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Analysis of different terminated inhomogeneous planar layered chiral media

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In this paper, an analytic frequency domain method based on Taylor's series expansion is investigated to analyze different terminated homogeneous and inhomogeneous planar layered chiral media. The validity of the presented method is verified considering some special types of chiral media, and then the application of inhomogeneous planar layered chiral media for reducing reflection from a PEC surface is concisely investigated.

1. Introduction

There has been increasing interest in studying interaction of electromagnetic fields with chiral media over the years. In addition to pioneering studies, recently, there is rapid development on the study of electromagnetic wave propagation in chiral media [1–6]. More recently, chiral metamaterials with many applications have attracted increasing attention [7–16]. The time-harmonic constitutive relations of an isotropic and homogeneous chiral medium assuming $e^{j\omega t}$ as time dependence are given by [7]:

$$\mathbf{D} = \varepsilon_r \varepsilon_0 \mathbf{E} - j\kappa\sqrt{\varepsilon_0\mu_0}\mathbf{H}, \quad \mathbf{B} = j\kappa\sqrt{\varepsilon_0\mu_0}\mathbf{E} + \mu_r\mu_0\,\mathbf{H} \tag{1}$$

where ε_r and μ_r are the relative permittivity and permeability of the chiral medium, respectively, and κ is the chirality parameter. Chiral media have two important properties: the first one is optical activity, which can rotate the polarization plane of a linearly polarized wave propagating through it, and the second property is circular dichroism. The wave equation in a homogeneous chiral medium is:

$$\nabla^2\mathbf{E} + 2\frac{\kappa\omega}{c_0}\nabla\times\mathbf{E} + \frac{\omega^2}{c_0^2}\left(\mu_r\varepsilon_r - \kappa^2\right)\mathbf{E} = 0 \tag{2}$$

where c_0 and ω are the speed of light in vacuum and the angular frequency, respectively. The right and left circularly polarized waves (RCP and LCP) are the eigenpolarization of the wave equation in a homogeneous chiral medium. The propagation wavevectors of k_+ and k_- can be introduced for the right and the LCP waves as follows [7]:

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$$k_{\pm} = \frac{\omega}{c_0}\left(\sqrt{\mu_r\varepsilon_r} \pm \kappa\right). \tag{3}$$

The study of wave propagation in inhomogeneous chiral media, which have some applications in the polarization correction of the lens and aperture antennas [17], is much more complicated than homogeneous chiral media. The wave propagation and scattering from planar layers of inhomogeneous media has been intensively investigated and several approaches have been presented [18–23]. In this study, a general method based on the Taylor's series expansion is used to frequency domain analysis of different terminated inhomogeneous planar layered chiral media.

2. Different terminated homogeneous chiral slab

In this section, the frequency domain analysis of wave propagation and scattering from different terminated homogeneous chiral media is investigated. Figure 1 shows a chiral slab which occupies $0 \leq z \leq d$. The plane $z = d$ is assumed to be perfect electric, perfect magnetic, or perfect electromagnetic conductor (PEMC). Perfect electric conductor (PEC) and perfect magnetic conductor (PMC) are basic concepts in electromagnetics. PEMC has been recently introduced as generalization of the PEC and PMC [24]. The PEMC boundary conditions are of the more general form:

$$\begin{cases} \hat{a}_z \times (\mathbf{H} + M\mathbf{E}) = 0 \\ \hat{a}_z \times (\mathbf{D} - M\mathbf{B}) = 0 \end{cases} \tag{4}$$

where M denotes the admittance of the PEMC boundary. It is obvious that PMC corresponds to $M = 0$, while PEC corresponds to $M = \infty$.

It is assumed that a plane wave with an arbitrary linear combination of TM ($E_i^{\|}$) and TE ($E_i^{\perp}$) polarizations:

$$\mathbf{E}_i = \left[E_i^{\|}(\cos\theta_0\hat{a}_x + \sin\theta_0\hat{a}_z) + E_i^{\perp}\hat{a}_y\right]e^{-jk_0(z\cos\theta_0 - x\sin\theta_0)} \tag{5}$$

is obliquely incident with incident angle of θ_0 from free space onto the homogeneous chiral slab. The reflected electric field may be written as:

$$\mathbf{E}_r = \left[E_r^{\|}(\cos\theta_r\hat{a}_x - \sin\theta_r\hat{a}_z) + E_r^{\perp}\hat{a}_y\right]e^{-jk_0(-z\cos\theta_0 - x\sin\theta_0)} \tag{6}$$

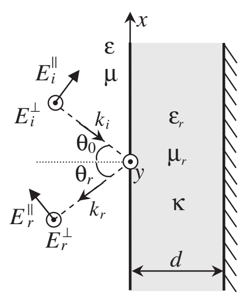

Figure 1. A typical homogeneous chiral slab exposed to an incident plane wave with an arbitrary linear combination of TM ($E_i^{\|}$) and TE ($E_i^{\perp}$) polarizations.

