Frequency-Domain Solution to Electromagnetic Scattering from Dispersive Chiroferrite Materials

Moamer Hasanovic, Chong Mei, Jay K. Lee, and Ercument Arvas

Department of Electrical Engineering and Computer Science
Syracuse University, Syracuse, NY 13244, USA
mhasanov@syr.edu, cmei@syr.edu, leejk@syr.edu, earvas@syr.edu

Abstract **─** Main purpose of this paper is to present a solution to electromagnetic scattering by bianisotropic dispersive materials. The presented solutions provide a reference baseline that can be used for comparison reasons by other researchers dealing with scattering by bianisotropic dispersive media. The solution algorithm based on the method of moments and mixed potential equations is tested through a few cases of dispersive scatterers and first known solutions to these problems are obtained. The proposed method has an advantage over the time domain methods as it does not rely on the Z-transform of the analytical expressions necessary to be used when dispersive media are present in the problem of interest.

Index Terms **─** Chiral, chiroferrite, dispersive, electromagnetic scattering, ferrite, and method of moments.

I. INTRODUCTION

Dispersive materials belong to the category of bianisotropic media, for which the following constitutive relations apply,

$$\begin{aligned} \overline{D} &= \overline{\overline{\varepsilon}} \cdot \overline{E} + \overline{\overline{\xi}} \cdot \overline{H} \\ \overline{B} &= \overline{\overline{\varsigma}} \cdot \overline{E} + \overline{\overline{\mu}} \cdot \overline{H}, \end{aligned} \tag{1}$$

where $\overline{\overline{\varepsilon}}$ is the permittivity tensor, $\overline{\overline{\mu}}$ is the permeability tensor, and $\overline{\overline{\xi}}$ and $\overline{\overline{\varsigma}}$ are the magnetoelectric tensors. In this paper, the overbar "–" denotes a vector and the double overbar "=" denotes a tensor.

Let us consider an inhomogeneous bianisotropic body of arbitrary three-dimensional shape characterized by the constitutive relations shown in equation (1). As shown in Fig. 1, if the body is illuminated by a time-harmonic electromagnetic wave with $e^{j\omega t}$ dependence, the fields in the body are described by Maxwell's equations as,

$$\begin{aligned} \nabla \cdot \overline{E} &= \frac{\rho_{eb}}{\varepsilon_0} \\ \nabla \cdot \overline{H} &= \frac{\rho_{mb}}{\mu_0}, \\ \nabla \times \overline{E} &= -j\omega\mu_0 \overline{H} - \overline{J}_{mp} , \\ \nabla \times \overline{H} &= j\omega\varepsilon_0 \overline{E} + \overline{J}_{ep} , \end{aligned} \tag{2}$$

where $\overline{J}_{ep}$ and $\overline{J}_{mp}$ are the electric and magnetic polarization currents, and ρ_{eb} and ρ_{mb} are electric bound charges and magnetic bound charges, respectively, that can be related to the electric and magnetic polarizations as given in [1].

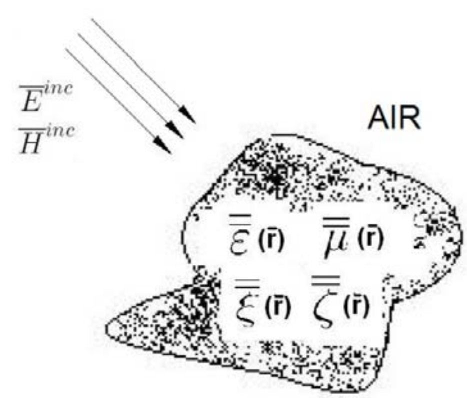

Fig. 1. Inhomogeneous bianisotropic body in free space illuminated by an electromagnetic wave.

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Separating the total fields into the incident field component $\left(\overline{E}^{inc}, \overline{H}^{inc}\right)$ produced by the primary sources and the scattered component $\left(\overline{E}^{s}, \overline{H}^{s}\right)$ produced as a result of scattering from the bianisotropic body, and then introducing the magnetic vector potential $\overline{A}$, the electric scalar potential V, the electric vector potential $\overline{F}$, and the magnetic scalar potential U, the total fields can be written as in [1],

$$\begin{aligned} \overline{E} &= \overline{E}^{inc} - j\omega\overline{A} - \nabla V - \frac{1}{\varepsilon_0}\nabla \times \overline{F} \\ \overline{H} &= \overline{H}^{inc} - j\omega\overline{F} - \nabla U + \frac{1}{\mu_0}\nabla \times \overline{A}. \end{aligned} \tag{3}$$

