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APPLICATION OF CHIRAL LAYERS AND METAMATERIALS FOR THE REDUCTION OF RADAR CROSS SECTION

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Abstract—In this paper, the applications of chiral layers and metamaterials as radar absorbing materials are investigated. A perfect electric conductor plate covered by a chiral metamaterial is considered and after the formulation of the problem, reflection of the structure under an oblique plane wave incidence of arbitrary polarization is investigated. Then several examples of the applications of chiral layers in nondispersive, dispersive, and chiral nihility conditions are provided to design of zero reflection coatings. Finally, application of chiral metamaterial structures as microwave absorbers is discussed. In some of the provided examples, the method of genetic algorithm is used to optimize chiral coatings for the minimization of co- and cross reflected power.

1. INTRODUCTION

The study of interaction of electromagnetic fields with chiral media is a recognized subject of modern electromagnetics dating back to the last decades. Unlike the ordinary materials, described by electric permittivity and magnetic permeability, chiral media include a magneto-electric coupling yielding to interesting properties such as optical activity, circular dichroism, and polarization transformation. Basically, chirality is defined as the property of a structure of being non-superimposable onto its mirror image [1]. Recently, there is rapid development on the study of electromagnetic wave propagation in chiral media [1–8]. The possibility of realizing negative refraction by chiral nihility was first discussed by Tretyakov et al. (2003) [9].

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In fact, chiral nihility is a special case of chiral media, for which permittivity and permeability are simultaneously zero. During the past several years, chiral metamaterials as a kind of artificial materials has attracted an enormous amount of interest that could be used to achieve many customized functionalities, such as the negative refraction and giant optical activity [10–20], and many other applications [21–38]. The constitutive equations for chiral media assuming a time harmonic dependence $e^{j\omega t}$ are [1]:

$$\begin{pmatrix} \bar{D} \\ \bar{B} \end{pmatrix} = \begin{pmatrix} \varepsilon_r\varepsilon_0 & -j\kappa\sqrt{\varepsilon_0\mu_0} \\ j\kappa\sqrt{\varepsilon_0\mu_0} & \mu_r\mu_0 \end{pmatrix} \begin{pmatrix} \bar{E} \\ \bar{H} \end{pmatrix} \tag{1}$$

where ε_r and μ_r are the relative permittivity and permeability of the chiral medium, respectively, and κ is the chirality parameter. The vectorial wave equation in a homogeneous chiral medium is:

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

where c 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 eigenpolarizations of the wave equation in a homogeneous chiral medium.

In this paper, we investigate the properties of wave propagation incident onto a perfect electric conductor (PEC), coated by a chiral layer or metamaterial. The formulation of problem will be done for zero reflection from a chiral coated PEC plate for different wave polarizations at particular angles of incidence. The chiral layers are first assumed dispersionless and then the study is extended to well-known dispersive chiral media [39] and finally chiral metamaterials (CMMs). The studies show that chiral absorbers may be designed for operation at a single frequency or in a narrow frequency band width, which may be straightforward. However, for realizing wide band absorbers, chiral layers have been used.

This paper is organized as follows. Section 2 is dedicated to the formulation and analysis of the properties of wave propagation incident onto a PEC plate coated by a chiral layer. Application of nondispersive and dispersive chiral layers for the reduction of radar cross section (RCS) is investigated in Section 3. In Section 4, a CMM structure as a dual-band zero reflection coating is introduced. Finally, summary and conclusions are provided in Section 5.