As stated before, the solution of source-free wave equation in an isotropic and homogeneous chiral media is represented by sum of LCP and RCP plane waves with different phase velocities. Therefore, in the chiral slab there are four waves, two propagating toward the right interface and the other two propagating toward the left interface:

$$\mathbf{E}_{\mathrm{c}} = \mathbf{E}_{\mathrm{c}}^{\text{right-going}} + \mathbf{E}_{\mathrm{c}}^{\text{left-going}} \tag{7}$$

in which:

$$\begin{aligned}\mathbf{E}_{\mathrm{c}}^{\text{right-going}} &= E_1^{\text{r-g}}\left(\cos\theta_+ \hat{a}_x + \sin\theta_+ \hat{a}_z - j\hat{a}_y\right)e^{-jk_+(z\cos\theta_+ - x\sin\theta_+)} \\ &\quad + E_2^{\text{r-g}}\left(\cos\theta_- \hat{a}_x + \sin\theta_- \hat{a}_z + j\hat{a}_y\right)e^{-jk_-(z\cos\theta_- - x\sin\theta_-)}\end{aligned} \tag{8}$$

$$\begin{aligned}\mathbf{E}_{\mathrm{c}}^{\text{left-going}} &= E_1^{\text{l-g}}\left(-\cos\theta_+ \hat{a}_x + \sin\theta_+ \hat{a}_z - j\hat{a}_y\right)e^{-jk_+(-z\cos\theta_+ - x\sin\theta_+)} \\ &\quad + E_2^{\text{l-g}}\left(-\cos\theta_- \hat{a}_x + \sin\theta_- \hat{a}_z + j\hat{a}_y\right)e^{-jk_-(-z\cos\theta_- - x\sin\theta_-)}\end{aligned} \tag{9}$$

One can write similar relations for magnetic field. To find the complex-constant amplitude vectors of the reflected and internal waves, the boundary conditions at interfaces should be applied to transverse components of electric and magnetic fields:

$$\begin{cases} [\mathbf{E}_i + \mathbf{E}_{\mathrm{r}} - \mathbf{E}_{\mathrm{c}}]_{\tan} = 0 \\ [\mathbf{H}_i + \mathbf{H}_{\mathrm{r}} - \mathbf{H}_{\mathrm{c}}]_{\tan} = 0 \end{cases} \tag{10}$$

at $z = 0$, and

$$\begin{cases} \hat{a}_x \times [\mathbf{H}_{\mathrm{c}} + M\mathbf{E}_{\mathrm{c}}] = 0 \\ \hat{a}_y \times [\mathbf{H}_{\mathrm{c}} + M\mathbf{E}_{\mathrm{c}}] = 0 \end{cases} \tag{11}$$

at $z = d$, where subscript tan indicates the tangential components of fields. Consequently, a system of six nonhomogeneous equations is obtained, which can be written in the following form:

$$\begin{pmatrix} E_{\mathrm{r}}^{\parallel} \\ E_{\mathrm{r}}^{\perp} \\ E_1^{r-g} \\ E_2^{r-g} \\ E_1^{l-g} \\ E_2^{l-g} \end{pmatrix} = \begin{pmatrix} -1 & 0 & p_+ & p_- & -p_+ & -p_- \\ 0 & 1 & -jgp_+ & jgp_- & jgp_+ & -jgp_- \\ 0 & -1 & -j & j & -j & j \\ 1 & 0 & g & g & g & g \\ 0 & 0 & (jY_{\mathrm{c}}+M)p_+e^{-jq_+} & (-jY_{\mathrm{c}}+M)p_-e^{-jq_-} & (-jY_{\mathrm{c}}-M)p_+e^{jq_+} & (jY_{\mathrm{c}}-M)p_-e^{jq_-} \\ 0 & 0 & (Y_{\mathrm{c}}-jM)e^{-jq_+} & (Y_{\mathrm{c}}+jM)e^{-jq_-} & (Y_{\mathrm{c}}-jM)e^{jq_+} & (Y_{\mathrm{c}}+jM)e^{jq_-} \end{pmatrix}^{-1} \times \begin{pmatrix} E_i^{\parallel} \\ E_i^{\perp} \\ E_i^{\perp} \\ E_i^{\parallel} \\ 0 \\ 0 \end{pmatrix} \tag{12}$$