The surface integrals can be calculated as follows,

$$\overline{A} = \mu_0 \int_V \overline{J}_{ep}(\overline{r}')G(\overline{r},\overline{r}')dv' \tag{4}$$

$$\begin{aligned} V &= \frac{1}{\varepsilon_0}\int_V \rho_{eb}(\overline{r}')G(\overline{r},\overline{r}')dv', \\ &+\frac{1}{\varepsilon_0}\int_V \sigma_{eb}(\overline{r}')G(\overline{r},\overline{r}')ds', \end{aligned} \tag{5}$$

$$\overline{F} = \varepsilon_0 \int_V \overline{J}_{mp}(\overline{r}')G(\overline{r},\overline{r}')dv', \tag{6}$$

$$\begin{aligned} U &= \frac{1}{\mu_0}\int_V \rho_{mb}(\overline{r}')G(\overline{r},\overline{r}')dv', \\ &+\frac{1}{\mu_0}\int_V \sigma_{mb}(\overline{r}')G(\overline{r},\overline{r}')ds'. \end{aligned} \tag{7}$$

If the unknown quantities $\overline{E}$ and $\overline{H}$ in the constructed integral equations are expressed in terms of $\overline{D}$ and $\overline{B}$, and then RWG basis functions [2, 3] and Galerkin's method are used. Equations (3) and (4) can be transformed into the system of linear equations,

$$\begin{bmatrix} (C_{mn}) & (Y_{mn}) \\ (Z_{mn}) & (A_{mn}) \end{bmatrix} \cdot \begin{bmatrix} (D_n) \\ (B_n) \end{bmatrix} = \begin{bmatrix} (E_m) \\ (H_m) \end{bmatrix}, \tag{8}$$

where Z_{mn}, A_{mn}, C_{mn}, and Y_{mn} are N by N matrices and D_n, B_n, E_n, and H_n are N dimensional vectors. The detailed analytical expressions for matrix elements Z_{mn}, A_{mn}, C_{mn}, and Y_{mn} are given in [1].

II. DISPERSIVE PROPERTIES OF FERRITE AND CHIRAL MEDIA

Although obtaining the analytical expressions of the material dispersion is not required by this method, the dispersion properties of the ferrites and chiral media are still given, in case researchers need to solve the problems in a time domain method for comparison in the future [4]. When the expressions modeled from the real world are evaluated, the constitutive parameters assigned to the material have some physical meaning.

When biased by a DC magnetic field $\overline{B}_0 = \hat{z}B_0$, ferrite materials, whose permittivity tensor $\overline{\overline{\varepsilon}} = \varepsilon_0\overline{\overline{I}}$, are characterized by their permeability tensors $\overline{\overline{\mu}} = \mu_0\overline{\overline{\mu}}_r$ where,

$$\overline{\overline{\mu}}_r = \begin{bmatrix} \mu_1 & j\mu_2 & 0 \\ -j\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_3 \end{bmatrix}. \tag{9}$$

The elements in the permeability tensor are formulated as in [5],

$$\begin{aligned} \mu_1 &= 1 + \frac{(\omega_0 + j\omega\alpha)\omega_m}{(\omega_0 + j\omega\alpha)^2 - \omega^2} \\ \mu_2 &= \frac{\omega\,\omega_m}{(\omega_0 + j\omega\alpha)^2 - \omega^2} \\ \mu_3 &= 1, \end{aligned} \tag{10}$$

where α is the ferrite damping factor, ω_0 is the Larmor precession frequency and ω_m is the saturation magnetization frequency.

The Larmor precession frequency ω_0 and the saturation magnetization frequency ω_m are determined by the DC magnetic field bias by,

$$\begin{aligned} \omega_0 &= \gamma_m H_0 \\ \omega_m &= \gamma_m M_0, \end{aligned} \tag{11}$$

where γ_m is the gyromagnetic ratio, H_0 is the magnitude of the applied DC magnetic field, and M_0 is the magnitude of saturated magnetization vector. $\overline{M}_0$ is in the same direction as the applied magnetic field $\overline{H}_0$.

