IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 18, 2021, accepted May 25, 2021, date of publication June 3, 2021, date of current version June 18, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3085949

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

MOHAMED LAMINE BOUKNIA[1], CHEMSEDDINE ZEBIRI[1], DJAMEL SAYAD[2], ISSA ELFERGANI[3,4],(Member, IEEE), MOHAMMAD ALIBAKHSHIKENARI[5], (Member, IEEE), JONATHAN RODRIGUEZ[3,6], (Senior Member, IEEE), RAED A. ABD-ALHAMEED[4], (Senior Member, IEEE), FRANCISCO FALCONE[7,8], (Senior Member, IEEE), AND ERNESTO LIMITI[5], (Senior Member, IEEE)

[1]Laboratoire d'Electronique de Puissance et Commande Industrielle (LEPCI), Department of Electronics, University of Ferhat Abbas, Sétif 19000, Algeria
[2]Laboratoire d'Electrotechnique de Skikda (LES), University 20 Aout 1955-Skikda, Skikda 21000, Algeria
[3]Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[4]School of Engineering and Informatics, University of Bradford, Bradford BD7 1DP, U.K.
[5]Electronic Engineering Department, University of Rome "Tor Vergata," 00133 Rome, Italy
[6]Faculty of Computing, Engineering and Science, University of South Wales, Pontypridd CF37 1DL, U.K.
[7]Electric, Electronic and Communication Engineering Department, Public University of Navarre, 31006 Pamplona, Spain
[8]Institute of Smart Cities, Public University of Navarre, 31006 Pamplona, Spain

Corresponding authors: Issa Elfergani (i.t.e.elfergani@av.it.pt; i.elfergani@bradford.ac.uk) and Mohammad Alibakhshikenari (alibakhshikenari@ing.uniroma2.it)

This work was supported in part by the Electronic Components and Systems (ECSEL) Joint Undertaking, which is part of the POSITION-II Project under Grant Ecsel-7831132- Position-II-2017-IA, www.position-2.eu, in part by Fundação para a Ciência e a Tecnologia–Ministério da Ciência, Tecnologia e Ensino Superior (FCT/MCTES) through National Funds and co-funded European Union (EU) Funds under Project UIDB/50008/2020-UIDP/50008/2020, in part by the General Directorate of Scientific Research and Technological Development (DGRSDT)–Ministry of Higher Education and Scientific Research (MESRS), Algeria, and in part by the Ministerio de Ciencia, Innovación y Universidades, Gobierno de España (MCIU/AEI-Agencia Estatal de Investigación- al Fondo Europeo de Desarrollo Regional (AEI/FEDER), UE) under Grant RTI2018-095499-B-C31.

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

The associate editor coordinating the review of this manuscript and approving it for publication was Conrad Rizal.

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

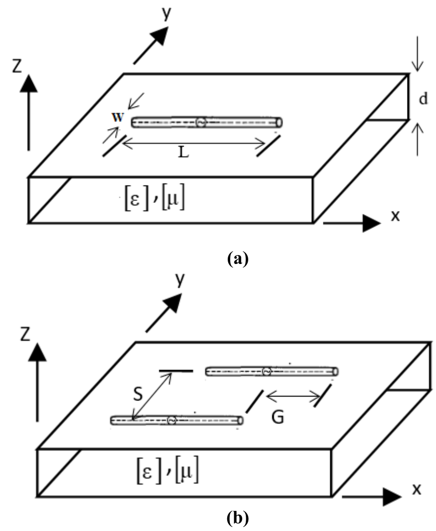


FIGURE 1. (a) Printed dipole (b) Geometry of mutual coupling configurations.

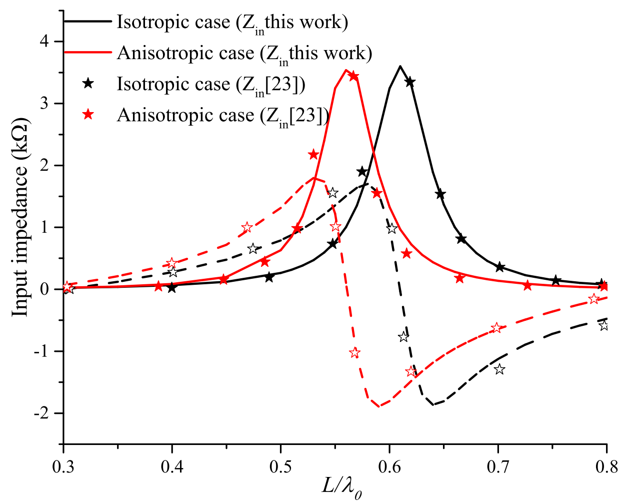


FIGURE 2. Comparison of our computed input impedance of printed dipoles on isotropic and anisotropic layer with those in [23], [24].

and permeability, respectively:

$$[\varepsilon] = \varepsilon_0 \begin{bmatrix} \varepsilon_t & 0 & 0 \\ 0 & \varepsilon_t & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} \tag{1a}$$

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

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]:

