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Gyro-Chirality Effect of Bianisotropic Substrate on the Resonant Frequency and Half-power Bandwidth of Rectangular Microstrip Patch Antenna

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Abstract: In this paper, the gyrotropic bi-anisotropy of the chiral medium in substrate constitutive parameters (ξ_c and η_c) of a rectangular microstrip patch antenna is introduced in order to observe its effects on the complex resonant frequency and half-power bandwidth. The analysis is based on the full-wave spectral domain approach using the Moment Method, with sinusoidal type basis functions. The numerical calculations related to the dominant mode have been carried out, and it has been observed that the resonant frequency and the bandwidth are directly linked to the medium chirality. The new results can be considered as a generalisation form of the previously published work.

Keywords: Microstrip antenna; Chiral; Gyrotropy; Bi-anisotropy; Moment Method.

1 Introduction

The possibility of employing chiral materials as substrates in the design of Microwave Integratrd Circuits and Antenna Printed Circuits, was reported by Lindell, Sihvola, Tretyskov, and Vitanen (1994). On the other hand, Pozar (1992) underlined the serious disadvantages of the use of these materials as substrates, because

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of the losses due to the surface waves excitation and the significant appearance of poles during numerical calculations [Zebiri, Benabdelaziz, Sayad (2012a)]. Whereas, [Toscano and Vegni (1997); Zebiri, Lashab, and Benabdelaziz (2010, 2011); Zebiri, Lashab, and Sayad (2012a)] have recently proved that the chiral substrates can advantageously be employed to increase the band-width of the microstrip antennas, and to enhance the input impedance [Zebiri, Benabdelaziz, and Lashab (2012b)]. In addition, the general electrical gyrotropic materials are proposed in the computation of the electric and magnetic Green's functions for the time-harmonic Maxwell's equations [Yakhno and Çiçek (2014)]

The effect of the bi-anisotropic media on the propagation in waveguides and antennas has also woken up the interest of many researchers. Thus, many research works on the electromagnetic propagation in waveguides filled with bi-isotropic/chiral materials are reported in the literature [Kamenetskii (1996), Cary and Waxman (1994)]. The use of chiral media in microstrip antennas is also proposed in [Zebiri (2012), Zebiri, Lashab, and Benabdelaziz (2010), Zebiri, Lashab, and Benabdelaziz (2011), Cary and Waxman (1994)], in order to reduce the losses due to the surface waves radiation in a microstrip antenna printed on a chiral substrate [Zebiri (2012), Cary and Waxman (1994), Engheta and Pelet (1991)].

Our previously published paper [Zebiri, Lashab, and Benabdelaziz (2013)] treats the asymmetrical effects on the resonant frequency and the bandwidth of a rectangular microstrip patch antenna in a bi-anisotropic substrate-superstrate configuration. The structure was studied theoretically and we have concluded that it must be borne in mind that the bi-anisotropy and specially the asymmetry of the substrates should always be taken into account in the design of the microstrip resonators.

In this paper, a full wave Moment Method in spectral domain is applied on the rectangular microstrip patch antennas with chiral substrate. The gyro-chirality is applied on the substrate. The chirality admittance concerning a cylindrical substrate is given in Yang and Uslenghi (1993), however the case of planar substrate with the previously mentioned chirality admittance is not reported in the literature. The effect on the resonant frequency and the half power bandwidth is presented and compared with published works. In our previous works [Zebiri, Benabdelaziz, and Sayad (2012a); Zebiri, Lashab, and Benabdelaziz (2010); Zebiri, Benabdelaziz, and Lashab (2012b); Zebiri, Lashab, and Benabdelaziz (2013)], we studied the effect of chiral substrates and superstrates on microstrip antenna characteristics, however in this paper a new effect has been studied and original results are presented. The effect in question concerns essentially the asymmetrical effect of the gyrotropic anisotropic chirality of the substrate on the electric and magnetic fields components.

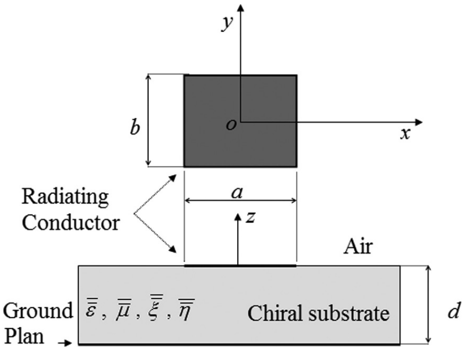


Figure 1: Rectangular microstrip patch antenna with chiral substrate.

