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RETRIEVAL APPROACH FOR DETERMINATION OF FORWARD AND BACKWARD WAVE IMPEDANCES OF BIANISOTROPIC METAMATERIALS

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Abstract—A simple approach is proposed for retrieving the forward and backward wave impedances of lossless and lossy bianisotropic metamaterials. Compared with other methods in the literature, its main advantage is that forward and backward wave impedances can be uniquely and noniteratively extracted. It has been validated for both lossless and lossy bianisotropic metamaterials by performing a numerical analysis. The proposed approach can be applied for checking whether the metamaterial structure shows the bianisotropic property by monitoring forward and backward wave impedances, since the forward and backward wave impedances of a metamaterial structure depend on different polarizations of the incident wave.

1. INTRODUCTION

Material characterization is an important issue in many material production, processing, and management applications in agriculture, food engineering, medical treatments, bioengineering, and the concrete industry [1]. In addition, microwave engineering requires precise knowledge of electromagnetic properties of materials at microwave frequencies since microwave communications are playing more and

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more important roles in military, industrial, and civilian life [1]. For these reasons, various microwave techniques have been proposed to characterize the electrical properties of conventional materials with consideration of the frequency range, required measurement accuracy, sample size, state of the material (liquid, solid, powder and so forth), destructiveness and non-destructiveness, contacting and non-contacting, etc. [2–37].

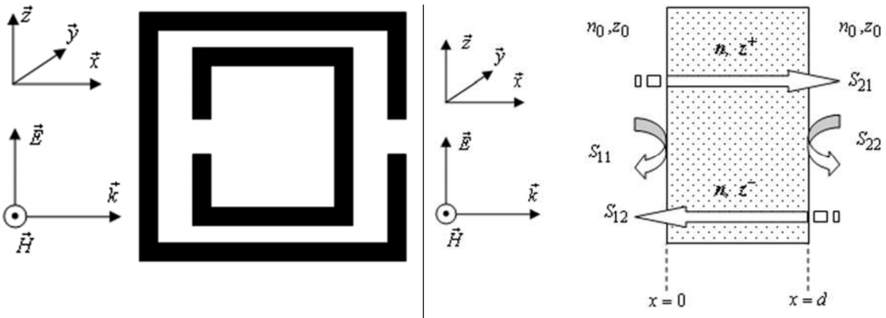
In 1968, Veselago [38] developed the concept of a material with a negative refractive index, which simultaneously exhibits negative relative permittivity (ε_r) and negative permeability (μ_r) [39]. These materials are referred to as either double negative metamaterials or left-handed materials and obey the left-hand rule. They extend the concept of conventional materials on account of properties engineered through artificially fabricated structures instead of chemical composition as in conventional electromagnetic properties [40]. Pendry et al. proposed two composite components for the construction of such materials as: a) arrays of thin metal wires giving a negative ε_r [41, 42] and b) arrays of split-ring resonators (SRR) resulting in negative μ_r [43].

Although, at a given frequency, any material supporting only one propagating mode will generally exhibit a well-defined refractive index, n, whether the material is continuous or not [44, 45], it is generally not possible to assign a normalized impedance, z, to a non-continuous material, since z strongly depends on surface termination or overall size of the material [44]. However, if the wavelength of the wave is much larger than the spacing between the composite components (scatterers) and the size of respective components of the metamaterials [39], then it is possible to consider the metamaterials as continuous materials and to obtain a non-ambiguous z [46].

While it is possible to completely specify the metamaterials in terms of n and z [44], it is often more convenient to choose a second set of analytic variables that carry a direct material interpretation, $\varepsilon_r = n/z$ and $\mu_r = nz$. In order to seek such effective constitutive parameters, there are three methods [39]. The first method is to numerically calculate the ratios of the electromagnetic field inside metamaterials [42]. It is appropriate for numerical simulations but not in experimental situations. The second method obtains the constitutive parameters by using approximate analytical models [47]. This method, however, is not much feasible for complex structures. The final method is to extract the parameters from scattering (S-) parameters [44], which is suitable for both numerical simulation and experimental point of view.