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

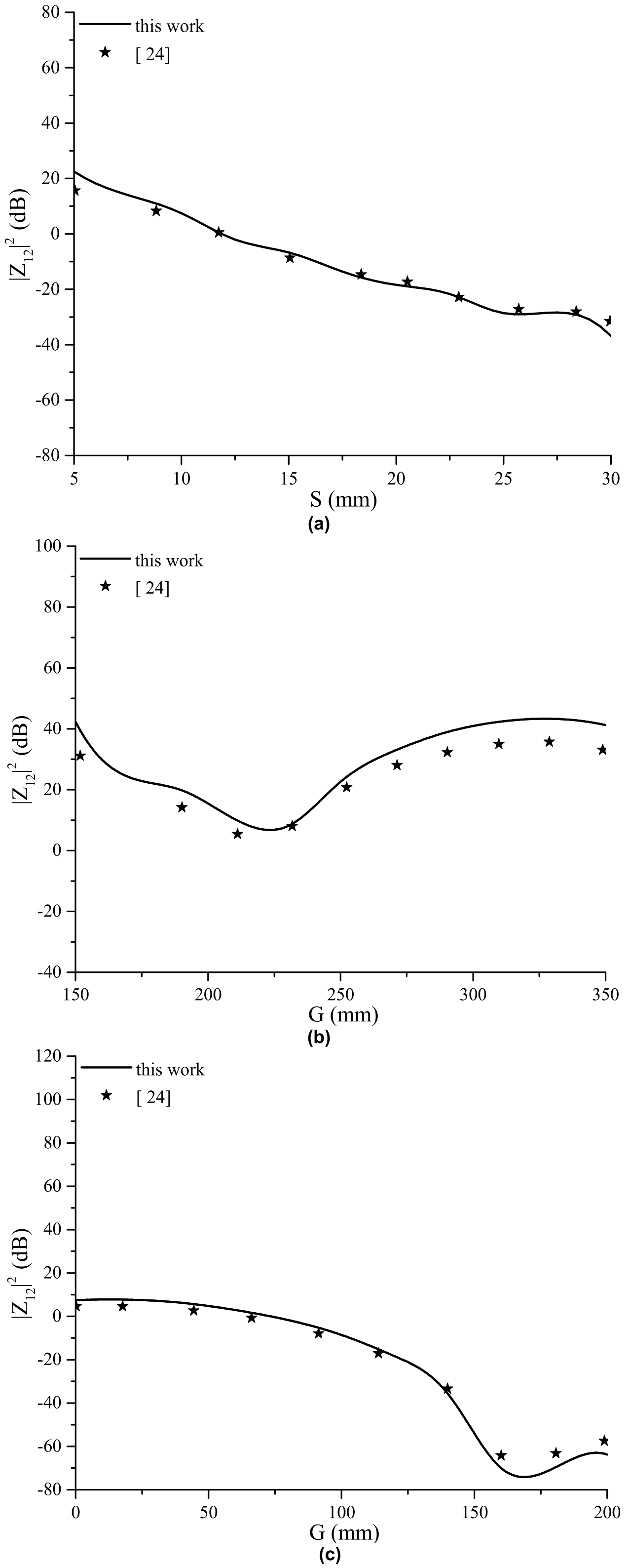


FIGURE 3. Comparison of our computed results of mutual coupling of printed dipoles on isotropic layer with those repotted in [24] of (a) broadside (b) collinear and, (c) echelon configurations.

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

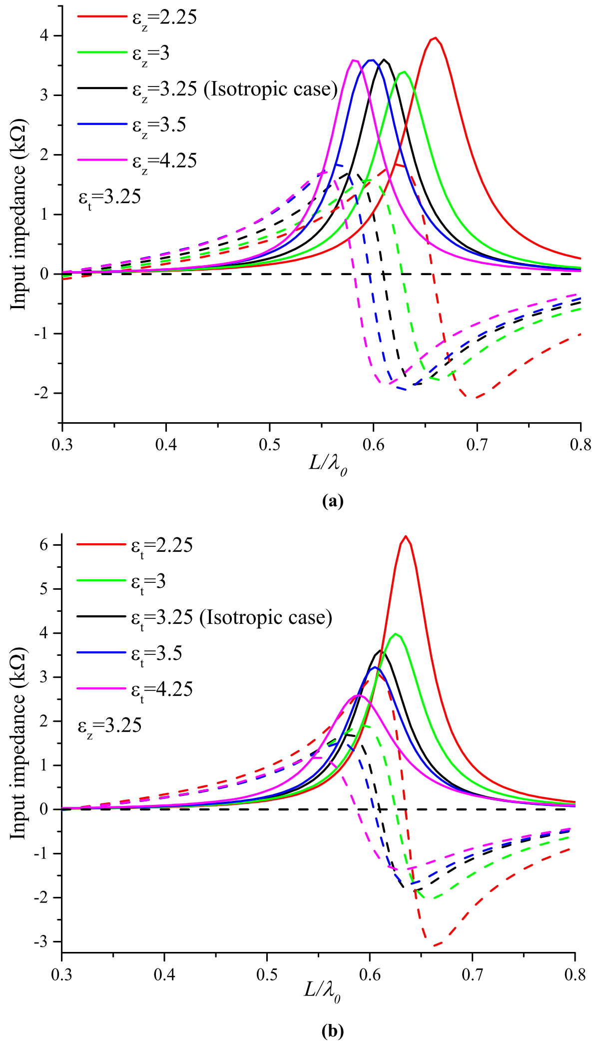


FIGURE 4. Real and imaginary parts of input impedance with uniaxial anisotropic substrate of printed dipole antenna (a) for various values of ε_z, (b) for various values of ε_t.

The dispersion relations are found to be as follows:

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

and

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

γ_e^2 and γ_h^2 represent the propagation constants of the TM and TE transverse modes, respectively. α, β are the Fourier variables corresponding to the space domain and κ_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:

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

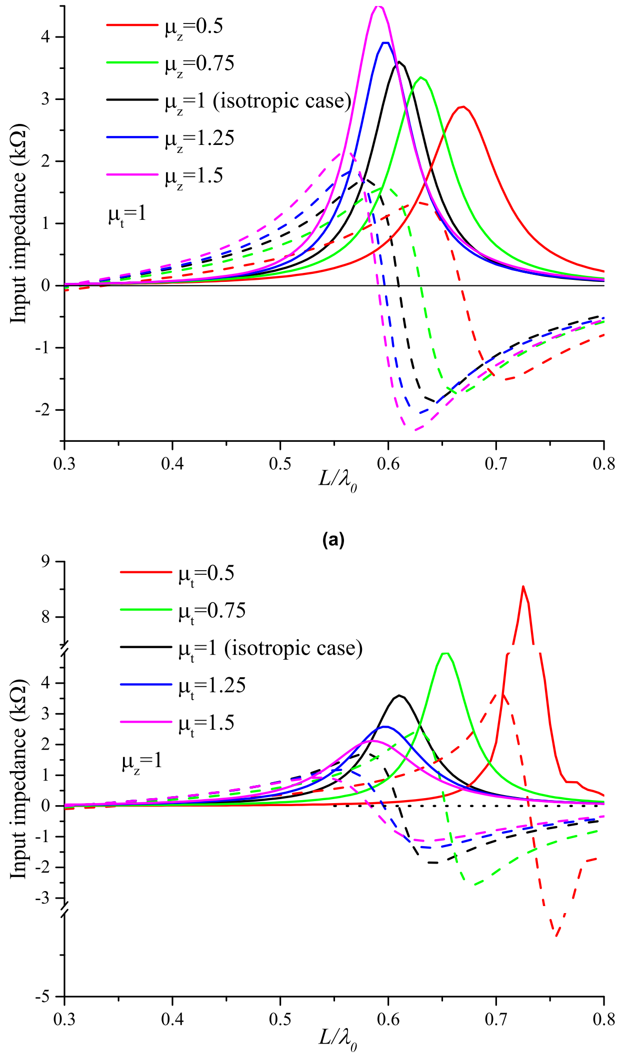


FIGURE 5. Real and imaginary parts of input impedance with uniaxial anisotropic substrate of printed dipole antenna (a) for various values of μ_z, (b) for various values of μ_t.

