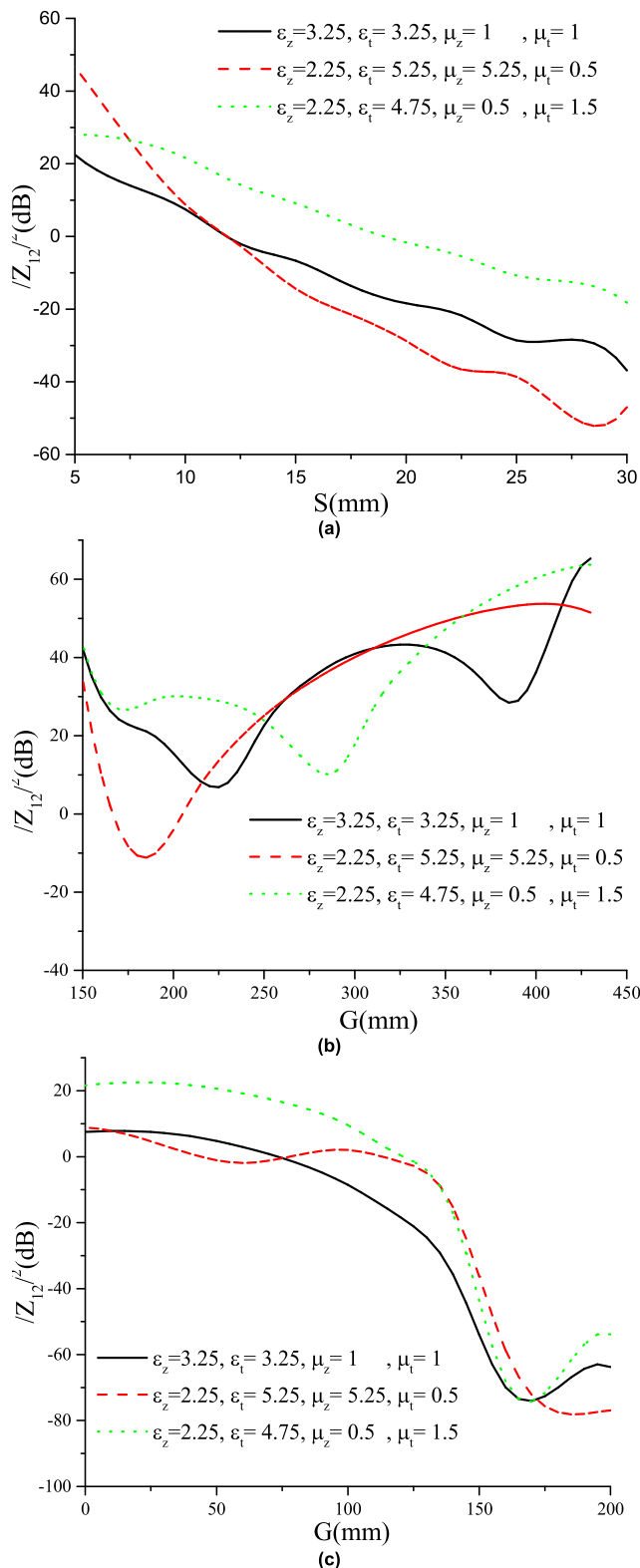
Figs. 9 and 10 show mutual impedance for the collinear case plotted versus the separation distance  $G$  for different uniaxial magnetic and electrical anisotropy elements. The mutual coupling decays very slowly with  $G$ . The period of oscillation of the mutual impedance as obtained from Fig. 6 is 150mm for the isotropic case, this value agrees with that reported in [26].

This agreement is excellent and confirms that the mutual coupling for the collinear configuration is only due to the surface waves TM mode [26]. The origin of the mutual coupling behavior for small values of  $G$  is due to the near zone field of the dipoles. This is because of the dominant mode in the substrate with no cutoff frequency. This may also explain the feeble and similar effect of the four constitutive elements. This agreement is good and shows that the coupling in collinear arrangement is dominated by the surface waves TM mode. This is due to the fact that most of the surface wave power carried by this mode flows inside the dielectric substrate [26].