where $p_{\pm} = \cos\theta_{\pm}/\cos\theta_0$, $q_{\pm} = k_{\pm}\, d\cos\theta_{\pm}$, $g = \sqrt{\varepsilon_r/\mu_r}$, $Y_c = g\eta_0^{-1}$, and $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ is the wave impedance in the free space. Furthermore, the co- and cross-reflection coefficients of the planar layered chiral layer at $z = 0$ can be expressed as the following:

$$\begin{bmatrix} E_r^{\perp} \\ E_r^{\parallel} \end{bmatrix} = \begin{bmatrix} R_{\text{TE-TE}} & R_{\text{TE-TM}} \\ R_{\text{TM-TE}} & R_{\text{TM-TM}} \end{bmatrix} \begin{bmatrix} E_i^{\perp} \\ E_i^{\parallel} \end{bmatrix} \tag{13}$$

Considering Snell's law $k_0\cos\theta_0 = k_0\cos\theta_r = k_{\pm}\cos\theta_{\pm}$, the analytical solution of Equation (12) leads to complicated expressions for unknown coefficients. Therefore, it is best to use numerical techniques to calculate inverse matrix. However, it is possible to obtain the analytic solutions of these equations when the slab is PEC backed and $\theta_0 = 0^{\circ}$. For instance, the coreflection coefficients are given by:

$$R_{\text{TE}} = R_{\text{TM}} = \frac{1 - jg^{-1}\tan\left(\frac{k_+ + k_-}{2} d\right)}{1 + jg^{-1}\tan\left(\frac{k_+ + k_-}{2} d\right)}. \tag{14}$$

3. Different terminated inhomogeneous planar layered chiral media

As stated before, the study of wave propagation in inhomogeneous chiral media is much more complicated than homogeneous one. In order to obtain the solution for the reflection coefficients of a PEC-, PMC-, or PEMC-backed inhomogeneous planar layered chiral media the problem illustrated in Figure 1 is reconsidered. In this case, the chiral layer has inhomogeneous parameters $\varepsilon(z,\omega) = \varepsilon_0\varepsilon_r(z,\omega)$, $\mu(z,\omega) = \mu_0\mu_r(z,\omega)$, and $\kappa(z,\omega)$ which are assumed to be z and frequency dependent. Substituting the constitutive equations, Equation (1), into curl Maxwell's equations, considering $\partial/\partial y = 0$ and $\partial/\partial x = +jk_0\sin\theta_0$, and by eliminating E_z and H_z from equations, the differential equations describing inhomogeneous chiral layer can be written in the following matrix form:

$$\frac{d}{dz}\begin{pmatrix} \mathbf{E}_T \\ \mathbf{H}_T \end{pmatrix} = \overline{\overline{\Gamma}}\begin{pmatrix} \mathbf{E}_T \\ \mathbf{H}_T \end{pmatrix} \tag{15}$$

where $\mathbf{E}_T = (E_x, E_y)$ and $\mathbf{H}_T = (H_x, H_y)$ are the transverse components of electric and magnetic fields, respectively, and the elements of matrix of $\overline{\overline{\Gamma}}$ are given by:

$$\overline{\overline{\Gamma}} = \begin{pmatrix} 0 & \frac{\omega}{c_0}\kappa(z)\left(1 - \frac{\sin^2(\theta_0)}{\kappa(z)^2 - \varepsilon_r(z)\mu_r(z)}\right) & 0 & -j\omega\mu_0\mu_r(z)\left(1 + \frac{\sin^2(\theta_0)}{\kappa(z)^2 - \varepsilon_r(z)\mu_r(z)}\right) \\ -\frac{\omega}{c_0}\kappa(z) & 0 & j\omega\mu_0\mu_r(z) & 0 \\ 0 & j\omega\varepsilon_0\varepsilon_r(z)\left(1 + \frac{\sin^2(\theta_0)}{\kappa(z)^2 - \varepsilon_r(z)\mu_r(z)}\right) & 0 & \frac{\omega}{c_0}\kappa(z)\left(1 - \frac{\sin^2(\theta_0)}{\kappa(z)^2 - \varepsilon_r(z)\mu_r(z)}\right) \\ -j\omega\varepsilon_0\varepsilon_r(z) & 0 & -\frac{\omega}{c_0}\kappa(z) & 0 \end{pmatrix} \tag{16}$$