2 Theory

2.1 Chiral medium

The geometry under consideration is shown in Figure 1, the rectangular patch with dimensions (*a*, *b*) along the two axes (*ox*, *oy*) respectively is printed on a grounded bianisotropic dielectric slab of thickness d_1. This bianisotropic medium is characterized by four independent constitutive tensors. For bianisotropic media, **D** and **B** are respectively related to both **E** and **H**. The expression of the field components will be restricted by consideration of the macroscopic constitutive relations in the following form Bilotti and Vegni (2003):

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

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

Where the permeability, permittivity and magneto-electric elements are given respectively by Bilotti and Vegni (2003):

$$\bar{\mu}, \bar{\bar{\varepsilon}} = \begin{bmatrix} \mu_t, \varepsilon_t & 0 & 0 \\ 0 & \mu_t, \varepsilon_t & 0 \\ 0 & 0 & \mu_z, \varepsilon_z \end{bmatrix}, \text{ and } \bar{\bar{\xi}}, \bar{\bar{\eta}} = j \begin{bmatrix} 0 & \xi_c, \eta_c & 0 \\ -\xi_c, -\eta_c & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3}$$

In Zebiri, Lashab, and Benabdelaziz (2010); Zebiri, Lashab, and Benabdelaziz (2011) a special case of above magneto-electric elements is treated.

2.2 Green's tensor evaluation

Assuming a $e^{i\omega t}$ time variation and starting from Maxwell's equations in the Fourier transform domain, we can show that the transverse magnetic (*TM* or *E*) and transverse electric (*TE* or *H*) counterparts of the tangential electric and magnetic fields in the Fourier domain for an anisotropic bounded region having anisotropy tensor type given by (3), can be expressed in compact matrix form as follows:

$$\tilde{E}_S(\kappa_s,z)=\begin{bmatrix}\tilde{E}^e(\kappa_s,z)\\ \tilde{E}^h(\kappa_s,z)\end{bmatrix}=e^{-\kappa_0\frac{1}{2}(\xi_c-\eta_c)\cdot z}\left(e^{j\bar{\kappa}_z z}\bar{A}(\kappa_s)+e^{-j\bar{\kappa}_z z}\bar{B}(\kappa_s)\right) \tag{4}$$

$$\tilde{H}_S(\kappa_s,z)=\begin{bmatrix}\tilde{H}^e(\kappa_s,z)\\ \tilde{H}^h(\kappa_s,z)\end{bmatrix}=e^{-\kappa_0\frac{1}{2}(\xi_c-\eta_c)\cdot z}\left(\bar{g}(\kappa_s)\bar{A}(\kappa_s)e^{j\bar{\kappa}_z z}+\bar{h}(\kappa_s)\bar{B}(\kappa_s)e^{-j\bar{\kappa}_z z}\right) \tag{5}$$

$\bar{\tilde{E}}_S$ and $\bar{\tilde{H}}_S$ are expressed according to the TE and TM modes by :

$$\bar{\kappa}_z=\begin{bmatrix}\kappa_z^e & 0\\ 0 & \kappa_z^h\end{bmatrix}= \tag{6}$$

$$\begin{bmatrix}\left(\kappa_0^2\left(\varepsilon_t\mu_t-\left(\frac{\xi_c+\eta_c}{2}\right)^2\right)-\frac{\varepsilon_t}{\varepsilon_z}\kappa_s^2\right)^{\frac{1}{2}} & 0\\ 0 & \left(\kappa_0^2\left(\varepsilon_t\mu_t-\left(\frac{\xi_c+\eta_c}{2}\right)^2\right)-\frac{\mu_t}{\mu_z}\kappa_s^2\right)^{\frac{1}{2}}\end{bmatrix}$$

$$\kappa_0=\omega\sqrt{\mu_o\varepsilon_o} \tag{7}$$

$$\kappa_s^2=\kappa_x^2+\kappa_y^2 \tag{8}$$

$$\bar{A}(\kappa_s)=\begin{bmatrix}j\frac{1}{\kappa_s^2}\frac{\varepsilon_z}{\varepsilon_t}\left(-\kappa_0\frac{1}{2}(\xi_c+\eta_c)+j\kappa_z^e\right)A^e\\ \frac{1}{\kappa_s^2}\omega\mu_0\mu_z A^h\end{bmatrix} \tag{9}$$