In the echelon configuration, the mutual coupling computations versus spacing  $G$  are shown in Fig. 11 and 12 for different dipole lengths. For  $G = 0$  both dipoles are in the broadside configuration, while for larger distances, the dipoles are approximately collinear.

As  $G$  increases, the coupling factor decreases rapidly from the broadside value and ultimately shows the same behavior, as shown by the dipoles in the collinear configuration [26].

From Figs. 11 and 12, it can be seen that, in this case, the component  $\mu_t = 0.5$  exhibits the weakest coupling effect



**FIGURE 14.** Optimal combined uniaxial electrical and magnetic anisotropy elements effect on (a): mutual coupling of broadside configuration ( $G = 0\text{mm}$ ,  $S$  changed), (b): mutual coupling of collinear configuration ( $S = 0\text{mm}$ ,  $G$  changed) and (c): mutual coupling of echelon configuration ( $S = 10\text{mm}$ ,  $G$  changed).

even for  $G = 0\text{mm}$ . The contribution of this component becomes weaker for a distance  $G$  close to  $\lambda_g/2$ , while the



effect of  $\varepsilon_z = 2.25$  is strongly reduced for  $G$  varying between 0 and  $\lambda_g/4$ . This is mainly due to the reduction of electrical and magnetic inductions. The other components have no effect on the coupling, this is due to the location of the two dipoles, we will return to this for the broadside configuration case presented by Figs. 7 and 8. For  $G$  beyond  $\lambda_g/2$ , the four components contribute well in the coupling and the oscillations begin to appear by the effect of surface waves, the configuration is similar to the collinear case commented and discussed in Figs. 9 and 10.

### E. OPTIMAL UNIAXIAL ELECTRICAL AND MAGNETIC ANISOTROPY ELEMENTS

According to Figs.13 and 14, it can be seen that one can either decrease the peak impedance or minimize the mutual coupling between the two dipoles only by playing on the four parameters without altering the resonance frequency of the isotropic case.

In the case ( $\varepsilon_t = 4.75$ ,  $\varepsilon_z = 2.25$ ,  $\mu_t = 1.5$  and  $\mu_z = 0.5$ ), compared to the isotropic case, it was possible to decrease to more than a half the input impedance peak (from 3.6K $\Omega$  to 1.73K $\Omega$ ), while saving the same resonance frequency. Consequently, it is likely possible, in the case ( $\varepsilon_t = 5.25$ ,  $\varepsilon_z = 2.25$ ,  $\mu_t = 0.5$  and  $\mu_z = 5.25$ ), to decrease the mutual coupling by more than 30dB in some cases.

### V. CONCLUSION

In this paper, the mutual coupling between dipoles, printed on an anisotropic substrate, for three different configurations: broadband, collinear and stepped is investigated after evaluating the input impedance of the dipole. It is shown that the surface waves increase the mutual coupling in a collinear arrangement of the printed dipoles. It is also concluded that surface waves contribute to the mutual coupling in a significant way, through the two components  $\varepsilon_z$  and  $\mu_t$ . Furthermore, the uniaxial electrical and magnetic anisotropy offers further degrees of freedom and more flexibility to either realize a good matching (direct effect on the input impedance  $Z_{in}$ ) or to control the mutual coupling between dipoles.