Due to asymmetry of the geometrical arrangement of the components such as SRRs [47, 48], most metamaterials possess intrinsically anisotropic behavior. However, for one wave propagation in a given direction, they can be considered as isotropic materials. Therefore, the well-known Nicolson-Ross-Weir technique can be utilized to extract the constitutive parameters of metamaterials provided that they show continuous media property [2–6, 49–51]. There are some severe problems in the retrieved values of z and n using this technique. For example, extracted z and n values using the technique are seriously affected by inaccuracy in the sample thickness [4, 44] and uncertainty associated with low-value S-parameters [4, 5, 50]. In addition, because of the presence of complex exponential in the expressions of S-parameters, a unique retrieval for n is generally a tricky issue, although some methods can handle such a problem [1, 19–26]. Another problem is the presence of undesired and inaccurate ripples in the extracted z values. The method proposed in [51] can be utilized as a remedy for most of the problems discussed above.

In some configurations, metamaterials could also exhibit bianisotropic properties, aside from anisotropic property, depending on the shape of inclusions or wave polarization [47, 52, 53]. Chen et al. [54] extracted effective constitutive parameters of bianisotropic metamaterials from S-parameters for various wave polarizations. They proposed a numerical approach for a plane wave polarized in the z direction ($\vec{E}//\widehat{z}$) and incident in the x direction ($\vec{k}//\widehat{x}$). In the remainder of the manuscript, such a wave is specified by the triplet $\{k_x, -H_y, E_z\}$ for right-handed coordinate system. Containing both H_y and E_z components, the incident wave induces an electric dipole in



(a) (b)

Figure 1. (a) Structure of the planar SRR and (b) a homogeneous bianisotropic material slab with thickness d suspended in air and S-parameters used in the determination of the forward and backward wave impedances.

the z direction and a magnetic dipole in the y direction (see Fig. 1(a) below). Since unknown complex variables for characterizing the problem are three (μ_y ξ_0, and ε_z), they utilized forward reflection and transmission complex S-parameters supplemented by data obtained from other polarizations. In addition, in their approach, extracted effective parameters must be obtained from a numerical method. To eliminate the need for obtaining/measuring S-parameter for other polarization and to obtain a noniterative result for the same problem, Li et al. [39] have proposed a noniterative approach using forward and backward reflection and transmission S-parameters for only $\{k_x, -H_y, E_z\}$ wave polarization. Although it eliminates the necessity of using a numerical approach and enables one to obtain the effective parameters using only $\{k_x, -H_y, E_z\}$ wave polarization, retrieval of effective constitutive parameters requires a prior knowledge of the correct branch for the natural logarithm of the complex transmission factor and the sample thickness as well. In addition, the method in [39] does not show whether the wave impinging the bianisotropic structure is a $\{k_x, -H_y, E_z\}$ wave polarization without assigning the correct branch value. In this research paper, we propose an approach for determining the polarity of the impinging wave without the necessity of finding the correct branch for the real part of refractive index and without knowing the sample thickness.

2. SCATTERING PARAMETERS

The problem of determining the wave impedance for forward and backward directions, Z^+ and Z^-, without assigning a correct branch value is shown in Fig. 1(a). In the figure, a plane wave polarized in the z axis propagates along the x direction and is incident upon a metamaterial structure consisting of SRRs. The SRR structure in Fig. 1(a) has a bianisotropic property, since the electric field in the z direction induces a magnetic dipole in the y direction due to asymmetry of the inner and outer rings, while the magnetic field in the y direction also induces an electric dipole in the z direction [39].