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

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:

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

where

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

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

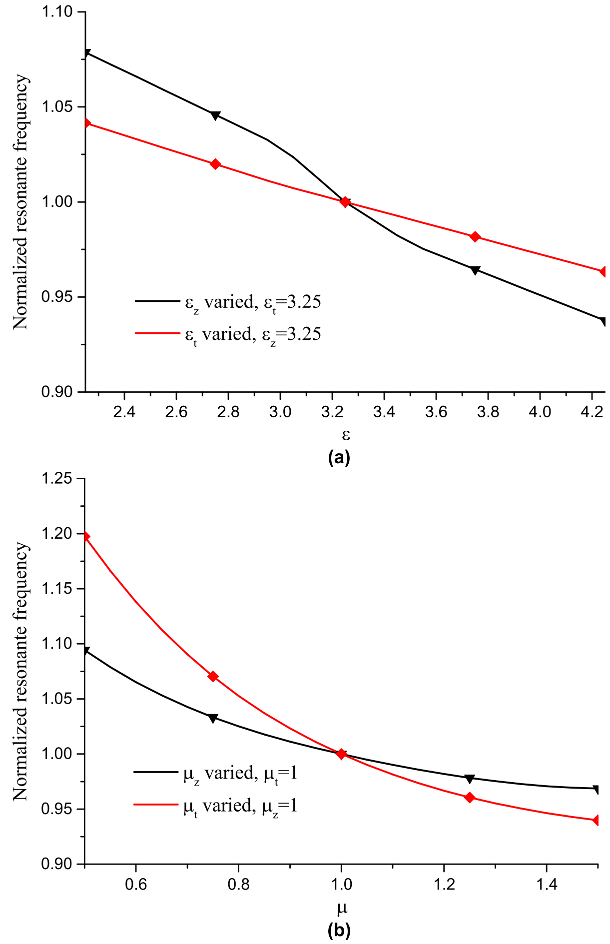


FIGURE 6. Normalized resonant frequency of the dipole with uniaxial anisotropic substrate for various values of (a): [ε] and (b): [μ].

at z = d:

$$\tilde{E}_{x1} = \tilde{E}_{y1} = 0 \tag{5a}$$
$$\tilde{E}_{x1} = \tilde{E}_{x2} \tag{5b}$$
$$\tilde{E}_{y1} = \tilde{E}_{y2} \tag{5c}$$
$$\tilde{H}_{y2} - \tilde{H}_{y1} = \tilde{J}_x \tag{5d}$$
$$\tilde{H}_{x1} - \tilde{H}_{x2} = \tilde{J}_y \tag{5e}$$

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].

$$\tilde{E}_x = \tilde{G}_{xx}\tilde{J}_x + \tilde{G}_{xy}\tilde{J}_y \tag{6a}$$
$$\tilde{E}_y = \tilde{G}_{yx}\tilde{J}_x + \tilde{G}_{yy}\tilde{J}_y \tag{6b}$$

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

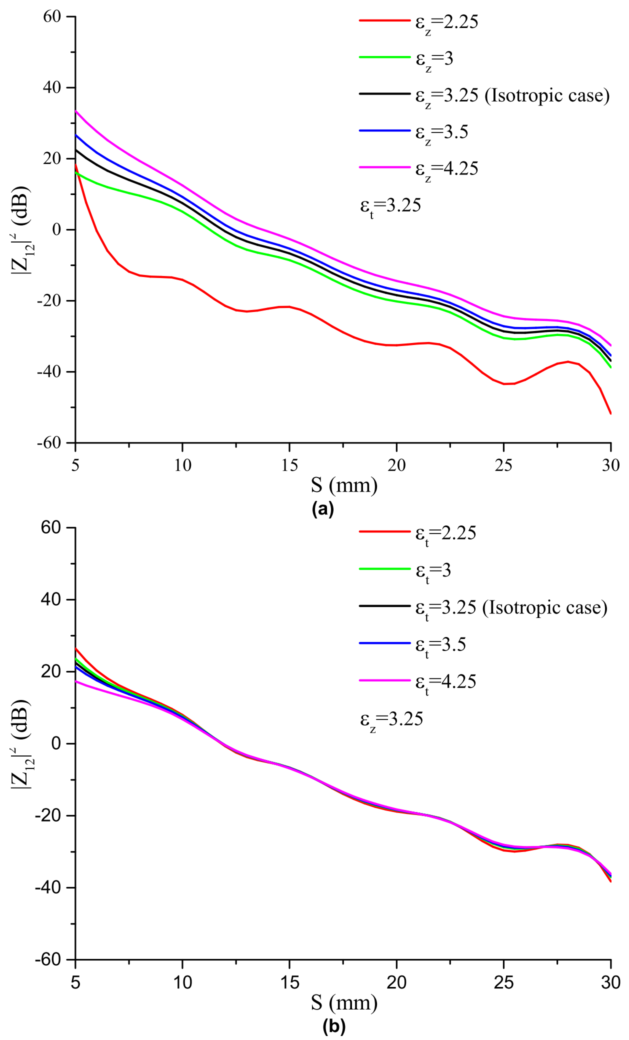


FIGURE 7. **Broadside mutual coupling for various values of (a): $[\varepsilon_z]$, (b): $[\varepsilon_t]$.**