2. THEORY AND FORMULATION

In this section, the frequency domain analysis of wave propagation and scattering from a PEC backed chiral slab is discussed. Figure 1 shows

a chiral slab which occupies $0 \leq z \leq d$. The region between the chiral layer and PEC plane, i.e., $d< z < d+t$ is free space, and the plane $z = d + t$ is assumed to be PEC. Assume that a plane wave with an arbitrary linear combination of TM ($E_i^{\parallel}$) and TE ($E_i^{\perp}$) polarizations

$$\bar{E}_i = \left[E_i^{\parallel}\left(\cos\theta_0 \hat{a}_x + \sin\theta_0 \hat{a}_z\right) + E_i^{\perp}\hat{a}_y\right] e^{-jk_0(z\cos\theta_0 - x\sin\theta_0)} \tag{3}$$

is obliquely incident with incident angle of θ_0 from free space onto the chiral slab, where k_0 is the wave number in free space. The reflected electric field may be written as

$$\bar{E}_r = \left[E_r^{\parallel}\left(\cos\theta_r \hat{a}_x - \sin\theta_r \hat{a}_z\right) + E_r^{\perp}\hat{a}_y\right] e^{-jk_0(-z\cos\theta_0 - x\sin\theta_0)}. \tag{4}$$

It is well-known that the eigenpolarizations of the wave equation in a homogeneous chiral medium are the RCP and LCP 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

$$\bar{E}_c = \bar{E}_c^{\text{right-going}} + \bar{E}_c^{\text{left-going}} \tag{5}$$

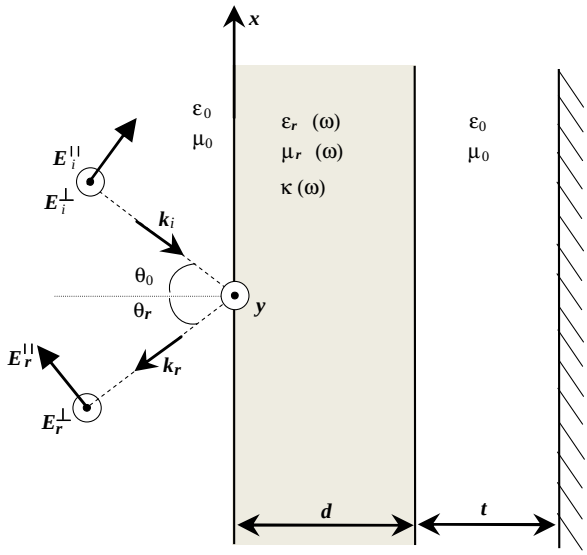

Figure 1. A typical PEC backed chiral slab exposed to an incident plane wave with an arbitrary linear combination of TM ($\mathrm{E}_i^{\parallel}$) and TE ($\mathrm{E}_i^{\perp}$) polarizations.

in which

$$\begin{aligned}
&\bar{E}_c^{\text{right-going}} \\
&= E_1^{r-g}\left(\cos\theta_+\hat{a}_x + \sin\theta_+\hat{a}_z - j\hat{a}_y\right)e^{-jk_+(z\cos\theta_+ - x\sin\theta_+)} \\
&\quad + E_2^{r-g}\left(\cos\theta_-\hat{a}_x + \sin\theta_-\hat{a}_z + j\hat{a}_y\right)e^{-jk_-(z\cos\theta_- - x\sin\theta_-)} \qquad (6)
\end{aligned}$$

$$\begin{aligned}
&\bar{E}_c^{\text{left-going}} \\
&= E_1^{l-g}\left(-\cos\theta_+\hat{a}_x + \sin\theta_+\hat{a}_z - j\hat{a}_y\right)e^{-jk_+(-z\cos\theta_+ - x\sin\theta_+)} \\
&\quad + E_2^{l-g}\left(-\cos\theta_-\hat{a}_x + \sin\theta_-\hat{a}_z + j\hat{a}_y\right)e^{-jk_-(-z\cos\theta_- - x\sin\theta_-)} \qquad (7)
\end{aligned}$$

where $k_\pm = k_0(\sqrt{\varepsilon_r\mu_r} \pm \kappa)$ are the wave numbers corresponding to RCP and LCP waves, and $\theta_\pm$ and θ_0 are determined using Snell's law: $k_0\sin\theta_0 = k_0\sin\theta_r = k_\pm\sin\theta_\pm$. One can write similar relations for the magnetic field in the chiral region.