Once the Larmor precession frequency, saturation magnetization frequency, and ferrite damping factor are given, the permeability tensor

$\overline{\overline{\mu}}$ can be evaluated at any frequency. For example, if we consider a ferrite material with the parameters of $\alpha = 0.1, \omega_0 = 2\pi \times 2 \times 10^9$, and $\omega_m = 2\pi \times 2 \times 10^9$, we have, at 0.4 GHz,

$$\overline{\overline{\mu}}_r = \begin{bmatrix} 2.0412 - 0.0226j & 0.0087 + 0.2081j & 0 \\ -0.0087 - 0.2081j & 2.0412 - 0.0226j & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

at 0.6 GHz,

$$\overline{\overline{\mu}}_r = \begin{bmatrix} 2.0974 - 0.0394j & 0.0217 + 0.3286j & 0 \\ -0.0217 - 0.3286j & 2.0974 - 0.0394j & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

at 1 GHz,

$$\overline{\overline{\mu}}_r = \begin{bmatrix} 2.3231 - 0.1101j & 0.0879 + 0.6571j & 0 \\ -0.0879 - 0.6571j & 2.3231 - 0.1101j & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

and at 1.2 GHz,

$$\overline{\overline{\mu}}_r = \begin{bmatrix} 2.5346 - 0.1951j & 0.1717 + 0.9104j & 0 \\ -0.1717 - 0.9104j & 2.5346 - 0.1951j & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

The constitutive equations for dispersive chiral media can be written as,

$$\begin{aligned} \overline{D}(\omega) &= \varepsilon(\omega)\overline{E}(\omega) - j\kappa(\omega)\sqrt{\varepsilon_0\mu_0}\,\overline{H}(\omega) \\ \overline{B}(\omega) &= \mu(\omega)\overline{H}(\omega) + j\kappa(\omega)\sqrt{\varepsilon_0\mu_0}\,\overline{E}(\omega). \end{aligned} \tag{12}$$

In most of the cases, the Lorentz model is used to characterize the dispersive nature of permittivity and permeability. The Condon model is generally used to describe the dispersive nature of chirality [6]. The Lorentz model is in the form,

$$\begin{aligned} \varepsilon(\omega) &= \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)\omega_\varepsilon^{\,2}}{\omega_\varepsilon^{\,2} - \omega^2 + j2\omega_\varepsilon\xi_\varepsilon\omega} \\ \mu(\omega) &= \mu_\infty + \frac{(\mu_s - \mu_\infty)\omega_\mu^{\,2}}{\omega_\mu^{\,2} - \omega^2 + j2\omega_\mu\xi_\mu\omega}. \end{aligned} \tag{13}$$

The Condon model is in the form,

$$\kappa(\omega) = \frac{\tau_\kappa\omega_\kappa^{\,2}\,\omega}{\omega_\kappa^{\,2} - \omega^2 + j2\omega_\kappa\xi_\kappa\omega}. \tag{14}$$

If a chiral material with the following parameters is considered,

$$\begin{aligned} &\varepsilon_\infty = 2\varepsilon_0;\ \varepsilon_s = 5\varepsilon_0 \\ &\omega_\varepsilon = 2\pi \times 2 \times 10^9;\ \xi_\varepsilon = 0.5 \\ &\mu_\infty = 1.1\mu_0;\ \mu_s = 1.8\mu_0 \\ &\omega_\mu = 2\pi \times 2 \times 10^9;\ \xi_\mu = 0.5 \\ &\tau_\kappa = \frac{0.5}{\omega_\kappa};\ \omega_\kappa = 2\pi \times 2 \times 10^9;\ \xi_\kappa = 0.3, \end{aligned} \tag{15}$$

the constitutive parameters can be evaluated at different frequencies. We have, at 0.4 GHz,

$\varepsilon_r = 4.9950 - 0.6240j$; $\mu_r = 1.7988 - 0.1456j$; $\kappa = 0.1026 - 0.0128j$,

at 0.6 GHz,

$\varepsilon_r = 4.9735 - 0.9803j$; $\mu_r = 1.7938 - 0.2287j$; $\kappa = 0.1586 - 0.0314j$,

at 1 GHz,

$\varepsilon_r = 4.7692 - 1.8462j$; $\mu_r = 1.7462 - 0.4308j$; $\kappa = 0.2874 - 0.1149j$,

and at 1.2 GHz,

$\varepsilon_r = 4.4948 - 2.3389j$; $\mu_r = 1.6821 - 0.5457j$; $\kappa = 0.3561 - 0.2003j$.