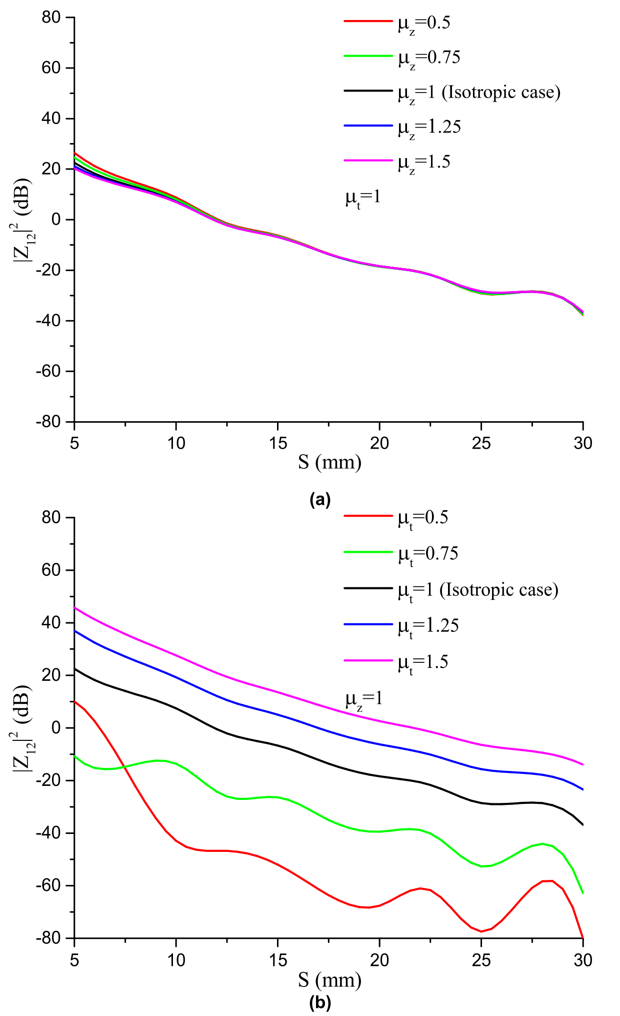


FIGURE 8. **Broadside mutual coupling for various values of (a): $[\mu_z]$ and (b): $[\mu_t]$.**

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

$$\tilde{G}_{xx} = \frac{-j}{\omega\varepsilon_0\left(\alpha^2+\beta^2\right)}\left(\frac{\alpha^2\gamma_0\gamma_e}{\left[\gamma_0\varepsilon_t\coth\left(\gamma_e d\right)+\gamma_e\right]} - \frac{\beta^2\kappa_0^2\mu_t}{\left(\gamma_h\coth\left(\gamma_h d\right)+\mu_t\gamma_0\right)}\right) \quad (7)$$

IV. NUMERICAL RESULTS

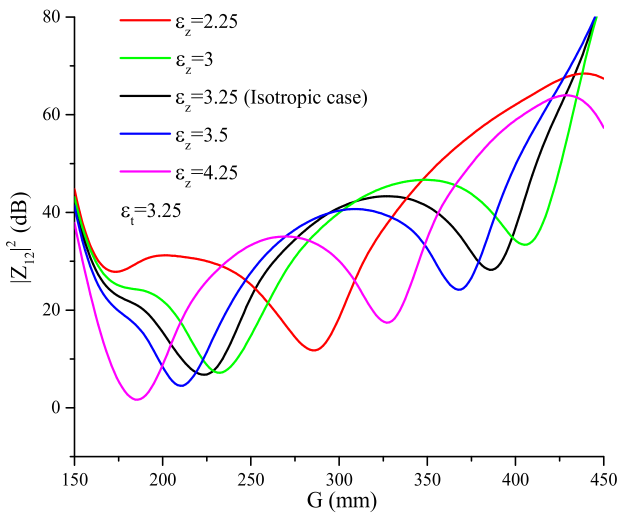
In this work, we are first interested in the input impedance, the resonant length of the dipole and second in the mutual coupling between two printed dipoles arranged in three configurations. Before discussing the results obtained of the uniaxial anisotropy case, a validation of the calculation code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

A. VALIDATION

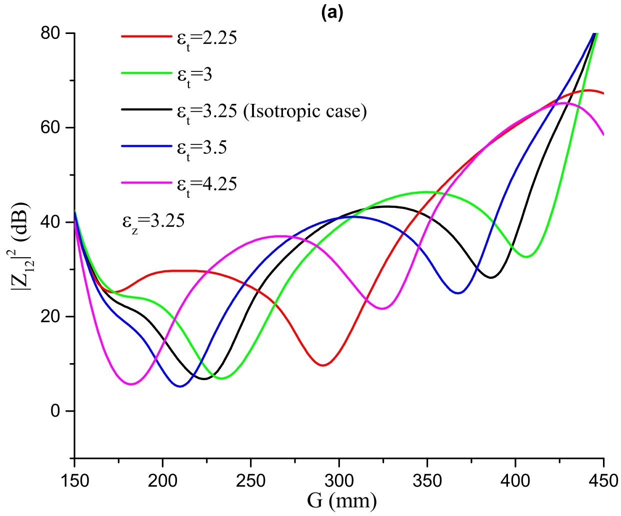
In this subsection, we investigate the effect of the substrate anisotropy on the input impedance of the dipole, in addition to the consideration of the mutual coupling for three cases of geometrical configurations. Extensive computations were performed involving a dipole structure printed on a uniaxial anisotropic structure. The results from these computations were successfully compared to the published results. We have initially considered the isotropic and uniaxial anisotropic cases ($\varepsilon_t = \varepsilon_z = 3.25$ and $\mu_r = \mu_z = 1$) and ($\varepsilon_t = 3.14$, $\varepsilon_t = 5.12$ 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/λ_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, echelon and broadside configurations, respectively, for various values of L = 150mm, W = 0.5mm, f = 500MHz and d = 1.58mm. 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].



(a)



(b)

FIGURE 9. Collinear mutual coupling for various values of (a): [ε_z], (b): [ε_t].

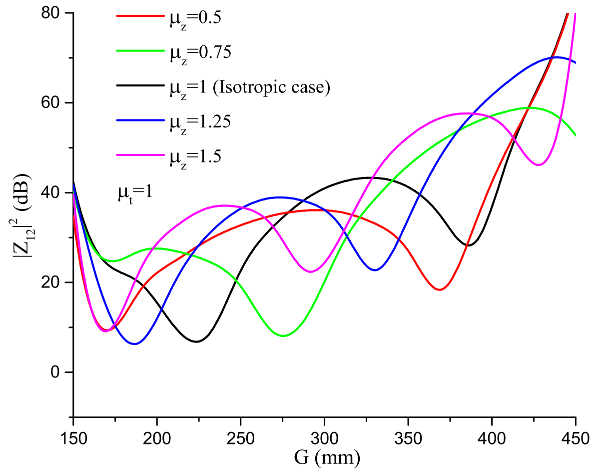
These results represent a validation of the accuracy of the present work computations for both isotropic and anisotropic substrates. A comparison representation of the input impedance and mutual coupling for the configuration of Fig. 1 are presented in Fig. 2 and 3.