In the free space region between chiral layer and PEC plane, there are two waves, one propagating toward the right interface and the other one propagating toward the left interface. Therefore, the electric and magnetic fields in this region may be written as

$$\begin{aligned}
\bar{E}_t &= \left[E_t^{\perp r-g}\left(\cos\theta_0\hat{a}_x + \sin\theta_0\hat{a}_z\right) + E_t^{\parallel r-g}\hat{a}_y\right]e^{-jk_0(z\cos\theta_0 - x\sin\theta_0)} \\
&\quad + \left[E_t^{\perp l-g}\left(\cos\theta_0\hat{a}_x - \sin\theta_0\hat{a}_z\right) + E_t^{\parallel l-g}\hat{a}_y\right]e^{jk_0(z\cos\theta_0 + x\sin\theta_0)} \qquad (8)
\end{aligned}$$

$$\begin{aligned}
\bar{H}_t &= \eta_0^{-1}\left[-E_t^{\perp r-g}\left(\cos\theta_0\hat{a}_x + \sin\theta_0\hat{a}_z\right) + E_t^{\parallel r-g}\hat{a}_y\right]e^{-jk_0(z\cos\theta_0 - x\sin\theta_0)} \\
&\quad + \eta_0^{-1}\left[E_t^{\perp l-g}\left(\cos\theta_0\hat{a}_x - \sin\theta_0\hat{a}_z\right) - E_t^{\parallel l-g}\hat{a}_y\right]e^{jk_0(z\cos\theta_0 + x\sin\theta_0)}. \qquad (9)
\end{aligned}$$

To find the complex-constant amplitudes of the reflected and internal waves, the boundary conditions at the interfaces should be applied to transverse components of electric and magnetic fields:

$$\begin{cases} \left[\bar{E}_i + \bar{E}_r - \bar{E}_c\right]_{\tan} = 0 \\ \left[\bar{H}_i + \bar{H}_r - \bar{H}_c\right]_{\tan} = 0 \end{cases} \qquad (10)$$

at $z = 0$, and

$$\begin{cases} \left[\bar{E}_c - \bar{E}_t\right]_{\tan} = 0 \\ \left[\bar{H}_c - \bar{H}_t\right]_{\tan} = 0 \end{cases} \qquad (11)$$

at $z = d$, and $[\bar{E}_t]_{\tan} = 0$ at $z = d+t$, which subscript tan indicates the tangential components of fields. After some simplifications, a system

of eight non-homogeneous equations is obtained, which can be written in the following form:

$$\begin{pmatrix} E_r^{\parallel} \\ E_r^{\perp} \\ E_1^{r-g} \\ E_2^{r-g} \\ E_1^{l-g} \\ E_2^{l-g} \\ E_t^{\parallel r-g} \\ E_t^{\perp r-g} \end{pmatrix} = \begin{pmatrix} -1 & 0 & p_+ & p_- & -p_+ \\ 0 & 1 & -jgp_+ & jgp_- & jgp_+ \\ 0 & -1 & -j & j & -j \\ 1 & 0 & g & g & g \\ 0 & 0 & p_+e^{-jq_+} & p_-e^{-jq_-} & -p_+e^{jq_+} \\ 0 & 0 & -je^{-jq_+} & je^{-jq_-} & -je^{jq_+} \\ 0 & 0 & jgp_+e^{-jq_+} & -jgp_-e^{-jq_-} & -jgp_+e^{jq_+} \\ 0 & 0 & ge^{-jq_+} & ge^{-jq_-} & ge^{jq_+} \end{pmatrix}$$