In following sections, we will investigate the scattering fields that involve the mixtures of the ferrite and the chiral materials using the above evaluated constitutive parameters.

III. DISPERSIVE HOMOGENIZED CHIROFERITE SPHERE

When equal volume of a ferrite material and a chiral material are mixed homogeneously, although currently there is no analytic model for the constitutive parameters of such a mixture, as an engineering approximation, one may assume that the material can be described on a macroscopic scale by the constitutive parameters,

$$\overline{\overline{\varepsilon}} = \frac{1}{2}\left(\overline{\overline{\varepsilon}}_{ferrite} + \overline{\overline{\varepsilon}}_{chiral}\right), \overline{\overline{\mu}} = \frac{1}{2}\left(\overline{\overline{\mu}}_{ferrite} + \overline{\overline{\mu}}_{chiral}\right),$$

$$\overline{\overline{\xi}} = \frac{1}{2}\left(\overline{\overline{\xi}}_{ferrite} + \overline{\overline{\xi}}_{chiral}\right), \overline{\overline{\varsigma}} = \frac{1}{2}\left(\overline{\overline{\varsigma}}_{ferrite} + \overline{\overline{\varsigma}}_{chiral}\right),$$

where $\overline{\overline{\varepsilon}}_{chiral}$, $\overline{\overline{\mu}}_{chiral}$, $\overline{\overline{\xi}}_{chiral}$, and $\overline{\overline{\varsigma}}_{chiral}$ are the constitutive tensors for the chiral material, and

$\bar{\bar{\varepsilon}}_{ferrite}$, $\bar{\bar{\mu}}_{ferrite}$, $\bar{\bar{\xi}}_{ferrite}$, and $\bar{\bar{\varsigma}}_{ferrite}$ are the constitutive tensors for ferrite material. Again, it is important to stress that the approximation proposed above does not have any physical or practical meaning but it is merely introduced here to test the validity of the proposed solution in the absence of a real-world material of chiroferrite nature.

For the chiral material, we have $\bar{\bar{\varepsilon}}_{chiral} = \varepsilon_0 \varepsilon_{r,chiral} \bar{\bar{I}}$, $\bar{\bar{\mu}}_{chiral} = \mu_0 \mu_{r,chiral} \bar{\bar{I}}$, $\bar{\bar{\xi}}_{chiral} = -j\kappa\sqrt{\varepsilon_0\mu_0}\,\bar{\bar{I}}$, and $\bar{\bar{\varsigma}}_{chiral} = j\kappa\sqrt{\varepsilon_0\mu_0}\,\bar{\bar{I}}$ where $\varepsilon_{r,chiral}$ is the relative permittivity of the chiral material, $\mu_{r,chiral}$ is the relative permeability of the chiral medium, and κ is the chirality parameter of the chiral material.

For the ferrite material, we have $\bar{\bar{\varepsilon}}_{ferrite} = \varepsilon_0 \bar{\bar{I}}$, $\bar{\bar{\mu}}_{ferrite} = \mu_0 \bar{\bar{\mu}}_{r,ferrite}$, and $\bar{\bar{\xi}}_{ferrite} = \bar{\bar{\varsigma}}_{ferrite} = 0$, where $\bar{\bar{\mu}}_{r,ferrite}$ is the relative permeability tensor of the ferrite material. Mixing homogeneously the chiral material and ferrite material mentioned in section II, the corresponding macroscopic constitutive parameters of the chiroferrite material can be evaluated at any frequency.

This section presents the results of scattering from such a dispersive homogenized chiroferrite sphere shown in Fig. 2. The sphere is of radius R = 7.2 *cm* and is illuminated by a plane electromagnetic wave propagating in the z direction, which has the electric field component in the x direction, i.e., $\bar{E}^{inc} = \hat{x}E^{inc}e^{-jk_0z}$ and $\bar{H}^{inc} = \hat{y}H^{inc}e^{-jk_0z}$ where $\bar{E}^{inc} = 1$ [V/m].

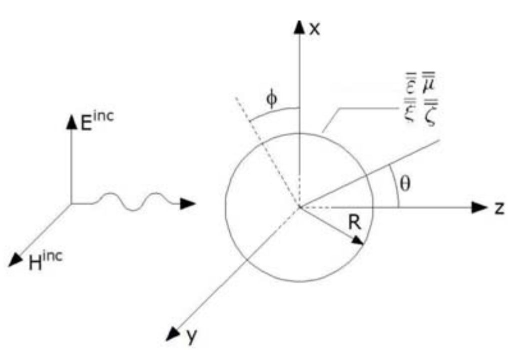

Fig. 2. A homogenized chiroferrite sphere illuminated by an EM plane wave.

