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 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 and permeability, respectively:

\[
\begin{align*}
\varepsilon &= \varepsilon_0 \begin{bmatrix}
\varepsilon_t & 0 & 0 \\
0 & \varepsilon_t & 0 \\
0 & 0 & \varepsilon_z 
\end{bmatrix} \\
\mu &= \mu_0 \begin{bmatrix}
\mu_t & 0 & 0 \\
0 & \mu_t & 0 \\
0 & 0 & \mu_z 
\end{bmatrix}
\end{align*}
\]

(1a)

(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]:

\[
\frac{\partial^2 \vec{E}_z}{\partial z^2} - \gamma^2 \vec{E}_z = 0
\]

(2a)
FIGURE 3. Comparison of our computed results of mutual coupling of printed dipoles on isotropic layer with those repotted in [24] of (a) broadside (b) collinear and, (c) echelon configurations.

\[ \frac{\partial^2 \tilde{H}_z}{\partial z^2} - \gamma_z^2 \tilde{H}_z = 0 \]  

(2b)

The dispersion relations are found to be as follows:

\[ \gamma_e = \sqrt{\frac{\varepsilon_t}{\varepsilon_z} \left( \alpha^2 + \beta^2 - \kappa_0^2 \varepsilon_t \mu_t \right)} \]  

(2c)

and

\[ \gamma_h = \sqrt{\frac{\mu_t}{\mu_z} \left( \alpha^2 + \beta^2 - \kappa_0^2 \varepsilon_t \mu_t \right)} \]  

(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:

\[ \tilde{E}_z (\gamma_e, z) = A_e \cosh (\gamma_e z) + B_e \sinh (\gamma_e z) \]  

(3a)

\[ \tilde{H}_z = C_z \]  

(3b)
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 $\mu_t$.

\[ H_z (\gamma_0, z) = A_h \sinh (\gamma_0 z) + B_h \cosh (\gamma_0 z) \]  

where $A_h$, $B_h$, $A_e$, and $B_e$ 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:

\[ \bar{E}_z (\gamma_0, z) = C_e e^{-\gamma_0 (z-d)} \]  
\[ \bar{H}_z (\gamma_0, z) = C_h e^{-\gamma_0 (z-d)} \]

where

\[ \gamma_0 = \sqrt{(\alpha^2 + \beta^2) - \kappa_0^2} \]  

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 $z = d$:

\[ \bar{E}_{x1} = \bar{E}_{y1} = 0 \]  (5a)
\[ \bar{E}_{x1} = \bar{E}_{x2} \]  (5b)
\[ \bar{E}_{y1} = \bar{E}_{y2} \]  (5c)
\[ \bar{H}_{x2} - \bar{H}_{y1} = J_x \]  (5d)
\[ \bar{H}_{x1} - \bar{H}_{x2} = J_y \]  (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 $J_x$ and $J_y$. Green’s tensor elements are obtained and arranged to satisfy the following system of equations [25], [28].

\[ \bar{E}_x = \tilde{G}_{xx} J_x + \tilde{G}_{xy} J_y \]  (6a)
\[ \bar{E}_y = \tilde{G}_{yx} J_x + \tilde{G}_{yy} J_y \]  (6b)
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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 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 ($\varepsilon = 3.25$ and $\mu = 0.5$, and $\varepsilon = 4.25$, respectively).

FIGURE 7. Broadside mutual coupling for various values of (a): $\varepsilon$, (b): $\mu$.

function of the green $G_{xx}$ is presented, since the others are not involved in the calculations.

$$\tilde{G}_{xx} = \frac{-j}{\omega \varepsilon_0} \left( \frac{\alpha^2 \gamma_0 \gamma_e}{[\gamma_0 \gamma_e \coth(\gamma_e d) + \gamma_e]} - \frac{\beta^2 \kappa_0^2 \mu_t}{(\gamma_e \coth(\gamma_e d) + \mu_t \gamma_0)} \right)$$

$$\gamma_e = \frac{\mu_t}{\varepsilon_0 \sqrt{2 \omega \mu_s}}$$

$$\alpha^2 = \frac{2 \omega L}{c}$$

$$\beta^2 = \frac{2 \omega d}{c}$$

$$\gamma_0 = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

$$\gamma_e = \frac{1}{\sqrt{\varepsilon_0 \mu_e}}$$

FIGURE 8. Broadside mutual coupling for various values of (a): $\varepsilon$ and (b): $\mu$.
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 \( \varepsilon_r \) 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 \( \varepsilon_z \) effects significantly the magnitude of the input impedance with an increase of its peak, where it is doubled, from 3kΩ for \( \varepsilon_t = 3.25 \) and \( \varepsilon_z = 2.25 \) to 6kΩ for \( \varepsilon_t = 2.25 \) and \( \varepsilon_z = 3.25 \), all with a slight shift in the resonant length(Fig. 4.b).