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.

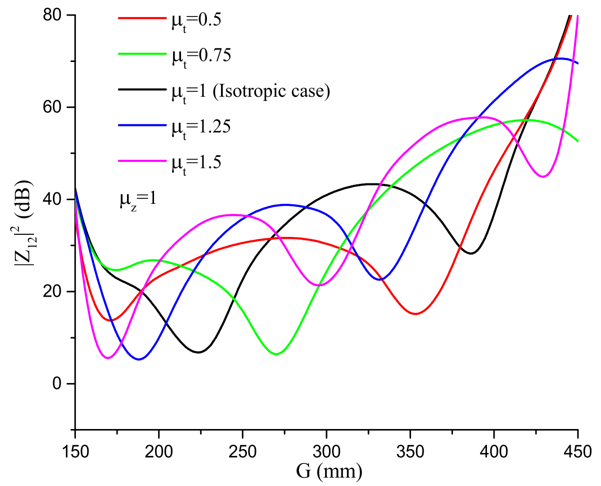
B. EFFECT OF THE UNIAXIAL ELECTRICAL AND MAGNETIC ANISOTROPY ON THE INPUT IMPEDANCE

Fig. 4.a shows the effect of ε_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 ε_t 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).



(a)



(b)

FIGURE 10. Collinear mutual coupling for various values of (a): [μ_z] and (b): [μ_t].

In Figs. 5.a and b, the effect of the two components of permeability μ_z and μ_t does not resemble to that of the permittivity components ε_z and ε_t. An increase in μ_z results in an increase in the input impedance peak, with a decrease in the resonance frequency.

The effect of the permeability component μ_t is reversed in this case, where an increase in the μ_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 (ε_t, ε_z, μ_t and μ_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

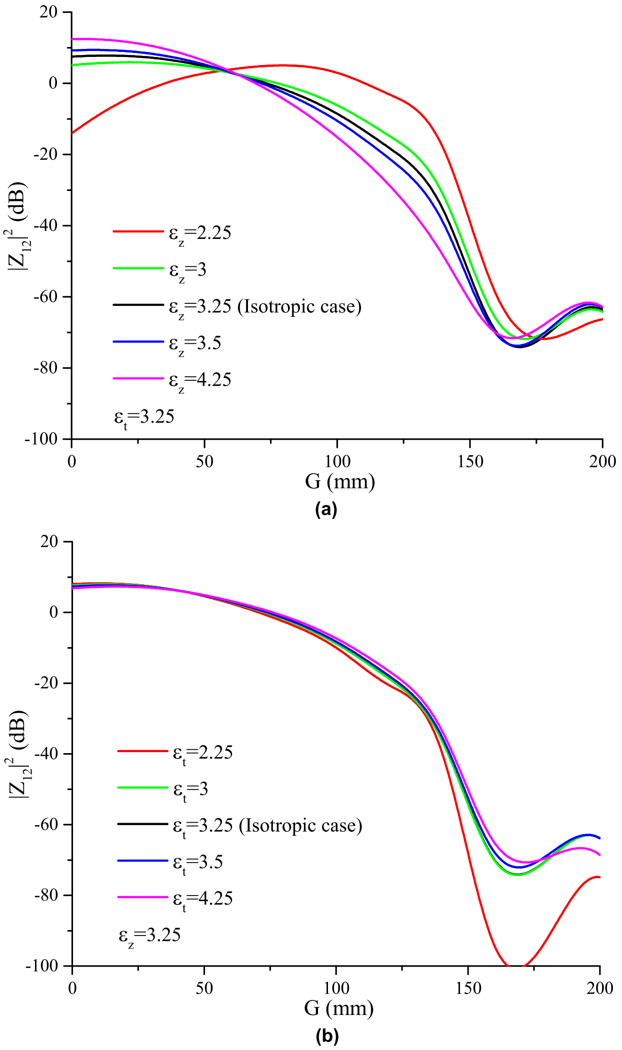


FIGURE 11. **Echelon mutual coupling for various values of (a): ε_z, (b): ε_t.**

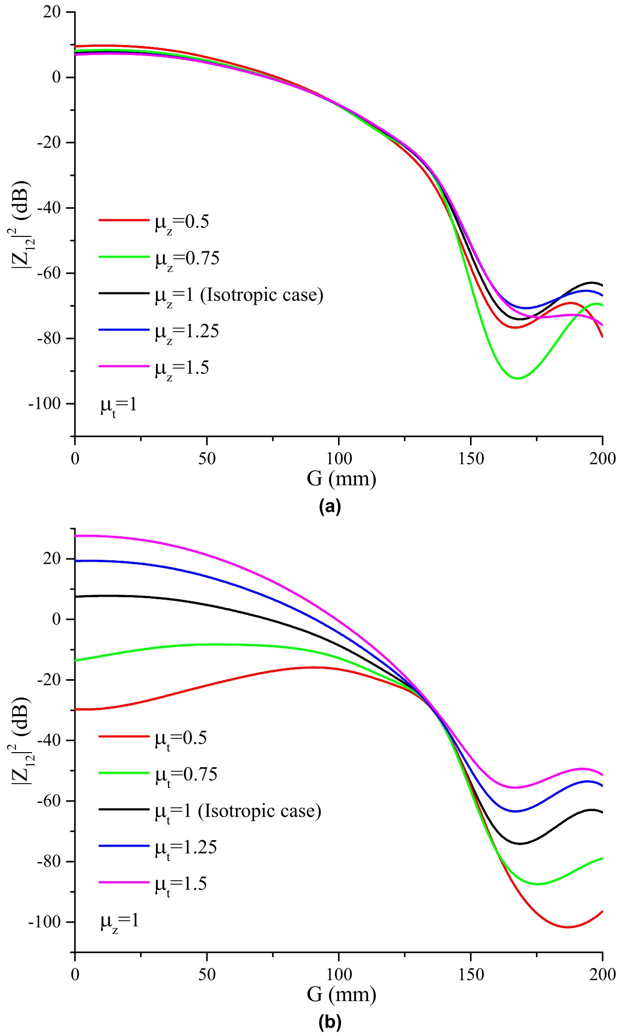


FIGURE 12. **Echelon mutual coupling for various values of (a): μ_z and (b): μ_t.**

frequency. The values of this latter have been obtained from the input impedance by varying ε and μ, 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 ε_z and μ_t are increased. In particular, the resonant frequency is mainly affected by the z-component of the permittivity and perpendicular permeability component μ_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.