Furthermore, there are four boundary conditions enforcing continuity of tangential electric and magnetic fields. At $z = 0$, by eliminating $E_r^{\parallel}$ and $E_r^{\perp}$ from the boundary conditions equations, one can write:

$$E_x(0) + \eta_0 \cos(\theta_0) H_y(0) = 2E_i^{\parallel} \cos(\theta_0) \tag{17}$$

$$E_y(0) - \frac{\eta_0}{\cos(\theta_0)} H_x(0) = 2E_i^{\perp} \tag{18}$$

Assuming PEMC interface at $z = d$, the boundary conditions are given by:

$$\begin{cases} [H_x(d) + ME_x(d)] = 0 \\ [H_y(d) + ME_y(d)] = 0 \end{cases} \tag{19}$$

Assuming that material parameters of inhomogeneous chiral layer could be expanded using Taylor's series approach, one can write:

$$w(z) = \sum_{n=0}^{\infty} W_n \left(\frac{z}{d}\right)^n \tag{20}$$

where $w(z)$ can be either $j\omega\varepsilon_0\varepsilon_r(z)$, $j\omega\mu_0\mu_r(z)$, $(\omega/c_0)\kappa(z)$, or $1/(\kappa^2(z) - \varepsilon_r(z)\mu_r(z))$ with the known Taylor's series coefficients W_n which can be either Y_n, Z_n, K_n, or A_n, respectively. Similarly, x- and y-components of electric and magnetic fields can be expressed using Taylor's series expansions with unknown coefficients Ex_n, Ey_n, Hx_n, and Hy_n, respectively. In order to determine the unknown coefficients of Taylor's series expansions of electric and magnetic fields, all of the expansions should be substituted in (16), which gives:

$$Ex_{n+1} = \frac{d}{n+1}\left[\sum_{p=0}^{n} C_{n-p}Ey_p - \sin^2(\theta_0)\sum_{p=0}^{n}\sum_{q=0}^{n-p} C_{n-p-q}A_qEy_p - \sum_{p=0}^{n} Z_{n-p}Hy_p - \sin^2(\theta_0)\sum_{p=0}^{n}\sum_{q=0}^{n-p} Z_{n-p-q}A_qHy_p\right] \tag{21}$$

$$Ey_{n+1} = \frac{d}{n+1}\left[-\sum_{p=0}^{n} C_{n-p}Ex_p + \sum_{p=0}^{n} Z_{n-p}Hx_p\right] \tag{22}$$

$$\begin{aligned} Hx_{n+1} = \frac{d}{n+1}\Bigg[&\sum_{p=0}^{n} Y_{n-p}Ey_p + \sin^2(\theta_0)\sum_{p=0}^{n}\sum_{q=0}^{n-p} Y_{n-p-q}A_qEy_p + \sum_{p=0}^{n} C_{n-p}Hy_p - \sin^2(\theta_0) \\ &\sum_{p=0}^{n}\sum_{q=0}^{n-p} C_{n-p-q}A_qHy_p\Bigg] \end{aligned} \tag{23}$$

$$Hy_{n+1} = \frac{d}{n+1}\left[-\sum_{p=0}^{n} Y_{n-p}Ex_p - \sum_{p=0}^{n} C_{n-p}Hx_p\right] \tag{24}$$

Truncating Taylor's series expansions at the positive integer N, Equations (21)–(24) for $n = 0, 1, 2, \ldots, N-1$ and boundary conditions at $z = 0$ and d, give a $(4N+4) \times (4N+4)$ system of coupled equations.