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 \( \varepsilon_z \) and \( \varepsilon_t \). 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 (\( \varepsilon_1, \varepsilon_2, \mu_1 \) and \( \mu_2 \)). 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...
frequency. The values of this latter have been obtained from the input impedance by varying $\varepsilon$ 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 $\varepsilon_z$ 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. 1b have a length of 15 cm, a width of 0.5 mm with a source frequency of 500 MHz.

The mutual coupling between the two printed dipoles in broadside case ($G = 0$), has been calculated, illustrated and compared with literature (Figs. 7a and 7b), for various values of the anisotropic permittivity elements $\varepsilon_t$ and $\varepsilon_z$ 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 $\varepsilon_t = 3.25$ and $\varepsilon_z = 5.12$, and smallest for $\varepsilon_t = 3.25$ and $\varepsilon_z = 2.25$, while as for the $\varepsilon_t$ component, it has no significant effect. The effect of the two components of the uniaxial magnetic anisotropy $\mu_x$ and $\mu_z$, 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 $TM_0$ is along the $z$-direction i.e. the optical axis and is in direct relation with $\varepsilon_z$ and $\mu_t$ \[25\]. In the case of a reduced mutual coupling a quasi-oscillation corresponding to lengths 7 and 5mm is noticed for $\varepsilon_z = 2.25$ (1st case).
and $\mu_t = 0.5$ (2nd 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 even for $G = 0$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) or to control the mutual coupling between dipoles.

REFERENCES


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context-aware environments. He has over 500 contributions in indexed international journals, book chapters, and conference contributions. He has been awarded the CST 2003 and CST 2005 Best Paper Awards, the Ph.D. Award from the Colegio Oficial de Ingenieros de Telecomunicación (COIT), in 2006, the Doctoral Award UPNA, 2010, 1st Juan Gomez Pehalver Research Award from the Royal Academy of Engineering of Spain, in 2010, the XII Talgo Innovation Award 2012, the IEEE 2014 Best Paper Award, 2014, the ECSA-3 Best Paper Award, 2016, and the ECSA-4 Best Paper Award, 2017.

ERNESTO LIMITI (Senior Member, IEEE) has been a Research and Teaching Assistant, an Associate Professor, and a Full Professor of electronics with the Engineering Faculty, University of Roma Tor Vergata, since 1991, 1998, and 2002, respectively. He represents the University of Roma Tor Vergata in the governing body of the MECSA (Microwave Engineering Center for Space Applications), an inter-university center among several Italian universities. He has been elected to represent the Industrial Engineering Sector in the Academic Senate of the University for the period 2007–2010 and 2010–2013. He is the President of the Consortium “Advanced Research and Engineering for Space” (ARES), formed between the university and two companies. Furthermore, he is the President of the Laurea and Laurea Magistrale degrees, in electronic engineering, of the University of Roma Tor Vergata. His research interests include three main lines, all of them belonging to the microwave and millimeter-wave electronics research areas. The first one is related to characterization and modeling for active and passive microwave and millimeter-wave devices.

Regarding active devices, the research line is oriented to the small-signal, noise, and large-signal modeling. Regarding passive devices, equivalent-circuit models have been developed for interacting discontinuities in microstrip, for typical MMIC passive components (MIM capacitors), and for waveguide/coplanar waveguide transitions analysis and design. For active devices, new methodologies have been developed for the noise characterization and the subsequent modeling, and equivalent-circuit modeling strategies have been implemented both for small- and large-signal operating regimes for GaAs, GaN, SiC, Si, and InP MESFET/HEMT devices. The second line is related to design methodologies and characterization methods for low-noise circuits. The main focus is on cryogenic amplifiers and devices. Collaborations are currently ongoing with the major radioastronomy institutes all around Europe within the frame of FP6 and FP7 programs (RadioNet). Finally, the third line is in the analysis methods for nonlinear microwave circuits. In this line, novel analysis methods (Spectral Balance) are developed, together with the stability analysis of the solutions making use of traditional (harmonic balance) approaches. The above research lines have produced more than 250 publications on refereed international journals and presentations within international conferences. He acts as a referee of international journals of the microwave and millimeter-wave electronics sector and is in the steering committee of international conferences and workshops. He is actively involved in research activities with many research groups, both European and Italian, and he is in tight collaborations with high-tech Italian (Selex–SI, Thales Alenia Space, Rheinmetall, Elettroonica S.p.A., Space Engineering …) and foreign (OMMIC, Siemens, UMS, …) companies. He contributed, as a researcher and/or as unit responsible, to several National (PRIN MIUR, Madess CNR, Agenzia Spaziale Italiana) and international (ESPRIT COSMIC, Manpower, Edge, Special Action MEPI, ESA, EUROPA, Korrigan, RadioNet FP6 and FP7 …) projects. Regarding teaching activities, Prof. Limiti teaches, over his institutional duties in the frame of the Corso di Laurea Magistrale in Ingegneria Elettronica, “Elettronica per lo Spazio” within the master course in Sistemi Avanzati di Comunicazione e Navigazione Satellitare. He is a member of the committee of the Ph.D. Program in Telecommunications and Microelectronics at the University of Roma Tor Vergata, tutoring an average of four Ph.D. candidates per year.

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