By assuming that the medium is reciprocal [55] and that the harmonic time dependence is $e^{-j\omega t}$, implying that $\varepsilon_r'' \geq 0$ and $\mu_r'' \geq 0$ simultaneously at all frequencies (for the remainder of the paper, we use primes and double primes for denoting real and imaginary parts of a quantity) the constitutive relations can be written (E–H or Tellegen representation [53]) as

$$\vec{D} = \overline{\overline{\varepsilon}} \cdot \vec{E} + \overline{\overline{\xi}} \cdot \vec{H}, \tag{1}$$

$$\vec{B} = \overline{\overline{\mu}} \cdot \vec{H} + \overline{\overline{\zeta}} \cdot \vec{E}, \tag{2}$$

where

$$\overline{\overline{\varepsilon}} = \varepsilon_0 \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}, \quad \overline{\overline{\mu}} = \mu_0 \begin{pmatrix} \mu_{xx} & 0 & 0 \\ 0 & \mu_{yy} & 0 \\ 0 & 0 & \mu_{zz} \end{pmatrix}, \tag{3}$$

$$\overline{\overline{\xi}} = \frac{1}{c} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -j\xi_0 & 0 \end{pmatrix}, \quad \overline{\overline{\varsigma}} = \frac{1}{c} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & j\xi_0 \\ 0 & 0 & 0 \end{pmatrix} \tag{4}$$

In (3) and (4) $\vec{E}$, $\vec{H}$, $\vec{D}$ and $\vec{B}$ are, respectively, the electric and magnetic field intensities and flux densities; and ε_0 and μ_0 are, respectively, the permittivity and permeability of the vacuum; c is the speed of light in vacuum; and other quantities are dimensionless and are unknowns. In the present study, we will only deal with the determination of forward and backward wave impedances entailed by ε_{zz}, μ_{yy}, and ξ_0, since other unknown four quantities (ε_{xx}, ε_{yy}, μ_{xx}, and μ_{zz}) are not related to the bianisotropic structure in Fig. 1(a) when a plane wave with a polarization in the z direction is incident in the x direction.

From Maxwell's curl equations [55] and using (3) and (4), we find

$$\frac{\partial^2 E_z}{\partial x^2} + k_x^2 E_z = 0, \qquad \frac{\partial^2 H_y}{\partial x^2} + k_x^2 H_y = 0, \tag{5}$$

$$Z^+ = \frac{-E_z^+}{H_y^+} = Z_0 \frac{\mu_{yy}}{(n + i\xi_0)}, \quad Z^- = \frac{E_z^-}{H_y^-} = Z_0 \frac{\mu_{yy}}{(n - i\xi_0)}, \tag{6}$$

$$z^+ = Z^+/Z_0, \qquad z^- = Z^-/Z_0, \tag{7}$$

where

$$k_x^2 = k_0^2 \left(\varepsilon_{zz}\mu_{yy} - \xi_0^2\right), \; Z_0 = \sqrt{\mu_0/\varepsilon_0}, \; k_x = nk_0, \; n = \mp\sqrt{\varepsilon_{zz}\mu_{yy} - \xi_0^2}. \tag{8}$$

Here, E_z and H_y are, respectively, the z and y components of $\vec{E}$ and $\vec{H}$; k_x and k_0 are, respectively, the wave number of the wave propagating in the x direction and in free-space; Z^+ and Z^- are, respectively, the wave impedances inside the medium for forward ($+\hat{x}$) and backward ($-\hat{x}$) propagations; z^+ and z^- are normalized (or nondimensionalized) wave impedances in respective directions; Z_0 is the wave impedance (or intrinsic impedance) in air; and n is the refractive index of the sample. It is seen from (5)–(8) that the important feature of a bianisotropic metamaterial is that wave impedances are different for waves propagating in forward and backward directions [39, 46].