$$\begin{pmatrix} -p_- & 0 & 0 \\ -jgp_- & 0 & 0 \\ j & 0 & 0 \\ g & 0 & 0 \\ -p_-e^{jq_-} & e^{-jq_0}(e^{-2jq_0t/d}-1) & 0 \\ je^{-jq_-} & 0 & e^{-jq_0}(e^{-2jq_0t/d}-1) \\ jgp_-e^{jq_-} & 0 & e^{-jq_0}(e^{-2jq_0t/d}+1) \\ ge^{jq_-} & -e^{-jq_0}(e^{-2jq_0t/d}+1) & 0 \end{pmatrix}^{-1} \begin{pmatrix} E_i^{\parallel} \\ E_i^{\perp} \\ E_i^{\perp} \\ E_i^{\parallel} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (12)$$

where $p_{\pm} = \cos\theta_{\pm}/\cos\theta_0$, $q_{\pm} = k_{\pm}d\cos\theta_{\pm}$, $q_0 = k_0 d\cos\theta_0$, and $g = \sqrt{\varepsilon_r/\mu_r}$. Once the unknown parameters are determined, the co- and cross-reflection coefficients of the planar layered chiral layer at $z = 0$ can be expressed as the following:

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

The analytical solution of Eq. (12) leads to the complicated expressions for the unknown coefficients, and so it is best to use numerical techniques to calculate inverse matrix. However, it is possible to obtain analytic expressions for the reflection coefficients in some special cases. For instance, assuming $t = 0$, in the case of normal incidence, the co-reflection coefficients may be obtained as

$$R_{TE\text{-}\mathrm{TE}} = R_{TM\text{-}TM} = \frac{\sqrt{\varepsilon_r} - j\sqrt{\mu_r}\tan\left(\frac{k_+ + k_-}{2}d\right)}{\sqrt{\varepsilon_r} + j\sqrt{\mu_r}\tan\left(\frac{k_+ + k_-}{2}d\right)}. \quad (14)$$

3. NUMERICAL EXAMPLES AND RESULTS

In this section, several examples of zero reflection from a PEC plane coated by chiral nihility, nondispersive and dispersive layers are considered. The first and second examples discuss application of chiral nihility layer for the reduction of RCS, and in the third example, the design of dispersive chiral absorbers is investigated.

3.1. Example 1 (Nondispersive Chiral Nihility Layer)

In the first example, we consider the reflection of a plane wave from a PEC backed chiral nihility layer of thickness $d = 0.2\,\mathrm{m}$ which the real parts of permittivity and permeability are equal to zero [9]. Assume a plane wave with unity amplitude and frequency of 12 GHz illuminates the assumed chiral nihility layer whose the electromagnetic parameters are $\varepsilon_r = -0.1j$, $\mu_r = -0.3j$ and $\kappa = 1.1$.

The amplitudes of co- and cross-reflected power versus the angle of incidence are shown in Figure 2. In order to investigate the effect of chirality parameter in the reduction of RCS, the amplitudes of reflection coefficients of a similar nonchiral layer are also shown in Figure 2. The Application of this typical double zero material for the reduction of RCS has been discussed in [40]. It is seen that the incident angle of no reflection is computed equal to $\theta_0 = 10.45°$; however, the appropriate angle width of TE reflection coefficient, i.e., when reflected power is lower than $-20\,\mathrm{dB}$, is very narrow band (17°). Observe that using similar chiral nihility slab with $\kappa = 1.1$ (an optimized value), the

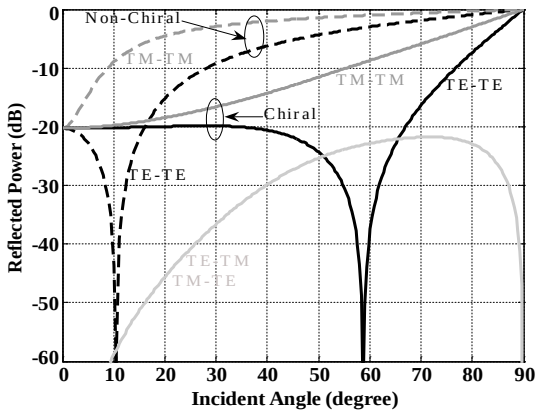

Figure 2. Reflected power as a function of incident angle θ_0 for PEC backed homogeneous non-chiral DZR and chiral nihility slabs.

appropriate angle width of reflection coefficient for TE polarization is considerably wideband (67°). Notice that as it is expected, the chirality parameter does not affect the reflection coefficient if the chiral is excited by normally incident electromagnetic plane wave [41].