### REFERENCES

- [1] S. X. Ta, H. Choo, and I. Park, "Broadband printed-dipole antenna and its arrays for 5G applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2183–2186, 2017.
- [2] R. K. Singh, A. Michel, P. Nepa, and A. Salvatore, "Wearable dual-band Quasi-Yagi antenna for UHF-RFID and 2.4 GHz applications," *IEEE J. Radio Freq. Identificat.*, vol. 4, no. 4, pp. 420–427, Dec. 2020.
- [3] Y. Yan, Y. Jiao, and C. Zhang, "Pattern and polarization reconfigurable circularly polarized antenna based on two pairs of planar complementary dipoles," *Microw. Opt. Technol. Lett.*, vol. 63, no. 3, pp. 876–882, Mar. 2021.
- [4] W. Honglei, Y. Kunde, and Z. Kun, "Performance of dipole antenna in underwater wireless sensor communication," *IEEE Sensors J.*, vol. 15, no. 11, pp. 6354–6359, Jul. 2015.
- [5] A. Novitsky, A. S. Shalin, and A. V. Lavrinenko, "Spherically symmetric inhomogeneous bianisotropic media: Wave propagation and light scattering," *Phys. Rev. A, Gen. Phys.*, vol. 95, no. 5, May 2017, Art. no. 053818.
- [6] W. Neng and G. P. Wang, "Effective medium theory with closed-form expressions for bi-anisotropic optical metamaterials," *Opt. Exp.*, vol. 27, no. 17, pp. 23739–23750, 2019.
- [7] J. A. Sihvola and I. V. Lindell, "Bianisotropic materials and PEMC," in *Theory and Phenomena of Metamaterials*, 1st ed. Boca Raton, FL, USA: CRC Press, 2009, ch. 26, sec. 4, pp. 1–26.
- [8] M. L. Bouknia, C. Zebiri, D. Sayad, I. Elfergani, J. Rodriguez, M. Alibakhshikenari, R. A. Abd-Alhameed, F. Falcone, and E. Limiti, "Theoretical study of the input impedance and electromagnetic field distribution of a dipole antenna printed on an electrical/magnetic uniaxial anisotropic substrate," *Electronics*, vol. 10, no. 9, p. 1050, Apr. 2021.
- [9] S. K. Tleukenov and A. M. Assilbekova, "Surface of wave vectors of electromagnetic waves in anisotropic dielectric media with rhombic symmetry," *Telecommun. Radio Eng.*, vol. 76, no. 14, pp. 1231–1238, 2017.
- [10] D. Sayad, C. Zebiri, I. Elfergani, J. Rodriguez, H. Abobaker, A. Ullah, R. Abd-Alhameed, I. Otung, and F. Benabdelaziz, "Complex bianisotropy effect on the propagation constant of a shielded multilayered coplanar waveguide using improved full generalized exponential matrix technique," *Electronics*, vol. 9, no. 2, p. 243, Feb. 2020.
- [11] D. Sayad, C. Zebiri, I. Elfergani, J. Rodriguez, R. Abd-Alhameed, and F. Benabdelaziz, "Analysis of chiral and achiral medium based coplanar waveguide using improved full generalized exponential matrix technique," *Radioengineering*, vol. 29, no. 4, pp. 560–591, 2020.
- [12] C. Zebiri and D. Sayad, "Effect of bianisotropy on the characteristic impedance of a shielded microstrip line for wideband impedance matching applications," *Waves Random Complex Media*, pp. 1–14, 2020, doi: 10.1080/17455030.2020.1752957.
- [13] C. Zebiri, M. Lashab, and F. Benabdelaziz, "Effect of anisotropic magneto-chirality on the characteristics of a microstrip resonator," *IET Microw., Antennas Propag.*, vol. 4, no. 4, pp. 446–452, Apr. 2010.
- [14] C. Zebiri, M. Lashab, and F. Benabdelaziz, "Rectangular microstrip antenna with uniaxial bi-anisotropic chiral substrate-superstrate," *IET Microw., Antennas Propag.*, vol. 5, no. 1, pp. 17–29, Jan. 2011.
- [15] D. Sayad, C. Zebiri, S. Daoudi, and F. Benabdelaziz, "Analysis of the effect of a gyrotropic anisotropy on the phase constant and characteristic impedance of a shielded microstrip line," *Adv. Electromagn.*, vol. 8, no. 5, pp. 15–22, Dec. 2019.
- [16] M. B. Heydari and A. Ahmadvand, "A novel analytical model for a circularly-polarized, ferrite-based slot antenna by solving an integral equation for the electric field on the circular slot," *Waves Random Complex Media*, pp. 1–20, 2020, doi: 10.1080/17455030.2020.1782510.
- [17] W. Lee, Y.-K. Hong, M. Choi, H. Won, J. Lee, S.-O. Park, S. Bae, and H.-S. Yoon, "Ferrite-cored patch antenna with suppressed harmonic radiation," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 3154–3159, Jun. 2018.
- [18] V. Kamra and A. Dreher, "Efficient analysis of multiple microstrip transmission lines with anisotropic substrates," *IEEE Microw. Wireless Compon. Lett.*, vol. 28, no. 8, pp. 636–638, Aug. 2018.
- [19] A. L. Buzov, M. A. Buzova, D. S. Klyuev, D. V. Mishin, and A. M. Neshcheret, "Calculating the input impedance of a microstrip antenna with a substrate of a chiral metamaterial," *J. Commun. Technol. Electron.*, vol. 63, no. 11, pp. 1259–1264, Nov. 2018.
- [20] D. S. Klyuev, M. A. Minkin, D. V. Mishin, A. M. Neshcheret, and D. P. Tabakov, "Characteristics of radiation from a microstrip antenna on a substrate made of a chiral metamaterial," *Radiophys. Quantum Electron.*, vol. 61, no. 6, pp. 445–455, Nov. 2018.
- [21] Y. Hu, Y. Fang, D. Wang, Q. Zhan, R. Zhang, and Q. H. Liu, "The scattering of electromagnetic fields from anisotropic objects embedded in anisotropic multilayers," *IEEE Trans. Antennas Propag.*, vol. 67, no. 12, pp. 7561–7568, Dec. 2019.
- [22] A. Eroglu and J. K. Lee, "Far field radiation from an arbitrarily oriented Hertzian dipole in the presence of a layered anisotropic medium," *IEEE Trans. Antennas Propag.*, vol. 53, no. 12, pp. 3963–3973, Dec. 2005.
- [23] B. D. Braaten, R. M. Nelson, and D. A. Rogers, "Input impedance and resonant frequency of a printed dipole with arbitrary length embedded in stratified uniaxial anisotropic dielectrics," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 806–810, 2009.
- [24] B. D. Braaten, D. A. Rogers, and R. M. Nelson, "Multi-conductor spectral domain analysis of the mutual coupling between printed dipoles embedded in stratified uniaxial anisotropic dielectrics," *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 1886–1898, Apr. 2012.
- [25] D. Sayad, F. Benabdelaziz, C. Zebiri, S. Daoudi, and R. A. Abd-Alhameed, "Spectral domain analysis of gyrotropic anisotropy chiral effect on the input impedance of a printed dipole antenna," *Prog. Electromagn. Res. M*, vol. 51, pp. 1–8, 2016.