For the derivation of S-parameters, we utilize the schematics of a homogeneous bianisotropic material slab with thickness d suspending in air as shown in Fig. 1(b). Writing incident, reflecting (if any), and transmitting wave fields in each region in Fig. 1(b) and imposing the boundary conditions of continuous electric and magnetic field transverse components at $x = 0$ and $x = d$, we derive the forward and backward reflection and transmission S-parameters in compact form as

$$S_{11} = \frac{\Gamma_A \left(1 - T^2\right)}{1 - \Gamma_B T^2}, \; S_{21} = S_{12} = \frac{\Gamma_C T}{1 - \Gamma_B T^2}, \; S_{22} = \frac{\Gamma_D \left(1 - T^2\right)}{1 - \Gamma_B T^2}, \quad (9)$$

where

$$\Gamma_A = \frac{z^+ - 1}{z^+ + 1} = \frac{\mu_{yy} - (n + i\xi_0)}{\mu_{yy} + (n + i\xi_0)}, \quad T = e^{ik_x d}, \quad (10)$$

$$\Gamma_B = \frac{(z^+ - 1)(z^- - 1)}{(z^+ + 1)(z^- + 1)} = \frac{(n - \mu_{yy})^2 + \xi_0^2}{(n + \mu_{yy})^2 + \xi_0^2}, \quad (11)$$

$$\Gamma_C = \frac{2(z^+ + z^-)}{(z^+ + 1)(z^- + 1)} = \frac{4\mu_{yy} n}{(\mu_{yy} + n)^2 + \xi_0^2}, \quad (12)$$

$$\Gamma_D = \frac{z^- - 1}{z^- + 1} = \frac{\mu_{yy} - (n - i\xi_0)}{\mu_{yy} + (n - i\xi_0)}. \quad (13)$$

Substituting the expressions for Γ_A, Γ_B, Γ_C and Γ_D in (10)–(13) into (9), we obtain the same expressions for S_{11}, S_{21} and S_{22} as in [39, 54]. The advantage of using compact form expressions instead of explicit ones in [39, 54] will become clearer when we obtain the forward and backward wave impedances noniteratively. In addition, having determined the wave impedance for the metamaterial under investigation, the Nicolson-Ross-Weir method [2–6, 27–37] or Smith-Schultz-Markos-Soukoulis method [44] can directly be applied to retrieve the remaining constitutive parameters.

Assuming that the bianisotropic behavior of the metamaterial under investigation for the specific $\{k_x, -H_y, E_z\}$ wave propagation evanishes, one can assume $z^+ = z^- = z$. Incorporating this condition into (9), we obtain

$$S_{11} = S_{22} = \frac{\Gamma(1 - T)}{1 - \Gamma^2 T^2}, \qquad S_{21} = S_{12} = \frac{T\left(1 - \Gamma^2\right)}{1 - \Gamma^2 T^2}, \quad (14)$$

where

$$\Gamma_A = \Gamma = \frac{z - 1}{z + 1}, \qquad \Gamma_B = \Gamma^2, \qquad \Gamma_C = 1 - \Gamma^2. \quad (15)$$

Therefore, determining the forward and backward wave impedances of a metamaterial will give an insight on whether it has bianisotropy.

3. RETRIEVAL OF WAVE IMPEDANCES FROM SCATTERING PARAMETERS

Although the Nicolson-Ross-Weir method [2–6, 27–37] or Smith-Schultz-Markos-Soukoulis method [44] is suitable for the retrieval of ε_r and μ_r of metamaterials, it is not appropriate for composite materials that possess reflection asymmetric structures ($S_{11} \neq S_{22}$) [33–37]. As a result, one should resort to other approaches for the problem depicted in Fig. 1.