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 ε_t and ε_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 ε_t component, it has no significant effect. The effect of the two components of the uniaxial magnetic anisotropy μ_z and μ_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 ε_z and μ_t [25]. In the case of a reduced mutual coupling a quasi-oscillation corresponding to lengths 7 and 5mm is noticed for $\varepsilon_z = 2.25$ (1^{st} case)

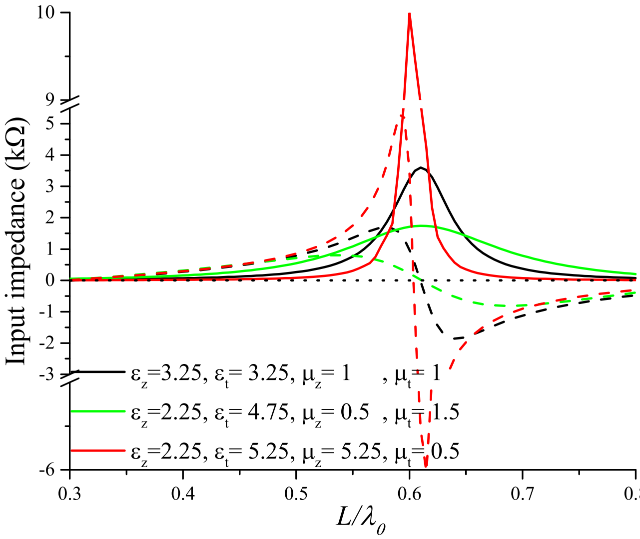


FIGURE 13. **Optimal combined uniaxial electrical and magnetic anisotropy elements effect on the input impedance of the dipole printed antenna.**

and $\mu_t = 0.5$ (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

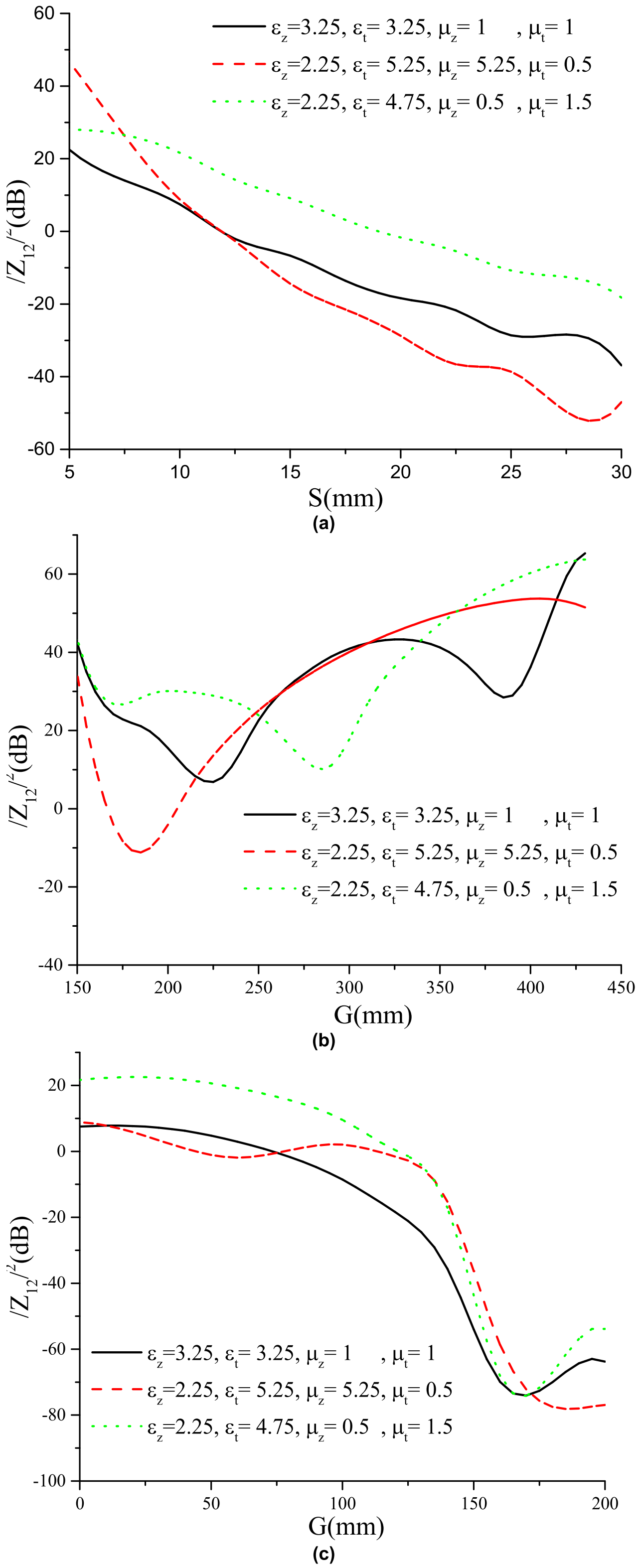


FIGURE 14. **Optimal combined uniaxial electrical and magnetic anisotropy elements effect on (a): mutual coupling of broadside configuration (G = 0mm, S changed), (b): mutual coupling of collinear configuration (S = 0mm, G changed) and (c): mutual coupling of echelon configuration (S = 10mm, G changed).**

even for G = 0mm. 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 3.6KΩ to 1.73KΩ), 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 ε_z and μ_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 Zin) 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.

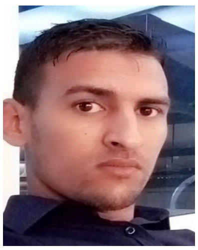
[22] A. Eroglu and J. K. Lee, "Far field radiation from an arbitrarily oriented Hertzian dipole in the presence of a layered anisotropic medium," *IEEE Trans. Antennas Propag.*, vol. 53, no. 12, pp. 3963–3973, Dec. 2005.

[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.

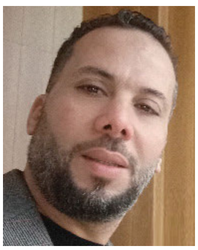
[24] B. D. Braaten, D. A. Rogers, and R. M. Nelson, "Multi-conductor spectral domain analysis of the mutual coupling between printed dipoles embedded in stratified uniaxial anisotropic dielectrics," *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 1886–1898, Apr. 2012.