A sphere of radius R is constructed and meshed by 520 tetrahedra and 1184 faces. As the first step of developing this mesh, the entire outer surface of sphere has been approximated by a grid of 72 triangles. Then a tetrahedral mesh has been grown from the outer triangulated surface into the sphere, producing a total of 256 tetrahedra and 548 faces. In order to achieve better accuracy of numerical results, refinement of the mesh in the close proximity of the outer surface has been undertaken, increasing the total number of tetrahedra to 520 and faces to 1184. At last, the radius of the sphere has been adjusted so that the total volume of the tetrahedral approximation of the sphere is equal to the actual volume of the initial sphere.

The numerical results are obtained at the frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz. The corresponding values of k_0R are 0.6032, 0.9048, 1.508, and 1.809, respectively. Figures 3 and 4 show the co-polarized and cross-polarized bistatic radar cross sections $\sigma_{\theta\theta}$ of $\phi = 0^o$ and $\sigma_{\phi\theta}$ of $\phi = 0^o$. It is noticed that the RCS of such a homogenized chiroferrite scatterer is similar to that of the two-layered chiroferrite sphere presented in [1] because they are composed of the same basic materials and dimensions.

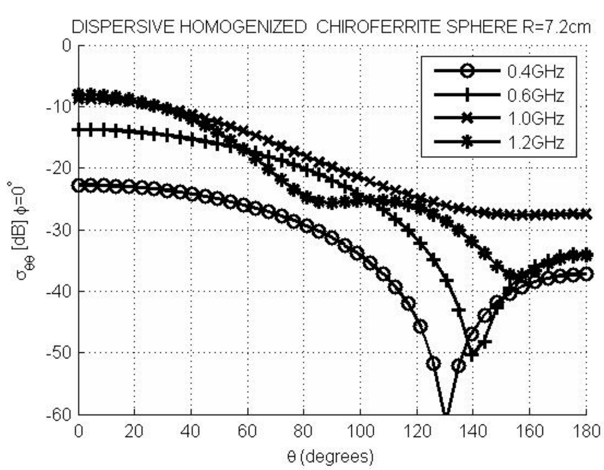

Fig. 3. Bistatic radar cross section $\sigma_{\theta\theta}$ of a homogenized chiroferrite sphere of radius R = 7.2 *cm* illuminated by an EM plane wave at frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz.

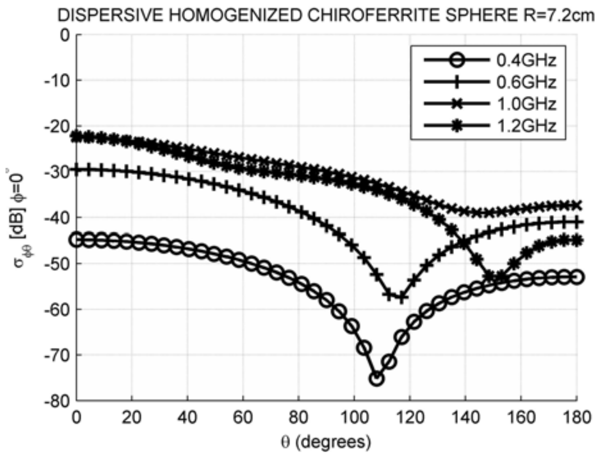

Fig. 4. Bistatic radar cross section $\sigma_{\phi\theta}$ of a homogenized chiroferrite sphere of radius R = 7.2 *cm* illuminated by an EM plane wave at frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz.

IV. DISPERSIVE HOMOGENIZED CHIROFERITE CUBE

In this section we present results for electromagnetic scattering from a dispersive homogenized chiroferrite cube illuminated by a plane electromagnetic wave. The macroscopic constitutive parameters of the chiroferrite material are obtained in section III. The length of a side of the cube is d = 14 *cm*. The dimension for the cube makes its size similar to that of the sphere investigated in section III. The incident plane electromagnetic wave propagates in the z direction, and it has the electric field component in the x direction, i.e., $\overline{E}^{inc} = \hat{x}E^{inc}e^{-jk_0z}$ and $\overline{H}^{inc} = \hat{y}H^{inc}e^{-jk_0z}$ where $\overline{E}^{inc} = 1$ [V/m], as shown in Fig. 5.