It is clear from (10)–(13) that out of the four quantities Γ_A, Γ_B, Γ_C and Γ_D, two of them give the remaining pair. For instance, the pair Γ_B and Γ_C is obtained from Γ_A and Γ_D as $\Gamma_B = \Gamma_A\Gamma_D$ and $\Gamma_C = (1+\Gamma_A) + (1+\Gamma_D) - (1+\Gamma_A)(1+\Gamma_D)$. Our aim is to eliminate T in S_{11}, S_{22} and S_{21} from (9), which produces a multiple-solutions set [29, 31]. To this end, using S_{11} in (9), we find

$$T^2 = \frac{S_{11} - \Gamma_A}{\Gamma_B S_{11} - \Gamma_A}, \quad T = \mp\sqrt{\frac{S_{11} - \Gamma_A}{\Gamma_B S_{11} - \Gamma_A}}. \tag{16}$$

Then, substituting T^2 in (16) into S_{21} in (9), we find

$$S_{21}^2\left(1 - z^+\right) = \left[(S_{11}+1) + (S_{11}-1)\,z^+\right]\left[1 - S_{11}\left(\frac{z^- - 1}{z^- + 1}\right)\right]. \tag{17}$$

Next, using S_{11} and S_{22} in (9), we find a relation between z^- and z^+ as

$$z^- = \frac{pz^+ + 1}{z^+ + p}, \; p = \frac{S_{11} + S_{22}}{S_{11} - S_{22}}. \tag{18}$$

Finally, incorporating z^- from (18) into (17), we derive an equation of z^+ only

$$\lambda_A z^{+2} + \lambda_B z^+ + \lambda_C = 0, \tag{19}$$

where

$$\lambda_A = S_{21}^2 - (1 - S_{11})(1 - S_{22}), \; \lambda_B = 2(S_{11} - S_{22}), \tag{20}$$

$$\lambda_C = (1 + S_{11})(1 + S_{22}) - S_{21}^2. \tag{21}$$

When $S_{11} = S_{22}$ (anisotropic metameterial) the general Equation (19) reduces to

$$z^+ = \mp\sqrt{\frac{S_{21}^2 - (1 + S_{11})^2}{S_{21}^2 - (1 - S_{11})^2}}, \tag{22}$$

from which $z^+ = z^- = z$ can be readily determined. We note that the equation in (22) is identical to the expression for the normalized impedance obtained from the inversion of the equations for the transmission and reflection coefficients in [44], which shows the validity of the derived expressions (forward and inverse problems).

Although (19) gives two solutions for z^+, only one of them is valid for a passive medium by satisfying the following requirements based on causality $z^{+'} \geq 0$ (and $z^{-'} \geq 0$). After z^- can be uniquely determined from (18). However, a unique solution for ε_{zz}, μ_{yy}, and ξ_0 cannot be obtained for one thicker slab material and a given frequency, since complex T contains multiple branch values.

4. VALIDATION OF THE DERIVED EXPRESSIONS FOR FORWARD AND BACKWARD WAVE IMPEDANCES IN A BIANISOTROPIC METAMATERIAL

In the inverse problem (retrieval for z^+ and z^- using S_{11}, S_{22}, and S_{21}), we utilize constitutive parameters similar to those in [54] to examine lossless and lossy bianisotropic metamaterials. Using the following coefficients

$$C_1 = 1.5,\ C_2 = 1.0,\ C_3 = 2.0,\ C_4 = 0.5,\ f_0 = 5.0\ \text{GHz}, \tag{23}$$

we find the constitutive parameters for a lossless bianisotropic medium as

$$\varepsilon_{xx}(f) = C_1,\ \varepsilon_{yy}(f) = 1,\ \varepsilon_{zz}(f) = \varepsilon_{xx}(f) + C_2\kappa,\ \kappa = 1\Big/\Big((f_0/f)^2 - 1\Big), \tag{24}$$

$$\mu_{xx}(f) = \mu_{zz}(f) = 1,\ \mu_{yy}(f) = 1 + C_3\kappa,\ \xi_0(f) = C_4(f_0/f)\kappa. \tag{25}$$