$$\bar{B}(\kappa_s)=\begin{bmatrix}j\frac{1}{\kappa_s^2}\frac{\varepsilon_z}{\varepsilon_t}\left(-\kappa_0\frac{1}{2}(\xi_c+\eta_c)-j\kappa_z^e\right)B^e\\ \frac{1}{\kappa_s^2}\omega\mu_0\mu_z B^h\end{bmatrix} \tag{10}$$

$$\bar{g}(\kappa_s)=diag\left[\frac{\omega\varepsilon_0\varepsilon_t}{j\left(-\kappa_0\frac{1}{2}(\xi_c+\eta_c)+j\kappa_z^e\right)},\frac{j\left(\kappa_0\frac{1}{2}(\xi_c+\eta_c)+j\kappa_z^h\right)}{\omega\mu_0\mu_t}\right] \tag{11}$$

$$\bar{h}(\kappa_s)=diag\left[\frac{\omega\varepsilon_0\varepsilon_t}{j\left(-\kappa_0\frac{1}{2}(\xi_c+\eta_c)-j\kappa_z^e\right)},\frac{j\left(\kappa_0\frac{1}{2}(\xi_c+\eta_c)-j\kappa_z^h\right)}{\omega\mu_0\mu_t}\right] \tag{12}$$

Using Maxwell's equations as defined previously, we express the longitudinal components of the electric and magnetic fields in the chiral medium according to the following expressions

$$\tilde{E}_z(\kappa_s, z) = A^e e^{j\kappa_z^e z} + B^e e^{-j\kappa_z^e z} \tag{13}$$

$$\tilde{H}_z(\kappa_s, z) = A^h e^{j\kappa_z^h z} + B^h e^{-j\kappa_z^h z} \tag{14}$$

Where the spectral coefficients A^e, A^h, B^e and B^h are functions of the variables κ_s, κ_z^e and κ_z^h, these are *respectively* the free space propagation and wave number for TE and TM modes.

$$\bar{\mathbf{G}}(\kappa_s) = \frac{1}{j\omega\varepsilon_0}\,\mathrm{diag}\left[\frac{N^e}{D^e}\kappa_z\kappa_z^e, \frac{1}{D^h}\kappa_0^2\mu_t\right]\cdot\sin(\bar{\kappa}_z d_1) \tag{15}$$

In which

$$N^e = \frac{1}{\kappa_z^{e2}}\left(\kappa_0^2\varepsilon_t\mu_t - \frac{\varepsilon_t}{\varepsilon_z}\kappa_s^2\right) \tag{16}$$

$$\begin{aligned} D^e = \Bigg(&\kappa_z\varepsilon_t\cos\left(\kappa_z^h d_1\right) + j\frac{1}{\kappa_z^e}\left(\kappa_z^{e2} + \frac{1}{2}\kappa_0(\xi_c + \eta_c)\right.\\ &\left.\left(\frac{1}{2}\kappa_0(\xi_c + \eta_c) - j\kappa_z\varepsilon_t\right)\right)\sin\left(\kappa_z^e d_1\right)\Bigg) \end{aligned} \tag{17}$$

$$D^h = \kappa_z^h\cos\left(\kappa_z^h d_1\right) + j\left(\kappa_z\mu_t - j\frac{1}{2}\kappa_0(\xi_c + \eta_c)\right)\sin\left(\kappa_z^h d_1\right) \tag{18}$$

$$\kappa_z^2 = \kappa_0^2 - \kappa_s^2 \tag{19}$$

For an electric and non magnetic medium having biaxial anisotropy with regard to the permittivity, the previous expressions are well detailed in Bouttout, Benabdelaziz, Fortaki, and Khedrouche (2000), and the case $\xi_c = \eta_c$ is treated in Zebiri, Lashab, and Benabdelaziz (2010).