Once unknown coefficients of Taylor's series expansions were determined, reflection coefficients could be identified. The co- and cross-reflection coefficients of the planar layered inhomogeneous chiral layer at $z = 0$ can be expressed based on the Taylor's series coefficients of the electric field as the following:

$$R_{\mathrm{TE-TE}} = \left[\frac{E_{\mathrm{r}}^{\perp}}{E_i^{\perp}}\right]_{E_i^{\parallel}=0} = \frac{Ey_0}{E_i^{\perp}} - 1, \quad R_{\mathrm{TE-TM}} = \left[\frac{E_{\mathrm{r}}^{\perp}}{E_i^{\parallel}}\right]_{E_i^{\perp}=0} = \frac{Ey_0}{E_i^{\parallel}} \tag{26}$$

$$R_{\mathrm{TM-TM}} = \left[\frac{E_{\mathrm{r}}^{\parallel}}{E_i^{\parallel}}\right]_{E_i^{\perp}=0} = \frac{Ex_0}{E_i^{\parallel}\cos(\theta_0)} - 1,$$

$$R_{\mathrm{TM-TE}} = \left[\frac{E_{\mathrm{r}}^{\parallel}}{E_i^{\perp}}\right]_{E_i^{\parallel}=0} = \frac{Ex_0}{E_i^{\perp}\cos(\theta_0)}. \tag{26}$$

4. Examples, results and discussions

In this section, two types of homogeneous and inhomogeneous chiral layers are considered for analysis of the wave propagation and reflection and transmission coefficients using the proposed methods. The first example has an exact solution and can be used to verify the accuracy of the proposed method based on the Taylor's series expansion approach. The second example discusses application of inhomogeneous chiral layers for reducing reflection from a PEC surface.

4.1. Example 1 (PEMC-backed homogeneous chiral slab)

In this section, the validity of the proposed methods in Sections 2 and 3 is verified. As a typical example, the problem of scattering from a PEMC-backed homogeneous chiral slab with thickness $d = 0.2$ m, relative permittivity $\varepsilon_{\mathrm{r}} = 4$, relative permeability $\mu_{\mathrm{r}} = 1$, and chirality parameter $\kappa = 1.5$ illuminated by oblique incident of a TE^z linearly polarized plane wave with unity amplitude, and the excitation frequency of 1 GHz. The amplitudes of co- and cross-reflection coefficients obtained from the analytic method and the Taylor's series

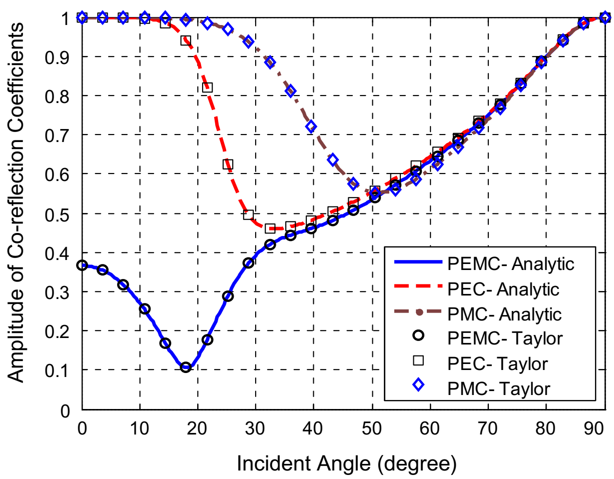

Figure 2. Coreflection coefficients for PEC-, PMC-, and PEMC-backed (with $M = 0.01$) chiral slab.

Table 1. Unknown coefficients of the relative permittivity profile of inhomogeneous nonchiral slab at $f = 1$ GHz with $d = 0.2$ mm.

n	0	1	2	3	4	5	6	7	8	9
$\mathrm{Re}\{E_n\}$	1.429	−0.908	−2.228	1.108	−2.754	0.502	0.486	−0.374	0.148	0.482
σ_n	0.009	0.203	0.831	−0.574	−1.300	0.167	−1.973	1.268	5.461	3.414
					$\kappa = 0$					

expansion method with $N = 50$ and assuming $M = 0.01$ vs. the angle of incidence are shown in Figure 2. Apparently, there is an excellent agreement between the results from two different methods.