- [26] N. Alexopoulos and I. Rana, "Mutual impedance computation between printed dipoles," *IEEE Trans. Antennas Propag.*, vol. AP-29, no. 1, pp. 106–111, Jan. 1981.
- [27] H. A. N. Hejase, "Analysis of a printed wire loop antenna," *IEEE Trans. Microw. Theory Techn.*, vol. 42, no. 2, pp. 227–233, Feb. 1994.
- [28] C. Zebiri, S. Daoudi, F. Benabdelaziz, M. Lashab, D. Sayad, N. T. Ali, and R. A. Abd-Alhameed, "Gyro-chirality effect of bianisotropic substrate on the operational of rectangular microstrip patch antenna," *Int. J. Appl. Electromagn. Mech.*, vol. 51, no. 3, pp. 249–260, Jul. 2016.
- [29] K. L. Wong, S. M. Wang, and S. Y. Ke, "Measured input impedance and mutual coupling of rectangular microstrip antennas on a cylindrical surface," *Microw. Opt. Technol. Lett.*, vol. 11, no. 1, pp. 49–50, 1996.
- [30] J. W. Graham and J. K. Lee, "Microstrip dipoles printed on biaxial substrates," in *Proc. IEEE Int. Symp. Antennas Propag.*, Jul. 2012, pp. 1–2.
- [31] C. Zebiri, F. Benabdelaziz, and D. Sayad, "Surface waves investigation of a bianisotropic chiral substrate resonator," *Prog. Electromagn. Res. B*, vol. 40, pp. 399–414, 2012.



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