In a similar fashion, using the following coefficients

$$C_1 = 2.0,\ C_2 = 1.0,\ f_e = 6.0\ \text{GHz},\ f_m = f_\xi = 5.0\ \text{GHz}, \tag{26}$$

$$F_e = F_m = 0.4,\ F_\xi = 0.15,\ \gamma_e = \gamma_m = \gamma_\xi = 0.4\ \text{GHz}, \tag{27}$$

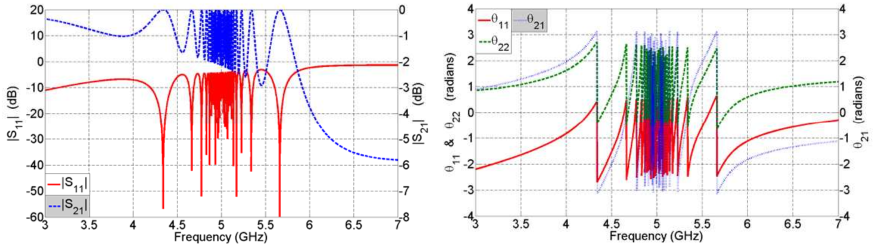
we find the constitutive parameters for a lossy bianisotropic medium as

$$\varepsilon_{xx}(f) = C_1,\ \varepsilon_{yy}(f) = C_2,\ \varepsilon_{zz}(f) = 1 - F_e f^2\big/\big(f^2 - f_e^2 + i\gamma_e f\big), \tag{28}$$

$$\mu_{xx}(f) = \mu_z(f) = C_2,\ \mu_{yy}(f) = 1 - F_m f^2\big/\big(f^2 - f_m^2 + i\gamma_m f\big), \tag{29}$$

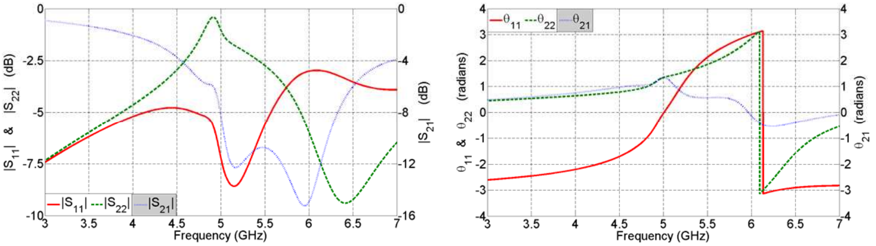
$$\xi_0(f) = 1 - F_\xi f^2\big/\big(f^2 - f_\xi^2 + i\gamma_\xi f\big). \tag{30}$$

Figs. 2 and 3 illustrate the dependence of the magnitudes and phases of forward and backward reflection and transmission S-parameters over frequency range 3–7 GHz for the above lossless and lossy bianisotropic metamaterial samples each with $d = 7$ mm. The chosen value of d is consistent with the size of SRRs (typically a square with 4 mm to a side) operating in the 3–7 GHz frequency range (see Figs. 2–5). Other values for d could equally be used provided the spacing between SRRs be kept much smaller than the operating wavelength.



(a) (b)

Figure 2. (a) Magnitudes (dB) and (b) phases (radians) of forward and backward reflection and transmission S-parameters for the lossless bianisotropic metamaterial with $d = 7\,\mathrm{mm}$ ($|S_{11}| = |S_{22}|$).



(a) (b)

Figure 3. (a) Magnitudes (dB) and (b) phases (radians) of forward and backward reflection and transmission S-parameters for the lossy bianisotropic metamaterial with $d = 7\,\mathrm{mm}$.