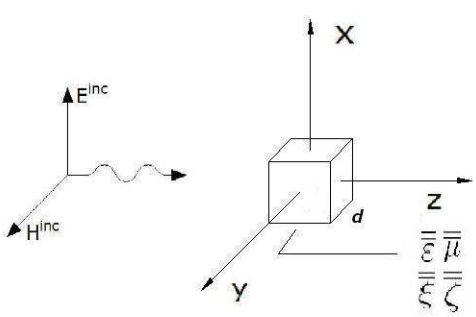

Fig. 5. A homogenized chiroferrite cube illuminated by an EM plane wave.

A meshing process similar to that in section III is realized, resulting in a total of 768 tetrahedra and 1632 faces. The numerical results are obtained at the frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz. The corresponding values of k_0d are 1.1729, 1.7593, 2.9322, and 3.5186, respectively. Figures 6 and 7 show the co- and cross-polarized bistatic radar cross sections $\sigma_{\theta\theta}$ of $\phi = 0^{o}$ and $\sigma_{\phi\theta}$ of $\phi = 0^{o}$. It is noticed that the RCS of such a cubic scatterer is at similar level of the ones of the homogenized chiroferrite sphere in section III because both cases are made of same materials and in have similar dimensions. We also note that the angular responses (dependence on θ) are different between the spherical and cubic scatterers. In particular, at f = 1.2 GHz, the difference is more pronounced.

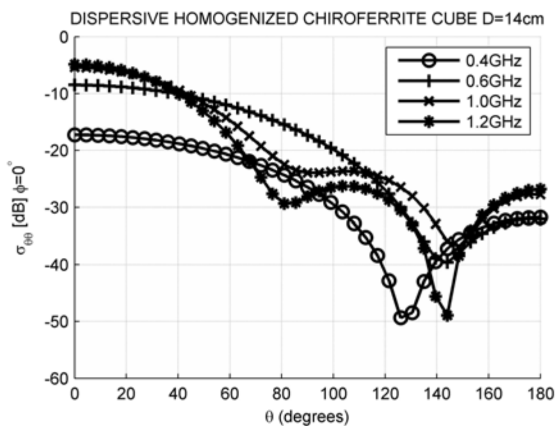

Fig. 6. Bistatic radar cross section $\sigma_{\theta\theta}$ of a homogenized chiroferrite cube of d = 14 *cm* illuminated by an EM plane wave at frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz.

V. DISPERSIVE HOMOGENIZED CHIROFERITE CYLINDER

In this section we present results for electromagnetic scattering from a finite circular cylinder of dispersive homogenized chiroferrite illuminated by an EM plane wave. The macroscopic constitutive parameters of the chiroferrite material are obtained in section III. The radius of the cylinder is R = 7 *cm* and the height of the cylinder is h = 14 *cm*. These dimensions for the cylinder make its size similar to that of the sphere investigated in section III. The incident plane wave propagates in the z direction, and it has the electric field component in the x direction, i.e., $\overline{E}^{inc} = \hat{x}E^{inc}e^{-jk_0z}$ and

$\overline{H}^{inc} = \hat{y}H^{inc}e^{-jk_0z}$ where $\overline{E}^{inc} = 1$ [V/m], as shown in Fig. 8.

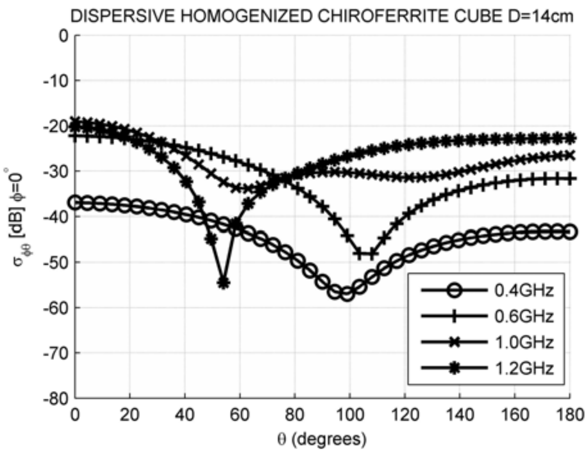

Fig. 7. Bistatic radar cross section $\sigma_{\phi\theta}$ of a homogenized chiroferrite cube of *d* = 14 *cm* illuminated by an EM plane wave at frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz.