[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.



MOHAMED LAMINE BOUKNIA is currently pursuing the Ph.D. degree in electronics with the University of Ferhat Abbas, Sétif, Algeria. His research interests include printed antennas, complex media (Chirality, Tellegen) and computational electromagnetic methods [method of moment (MoM), and finite element method (FEM)].



CHEMSEDDINE ZEBIRI received the degree in electronics engineering from the University of Constantine, Algeria, in 2001, the Magister degree from the University of Ferhat Abbas, Sétif, Algeria, in 2003, and the Ph.D. degree in electronics from the University of Constantine, in 2011. In 2006, he was a Senior Lecturer with the Department of Electronics, University of Ferhat Abbas, where he is currently an Associate Professor. He has published up to 100 journal articles and refereed conference papers. His current research interests include dielectric resonator antennas, MIMO antennas, mmWave antennas, magnetic materials, complex material components in the microwaves, and optical domains.

DJAMEL SAYAD received the Ph.D. degree in electronics from the University of Skikda, Algeria, in 2017. He is currently an Assistant Lecturer with the Department of Electrical Engineering, University of Skikda. He has several journals and conference article publications covering a wide area in the design of antennas using metamaterial and dielectric antennas. His current research interests include electromagnetics and complex media, microwave propagation, and antennas.

ISSA ELFERGANI (Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical and electronic engineering from the University of Bradford, U.K., in 2008 and 2013, respectively. Since 2013, he has been a Postdoctoral Researcher and then as the Investigador Junior with the Mobile Systems Group, Instituto de Telecomunicações, Aveiro, Portugal. In 2014, he received the prestigious FCT Fellowship for his postdoctoral research. The evaluation of the first triennium of this scholarship was given an excellent rating by the evaluators. In 2019, he received a contract "Investigador Júnior." He has been involved in several research and development projects, such as Agile RF Transceivers and Front-Ends for Future Smart Multi-Standard Communications Applications (ARTEMOS), where he was the Task Leader of "Development of tunable filters and tunable resonators" and a Technical Responsible Investigator of designing the RF tunable bandpass filter operating over a wide continuous frequency range from 1800 to 2600 MHz for use in GSM and LTE applications; Green Terminals for Next Generation Wireless Systems (GREEN-T), for which he was the coordinator; and Best ENergy EFficiency solutions for heterogeneous multI-core Communicating systems (BENEFIC) and Coexistence of RF Transmissions in the Future (CORTIF), where he was the Task Leader of "test results and validation." Currently, all projects have been successfully concluded. He is currently working with (5GWAR) Novel 5G Millimetre-Wave Array Antennas for Future Mobile Handset Applications as a Principle Investigator and (SECRET): SEcure Network Coding for Reduced Energy nexT generation Mobile Small cells, where his role is the key responsible for the respective technical aspect of 5G Efficient power amplifier, antenna and tunable filters within the "WP4-Green RF for 5G Handsets. He has several years of experience in 3G/4G and 5G radio frequency systems research with particular expertise on several and different antenna structures along with novel approaches in accomplishing a size reduction, low cost, improved bandwidth, gain, and efficiency. He is currently conducting excellent work toward the 4G/5G single and MIMO antennas, including the physical human interaction, and links to health concerns. He is a member of AASCIT. He is a Guest Editor of the Special Issue of *Electronics* on "Recent technical developments in energy-efficient 5G mobile cells" (ISSN 2079-9292), the Special Issue on "Recent advances" in *Engineering Systems Journal (ASTESJ)* (ISSN 2017/2019), and the Special Issue of *Electronics* on "Recent advances in antenna design for 5G heterogeneous networks (ISSN 2079-9292). He was the Chair of the 4th, 5th, and 6th (EERT) international workshops. Since his Ph.D. graduation, he has successfully completed the supervision of Bolseiro de Investigação Cientifica with the title "UWB antenna design with fixed and tuneable rejected frequency bands" for a duration of one year, which led to one book chapter, one journal, and an IEEE conference paper. He is co-supervising some Ph.D. students and several master students. He has around 140 high-impact publications in international conferences, journal articles, and book/book chapters with a total number of citations more than 1100, an H-index of 17, and I10-indext of 31 reported by the Google Scholar Citation. Some key works to mention are his three edited books, namely, *Antenna Fundamentals for Legacy Mobile Applications and Beyond* (Springer International Publishing AG 2018), *Optical and Wireless Convergence for 5G Networks* (Wiley_IEEE Press., 2019), and *Recent Technical Developments in Energy-Efficient 5G Mobile Cells* (Electronics. Switzerland 2020). He reviewed several good ranked journals such as the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, IEEE ACCESS, *IET Microwaves, Antennas and Propagation*, *Radio Engineering Journal*, *IET-SMT*, and *IET Journal of Engineering*. He has been on the technical program committee of a large number of IEEE conferences, including EuCAP (2015, 2016, 2017, 2018, 2019, 2020, 2021) and ITA (15, 17).