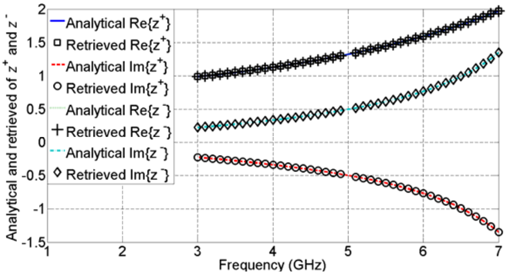
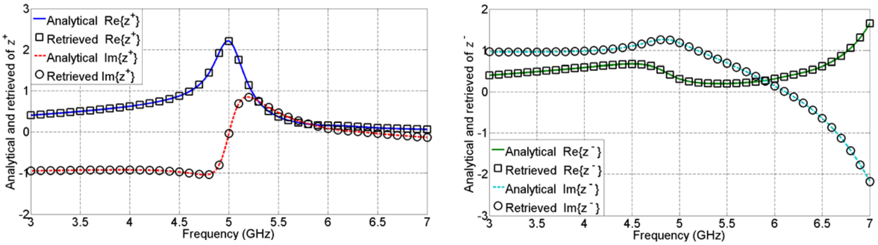


Figure 4. Analytical and retrieved values of normalized forward and backward wave impedances (ohm) for the lossless bianisotropic metamaterial.



(a) (b)

Figure 5. (a) Forward and (b) backward anaytical and retrieved normalized wave impedances (ohm) for the lossy bianisotropic metamaterial.

Applying our proposed method, we extracted forward and backward wave impedances for both sample, as shown in Figs. 4 and 5. It is seen from Figs. 4 and 5 that our proposed method is in good agreement with the analytical formulae in (7). Since ε, μ, and ξ_0 for lossless materials in (23)–(25) are real functions, we note that $z^{+'}$ and $z^{-'}$ (Fig. 4) overlap at the same value $\mu_{yy}n'/(|n|^2+\xi_0^2)$ ($|\cdot|$ designates the absolute value of a quantity), an expression readily derived from (6) and (7). But, we see that $z^{+''}$ and $z^{-''}$ are symmetric about the frequency axis with corresponding values $-\mu_{yy}(n'' \pm \xi_0^2)\Big/(|n|^2+\xi_0^2)$ with $\mu_{yy}\xi_0 < 0$ at all frequencies.

On the other hand, the lossy metamaterial (Fig. 5) shows two different impedances for opposite directions on the propagation axis. At frequencies close to the resonance (in our case, $f = 5.0\,\text{GHz}$), the SRR medium exhibits asymmetric and inhomogeneous features. However, up to $f = 4.3\,\text{GHz}$, the impedances are essentially the same ($z^{+'} \approx z^{-'}$ and $z^{+''} \approx -z^{-''}$), implying that away from the resonance the medium is much like a homogeneous material. In this regard, Lorentz description for the constitutive parameters ε, μ, and ξ_0 in expressions (28)–(30) with resonant behavior are consistent with the polarization considered. Upon exciting the resonant oscillation, the electric field makes the current circulate inside the SRR and hence couples to the magnetic resonance. As result, the SRR exhibits a magnetoelectric coupled response which cannot be described embodying only permittivity and permeability tensors [47, 52].

While the explicit forms for the S parameters (cf. Equations (5) and (6) in [2]) require that the sample thickness be known, the formalism developed here makes the specification of such a parameter unnecessary. In fact, we note that the sample thickness d is explicitly incorporated in equation (10) for the propagation factor T, which in turn has been eliminated by combining S_{11}, S_{21}, and S_{22} from (9) to give relation (17) independent of T. This is consistent with the fact that the impedance of a homogeneous slab of material does not depend on its thickness.

5. CONCLUSION

A retrieval method has been proposed for extracting the forward and backward wave impedances of lossless and lossy bianisotropic metamaterials. The underlying expressions of forward and backward reflection and transmission S-parameters are derived in a compact form to able to noniteratively and unambiguously determine the forward and backward wave impedances of bianisotropic metamaterials. The proposed method has been validated for a lossless and a lossy bianisotropic metamaterial by performing a numerical analysis. It can be applied for checking whether the metamaterial structure shows the bianisotropic property by monitoring forward and backward wave impedances, since the forward and backward wave impedances of a metamaterial structure manifest themselves at a specific wave polarization.

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