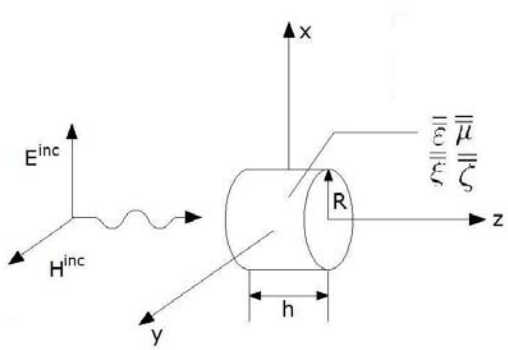

Fig. 8. A homogenized chiroferrite cylinder illuminated by an EM plane wave.

A meshing process similar to that in section III is realized, resulting in a total of 864 tetrahedra and 1920 faces. The numerical results are obtained at the frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz. The corresponding values of k_0h are 1.1729, 1.7593, 2.9322, and 3.5186, respectively. Figures 9 and 10 show the co- and cross-polarized bistatic radar cross sections $\sigma_{\theta\theta}$ of $\phi = 0^o$ and $\sigma_{\phi\theta}$ of $\phi = 0^o$. It is noticed that the RCS of such a scatterer is at similar level of the RCS of the homogenized chiroferrite sphere or cube in sections III and IV because they are made of the same materials and in have similar dimensions.

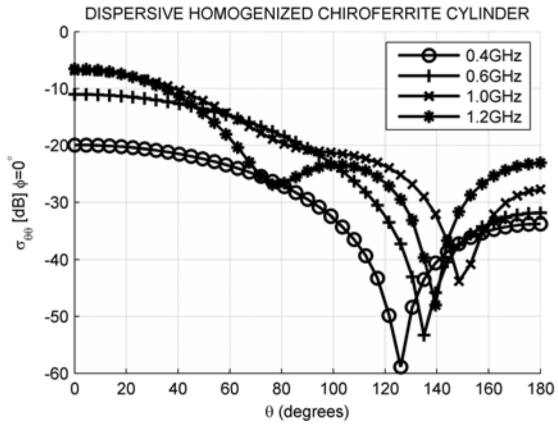

Fig. 9. Bistatic radar cross section $\sigma_{\theta\theta}$ of a homogenized chiroferrite cylinder of radius *R* = 7*cm* and height *h* = 14 *cm* illuminated by an EM plane wave at frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz.

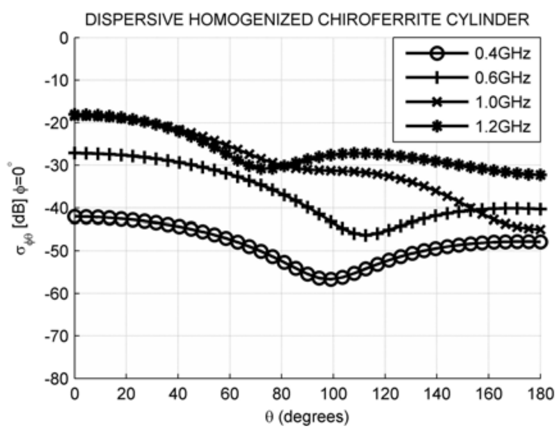

Fig. 10. Bistatic radar cross section $\sigma_{\phi\theta}$ of a homogenized chiroferrite cylinder of radius *R* = 7 *cm* and height *h* = 14 *cm* illuminated by an EM plane wave at frequencies of 0.4 GHz, 0.6 GHz, 1 GHz, and 1.2 GHz.

VI. CONCLUSION

Taking advantage of the flexibility of the method presented in [1], scattering problems that involve dispersive bianisotropic materials are solved and presented in this paper. As an example, the method is applied to investigate the scattering fields from a dispersive chiroferrite material in which chiral materials and ferrite materials are mixed. Currently, these problems are difficult to solve by conventional methods. The solutions to a few of these problems are presented in [7]. This paper represents a more comprehensive report on the same work. The combination of chirality and anisotropic property makes these problems difficult to solve by other current frequency domain methods that may handle either chirality or the anisotropic property one at a time but not both at the same time. The ferrite material and chiral material are assumed dispersive, i.e., the constitutive relations have frequency dependency.