MOHAMMAD ALIBAKHSHIKENARI (Member, IEEE) was born in Mazandaran, Iran, in 1988. He received the Ph.D. degree (Hons.) in electronic engineering from the University of Rome "Tor Vergata," Italy, in February 2020. In 2018, he was working with the Antenna System Division, Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden, as a Ph.D. Visiting Researcher, for eight months. During his Ph.D. degree, his training included a research stage at the Swedish Company Gap Waves AB that is developing components in a technology. During his Ph.D. research period, he had participated in 14 international IEEE conferences over the world, where he has presented 20 articles mostly in oral presentations. During his Ph.D. studies, he was a winner of 13 grants for participating in the European doctoral and postdoctoral schools on antennas and metamaterials organized by several European Universities and the European School of Antennas (ESoA). He acts as a referee in several high reputed journals and IEEE international conferences. The above research lines have produced more than 100 publications on refereed-international journals, presentations within international-conferences, and book chapters with a total number of the citations more than 1700, H-index of 30, and I10-indext of 51 reported by the Google Scholar Citation. His research interests include antennas and wave-propagations, phased antenna arrays, metamaterials and metasurfaces, synthetic aperture radars (SAR), multiple-input multiple-output (MIMO) systems, waveguide slotted antenna arrays, substrate integrated waveguides (SIWs), impedance matching circuits, on-chip antennas, microwave components, millimeter-waves and terahertz integrated circuits, and electromagnetic systems. He was a recipient of two years postdoctoral research grant awarded by the Electronic Engineering Department of the University of Rome "Tor Vergata" started in November 2019and the International Postgraduate Research (Ph.D.) Scholarship (IPRS) by the Italian Government in 2016 for three years. He was a recipient of two Young Engineer Prizes of the 47th and 48th European Microwave Conference (EuMC), Nuremberg, Germany, in 2017, and in 2018, Madrid, Spain, where he had presented his articles. In August 2019, he gave an invited lecture entitled "Metamaterial Applications to Antenna Systems" at the Department of Information and Telecommunication Engineering, Incheon National University, Incheon, South Korea, which was in conjunction with the 8th Asia–Pacific Conference on Antennas and Propagation (APCAP 2019), where he was the Chair of the Metamaterial Session as well. He is serving as an Associate Editor for *IET Journal of Engineering* and a Guest Editor for two Special Issues entitled "Millimeter-wave and Terahertz Applications of Metamaterials" and "Innovative Antenna Systems: Challenges, Developments, and Applications" in *Applied Sciences* and *Electronics*, respectively. In April 2020, his article entitled "High-Gain Metasurface in Polyimide On-Chip Antenna Based on CRLH-TL for Sub Terahertz Integrated Circuits" published in "Scientific Reports" was awarded as the Best Month Paper with the University of Bradford, U.K.

JONATHAN RODRIGUEZ (Senior Member, IEEE) received the master's degree (Hons.) in electronic and electrical engineering and the Ph.D. degree from the University of Surrey, U.K., in 1998 and 2004, respectively. In 2005, he became a Researcher at the Instituto de Telecomunicações, Portugal, where he was a member of the Wireless Communications Scientific Area. In 2008, he became a Senior Researcher, where he established the 4TELL Research Group targeting next-generation mobile systems. He has served as a Project Coordinator for major international research projects, including Eureka LOOP and FP7 C2POWER while serving as technical manager for FP7 COGEU and FP7 SALUS. He is currently the Coordinator of the H2020-MSCA-SECRET Innovative Training Network. Since 2009, he has been serving as an Invited Assistant Professor with the University of Aveiro, Portugal, and attained Associate Level, in 2015. In 2017, he was appointed as a Professor of mobile communications with the University of South Wales, U.K. He is the author of more than 500 scientific works, including 11 book editorials. His professional affiliations include the Chartered Engineer (CEng), since 2013, and a Fellow of the IET (2015).

RAED A. ABD-ALHAMEED (Senior Member, IEEE) received the B.Sc. and M.Sc. degrees from Basrah University, Basrah, Iraq, in 1982 and 1985, respectively, and the Ph.D. degree from the University of Bradford, West Yorkshire, U.K., in 1997. He is currently a Professor of electromagnetic and radio frequency engineering with the University of Bradford, U.K. He is the Leader of radio frequency, propagation, sensor design and signal processing, in addition to leading the communications research group for years within the School of Engineering and Informatics, Bradford University. He is also a Chartered Engineer. He is the Principal Investigator for several funded applications to EPSRCs and the Leader of several successful knowledge Transfer Programmes, such as with Arris (previously known as Pace plc), Yorkshire Water plc, Harvard Engineering plc, IETG Ltd., Seven Technologies Group, Emkay Ltd., and Two World Ltd., including many Research Development Projects awards supported by Regional European Funds. He has been a Co-Investigator with several funded research projects, including 1) H2020 MARIE Skłodowska-CURIE ACTIONS: Innovative Training Networks (ITN) "Secure Network Coding for Next Generation Mobile Small Cells 5G-US," 2) nonlinear and demodulation mechanisms in biological tissues (Department. of Health, Mobile Telecommunications and Health Research Programme, and 3) Assessment of the Potential Direct Effects of Cellular Phones on the Nervous System (EU: collaboration with six other major research organizations across Europe). He has published over 600 academic journal articles and conference papers. In addition, he is the co-author of four books and several book chapters. His research interests include radio frequency, signal processing, propagations, antennas, and electromagnetic computational techniques. He was awarded the Business Innovation Award for his successful KTP with Pace and Datong companies on the design and implementation of MIMO sensor systems and antenna array design for service localizations. He is the Chair of several successful workshops on Energy Efficient and Reconfigurable Transceivers (EERT): Approach toward Energy Conservation and CO2 Reduction that addresses the biggest challenges for future wireless systems. He has also appointed as a Guest Editor for the IET Science, Measurements and Technology Journal, since 2009, and 2012. He has been a Research Visitor for Wrexham University, Wales, since September 2009, covering the wireless and communications research areas. His research interests include 5G green communications systems, computational methods and optimizations, wireless and Mobile communications, sensor design, EMC, MIMO systems, beam steering antennas, energy-efficient PAs, and RF predistorter design applications. He is a fellow of the Institution of Engineering and Technology and the Higher Education Academy.

FRANCISCO FALCONE (Senior Member, IEEE) received the degree in telecommunication engineering and the Ph.D. degree in communication engineering from the Universidad Pública de Navarra (UPNA), Spain, in 1999 and 2005, respectively. From February 1999 to April 2000, he was the Microwave Commissioning Engineer with Siemens-Italtel, deploying microwave access systems. From May 2000 to December 2008, he was a Radio Access Engineer with Telefónica Móviles, performing radio network planning and optimization tasks in mobile network deployment. From January 2009, as a Co-Founding Member, he has been the Director of Tafco Metawireless, a spin-off company from UPNA, until May 2009. In parallel, he is an Assistant Lecturer with the Electrical and Electronic Engineering Department, UPNA, from February 2003 to May 2009. In June 2009, he became an Associate Professor with the EE Department, where he was the Department Head, from January 2012 to July 2018. From January 2018 to May 2018, he was a Visiting Professor with the Kuwait College of Science and Technology, Kuwait. He is also affiliated with the Institute for Smart Cities (ISC), UPNA, which hosts around 140 researchers. He is currently acting as the Head of the ICT Section. His research interest includes computational electromagnetics applied to the analysis of complex electromagnetic scenarios, with a focus on the analysis, design, and implementation of heterogeneous wireless networks to enable 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 Peñalver 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, Elettronica 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 istitutional 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.