2.3 Integral equation solution

The integral equation describing the electric field on the patch is expressed by applying the boundary conditions [Zebiri, Lashab, and Benabdelaziz (2010); Zebiri, (2012), Bouttout, Benabdelaziz, Fortaki, and Khedrouche (2000)] as:

$$\int_{-\infty}^{\infty}\int d\kappa_s\bar{F}(\bar{\kappa}_s, \bar{r}_s)\cdot\bar{\mathbf{G}}(\kappa_s)\cdot\tilde{\mathbf{J}}(\kappa_s) = 0 \tag{20}$$

The Galerkin procedure of the Moment Method in the Fourier domain can be used, which enables the integral equation in (20) to be discretized into a matrix equation.

This matrix equation has a non trivial solution only in the case where the condition below is verified.

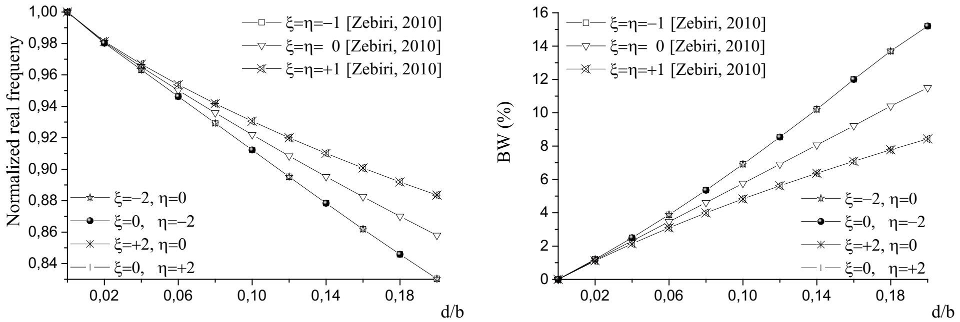
$$\det(\bar{\mathbf{B}}(\omega)) = 0 \tag{21}$$

Since the resonator is designed to operate near its resonant frequency, all its characteristics are estimated around this frequency. Equation (21) is called characteristic equation for the complex resonant frequency $f = f_r + i f_i$, where f_r: is the resonant frequency and f_i: expresses the losses by radiation in the case of a radiating antenna. The half power bandwidth are defined in Zebiri, Lashab, and Benabdelaziz (2010); Zebiri (2012); Bouttout, Benabdelaziz, Fortaki, and Khedrouche (2000) as:

$$BW = \frac{2f_i}{f_r} \tag{22}$$

3 Numerical analysis

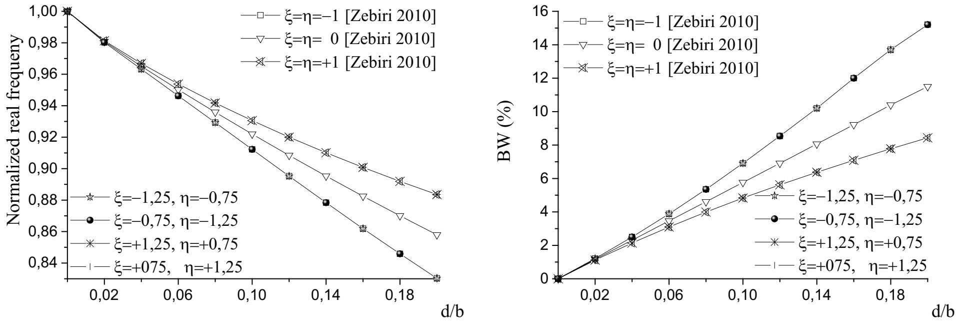
The effect of bianisotropic substrate provided with gyro-chirality upon the complex resonant frequency and the half-power bandwidth has been studied. It is assumed the relative permittivity of the medium is $\boldsymbol{\varepsilon_{1x}} = \varepsilon_{1z} = 2.32$, and the dimensions of the rectangular patch are 1 cm × 1.5 cm as shown in Fig. 1. The normalized real part of the resonant frequency with respect to the fundamental mode frequency f_o, is given in Fig. 2(a), 3(a) and 4(a) respectively. The half-power bandwidth with respect to the substrate thickness and for different values of the magneto-electric element is presented in Fig. 2(b)–4(b).