As discussed earlier, this method has the advantage over the time domain methods. The time domain methods rely on the Z-transform of the analytical expressions that describe the dispersion properties of the material. And these analytical expressions are in many cases very difficult to obtain. When there is more than one kind of dispersive material involved, the situation becomes even more complicated for these methods. If the material is of a periodic nature, homogenization techniques may be used to simplify the problem [8]. Corresponding computer programs need to be adapted for the different dispersion properties of the materials. The solution algorithm used in this paper is based on the method of moments. In the method of moments, problems are solved in the frequency domain, and as long as the numerical values of the material properties at the operating frequency are provided, there is no need to obtain the analytic expressions of the material dispersion over a frequency band.

The main goal of this article is not to provide a comprehensive analytical solution to the problems of interest as the analytical algorithm is described and derived in detail by the same authors in [1]. Scattering by dispersive media with mixed chiral and anisotropic properties has not been extensively studied in the past. To our best knowledge, there was no research reported that would provide solution to this type of scattering problems and that can be used as a reference to check validity of proposed algorithms. This article intends to fill that gap. With this article, the authors offered a solution to a few scenarios of scattering by mixed chiral and anisotropic media that can be used by other researchers as a baseline to confirm validity of their solutions to the problems of similar nature.

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Moamer Hasanovic received the B.Sc. degree from the University of Sarajevo in 1997 and the M.Sc. and Ph.D. degrees in Electrical Engineering from Syracuse University, New York (USA) in 2002 and 2006, respectively. He was an Electrical Engineer with BH Telecom Engineering Sarajevo for two years and RF Design Engineer with Anaren Microwave, Syracuse, NY. He is currently working as a Senior RF Design Engineer with EMC Technology/Florida RF Labs in Stuart, FL. He is also an Adjunct Professor at the L.C. Smith College of Engineering and Computer Science at

Syracuse University as well as an Assistant Professor at University of Sarajevo, Bosnia-Herzegovina. His research interests are in the area of computational electromagnetics, and RF/microwave devices on conventional and metamaterial platforms. Dr. Hasanovic is a member of the Applied Computational Electromagnetics Society and IEEE Antennas and Propagation Society.

Chong Mei received B.Sc. and M.Sc. degrees from Huazhong University of Science and Technology, Wuhan, China, in 1997 and 2000, respectively, and Ph.D. degree from Syracuse University, Syracuse, NY, in 2007, all in Electrical Engineering. He has been with Anaren Microwave, Inc. in East Syracuse, NY since 2002, as a Leading Engineer designing various RF/Microwave devices for the wireless infrastructure market. His research interests are in RF/microwave devices and computational electromagnetics.

Jay K. Lee received the B.Sc. degree from Seoul National University, Seoul, Korea in 1976 and the S.M. and Ph.D. degrees in Electrical Engineering from Massachusetts Institute of Technology, Cambridge, MA in 1981 and 1985, respectively. He is a Professor of Electrical Engineering and Computer Science at Syracuse University, where he served as Program Director of Electrical Engineering (2004-09). His current research interests are electromagnetic theory, waves in anisotropic media, microwave remote sensing, and antennas and propagation. He was a Research Fellow at Naval Air Development Center, Rome Air Development Center and Naval Research Laboratory and was an Invited Visiting Professor at Seoul National University in Seoul, Korea. He is a Senior Member of the IEEE. He served as Chair of IEEE Syracuse Section and as Faculty Advisor of IEEE Student Branch at Syracuse University. He has received the Eta Kappa Nu Outstanding Undergraduate Teacher Award (1999), the IEEE Third Millennium Medal (2000), and the College Educator of the Year Award from the Technology Alliance of Central New York (2002). He is the co-author of the book, {\it Electromagnetics} (by Adams and Lee, University Readers, 2012).

Ercument Arvas received the B.Sc. and M.Sc. degrees from the Middle East Technical University, Ankara, Turkey, in 1976 and 1979, respectively, and the Ph.D. degree from Syracuse University, Syracuse, NY, in 1983, all in Electrical Engineering. From 1984 to 1987, he was with the Electrical Engineering Department, Rochester Institute of Technology, Rochester, NY. In 1987, he joined the Electrical Engineering and Computer Science Department, Syracuse University, where he is currently a Professor. His research and teaching interests are in computational electromagnetic radiation and scattering, and microwave devices. He is a Member of the Applied Computational Electromagnetics Society (ACES) and a Fellow of IEEE.