4.2. *Example 2 (application of Inhomogeneous chiral layer as radar absorbing material)*

In the second example, the propagation of a plane wave through a PEC-backed inhomogeneous layer with thickness $t = 0.2$ m and $\mu_r = 1$ is considered. Assume that a plane wave with TE^z polarization, unity amplitude, and the frequency of $f = 1$ GHz illuminates the considered PEC baked slab in the first example. In this section, the proposed method in Section 3 is used to optimally design lossy inhomogeneous chiral layer as microwave absorbers. In the first case, we consider zero value for chirality parameter and the truncated Taylor's series expansions with 10 terms for the z-dependent relative permittivity as the following:

$$\varepsilon_r = \sum_{n=0}^{9} E_n z^n = \sum_{n=0}^{9} [\mathrm{Re}\{E_n\} - j\mathrm{Im}\{E_n\}] z^n \equiv \sum_{n=0}^{9} \left[\mathrm{Re}\{E_n\} - j\frac{60c_0}{f}\sigma_n \right] z^n \qquad (27)$$

where σ is the electrical conductivity of medium. An optimally designed microwave absorber requires the input reflection coefficient as small as possible in a desired incidence angle range for TE^z polarized incident wave. To solve the constrained minimization problem, we can use the enhanced genetic algorithm (GA) method which is a common optimization method widely using in different applications [25]. The unknown coefficients of the truncated Taylor's series are written in Table 1. Figure 3 illustrates coreflected power as a function of incident angle θ_0 for this PEC-backed inhomogeneous nonchiral layer. It is seen that the appropriate angle width of reflection coefficient, i.e. when reflected power is lower than -20 dB, is almost 36°.

In the next case, a PEC-backed inhomogeneous chiral layer with z-independent value for chirality parameter, which should be optimized, and with truncated Taylor's series expansion with 10 terms for the z-dependent relative permittivity is considered. Using GA method to optimally design a microwave absorber for TE-polarized incident wave, the optimized value for chirality parameter and unknown coefficients of the truncated Taylor's series of relative permittivity are obtained and written in Table 2. It is clearly seen that using this chiral layer the appropriate angle of reflection coefficient is increased to almost 68.5°, which is very significant.

The most valuable and interesting property of the presented method is its systematic approach, allowing one to simply implement it in a programing language supporting matrix manipulations such as MATLAB. In addition, the consumed time for this method is much less than that for numerical methods such as finite-difference technique. For instance, the time consumed for the three examples presented in this paper was less than 1 s using a computer with Intel Core(TM) I5 CPU and MATLAB program.

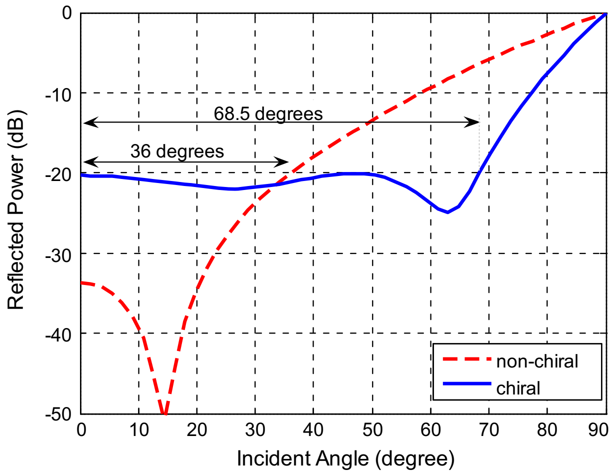

Figure 3. Coreflected power for PEC-backed inhomogeneous chiral and nonchiral slab.

Table 2. Unknown coefficients of the relative permittivity and chirality parameter profiles of inhomogeneous chiral slab at $f = 1$ GHz with $d = 0.2$ mm.

n	0	1	2	3	4	5	6	7	8	9
$\mathrm{Re}\{E_n\}$	0.912	0.229	−1.669	1.149	0.797	1.537	1.768	1.012	0.114	1.769
σ_n	0.012	0.167	2.686	4.243	5.373	1.005	1.202	0.461	1.760	0.390
$\kappa = 2.1 - j0.185$										

5. Conclusions

An analytic frequency domain approach was introduced to solve the problem of propagation of electromagnetic waves in different terminated homogeneous and inhomogeneous planar layered chiral media. In order to verify the validity of the presented methods, we use the presented methods to solve the scattering problem from some special types of homogeneous and inhomogeneous chiral slabs. The examples show that the obtained results from the presented methods are in an excellent agreement. The proposed methods are very simple and programmable and can also be generalized to solve the problem of propagation of electromagnetic waves in different terminated inhomogeneous bi-isotropic media.

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