(a) (b)

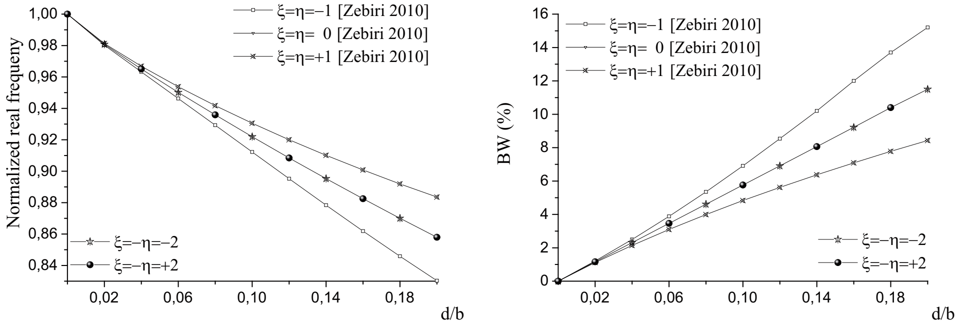
Figure 2: Chirality effect on the (a) real part of resonant frequency, (b) half-power bandwidth; for ($\bar{\bar{\xi}} \neq \bar{\bar{\eta}}$, ($\bar{\bar{\xi}} \neq 0$, $\bar{\bar{\eta}} = 0$) and ($\bar{\bar{\xi}} = 0$, $\bar{\bar{\eta}} \neq 0$)), a = 1.5 cm, b = 1 cm, $\varepsilon_r = 2.35$.

According to the results shown in Fig. 2, 3 and 4 of the resonant frequency and the bandwidth; the following summarized remarks could be illustrated:



(a) (b)

Figure 3: Chirality effect on the (a) real part of resonant frequency, (b) half-power bandwidth; for ($\bar{\bar{\xi}} \neq \bar{\bar{\eta}}$, $\bar{\bar{\xi}} \neq 0$ and $\bar{\bar{\eta}} \neq 0$), a = 1.5 cm, b = 1 cm, $\varepsilon_r = 2.35$.



(a) (b)

Figure 4: Chirality effect on the (a) real part of resonant frequency, (b) half-power bandwidth; for ($\bar{\bar{\xi}} = -\bar{\bar{\eta}}$), a = 1.5 cm, b = 1 cm, $\varepsilon_r = 2.35$.

- The effect of the chirality is remarkable only for thick layers, whereas for those infinitely small this effect is unperceived.

- In the case of a positive chirality, for all of the four cases (($\xi_c = 0$, $\eta_c = +\,2$), ($\xi_c = +\,2$, $\eta_c = 0$) in Fig. 2, ($\xi_c = +$ 1,25, $\eta_c = +$ 0,75) in Fig. 3; the real resonant frequency increases, but the band-width part decreases; and actually the effect of the two parameters in this case is added and they were in good agreement with those found in literature [Zebiri, Lashab, and Benabdelaziz (2010)]. However for the negative chirality case characterized by ($\xi_c = 0$, $\eta_c = -2$), ($\xi_c = -2$, $\eta_c = 0$)), leads to opposite variations compared to the preceding ones, and also compared with the case ($\xi_c = \eta_c = -1$) that it gives the same effect as in [Zebiri, Lashab, and Benabdelaziz (2010)].

- In the latter case ($\xi_c = -\eta_c$), it is noted that no effect of chirality was absolutely observed on the resonance frequency and bandwidth, though it is apparently remarkable in the formula of equations (4), 5 and 15.

4 Conclusion

The effect of bianisotropic substrate provided with gyro-chirality on microstrip patch antenna has been presented. The results in terms of the complex resonant frequency, half-power bandwidth and input impedance have been calculated and compared with earlier work. Two new results were concluded; the first was that the effective magneto-electric element $\frac{1}{2}(\xi_c + \eta_c)$ is the addition of the two elements ξ_c and η_c on the input impedance. The second effect with the gyro-chiral parameter on the transverse components was appearing in equations (4) and (5)), by the introducing the coefficient $e^{-\kappa_0 \frac{1}{2}(\xi_c - \eta_c)\cdot z}$, that expresses loss or gain, subject to the choice of the two constitutive parameters ξ_c and η_c. It can also be noted that it represents the asymmetric and the non-reciprocity effect that can be added to these parameters in the transverse components.

At the end of this work we can conclude that introduction of chirality in the substrate opens a wide range of applications, and definitely its major effect is the aptitude for structure miniaturization.

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