3.2. Example 2 (Nondispersive Wide Band Chiral Nihility Absorber)

In the second example, we intend to use nondispersive chiral nihility layers for the design of microwave absorbers to minimize reflected power from a PEC plane in a specified frequency bandwidth and a range of incident angles. Consider an absorber for the both TE and TM polarizations and bandwidth 8–12 GHz with the interval of incidence angle $0 \leq \theta_0 \leq 30°$. To solve the constrained minimization problem, we can use the Genetic Algorithm (GA) method which is a common optimization method widely using in different applications. Using GA method to optimally design a microwave absorber for both TE and TM polarized incident wave, the optimized value for relative permittivity, relative permeability, chirality parameter, thickness of chiral layer, and the distance between the chiral layer and PEC plane are evaluated as

$$\begin{cases} \varepsilon_r = -j0.180,\ \mu_r = -j0.201,\ \kappa = 1.431 - 0.008j \\ d = 1.6 \text{ mm},\ t = 8.1 \text{ mm} \end{cases}. \tag{15}$$

The amplitudes of co- and cross-reflected power at incident angle $\theta_0 = 0$ and 30° versus the frequency are shown in Figure 3. Observe that the

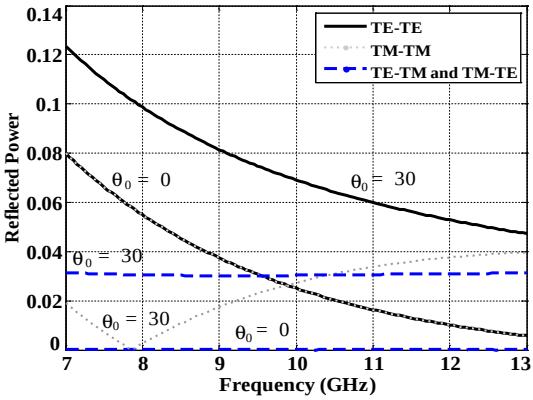

Figure 3. Co- and cross reflected power from a PEC backed nondispersive chiral nihility layer as a function of frequency at incident angles $\theta_0 = 0$ and 30°.

designed absorber has a good performance of low reflection for both TE and TM incidence in a wide frequency bandwidth and wide angles of incidence. Notice that the condition $|\mathrm{Im}\{\kappa\}| < \sqrt{|\mathrm{Im}\{\varepsilon_r\}||\mathrm{Im}\{\mu_r\}|}$ which is known as one of the necessary conditions for the lossy chiral media is also satisfied [1].

3.3. Example 3 (Dispersive Chiral Absorber)

In the third example, we consider a well-known dispersion model for the chiral layer. Assuming the aforementioned constitutive relations, time harmonic dependence as $e^{j\omega t}$, and the theoretical dispersive model of chiral media discussed in [39], the dispersion frequency forms of the constitutive parameters of a homogenous chiral layer are considered as follows

$$\begin{cases} \varepsilon_r = \varepsilon_b - \dfrac{\Omega_{\varepsilon 1}\omega_{10}^2}{\omega^2 - \omega_{10}^2 - j\omega\omega_{10}\Gamma_1} - \dfrac{\Omega_{\varepsilon 2}\omega_{20}^2}{\omega^2 - \omega_{20}^2 - j\omega\omega_{20}\Gamma_2} \\ \mu_r = \mu_b - \dfrac{\Omega_{\mu 1}\omega^2}{\omega^2 - \omega_{10}^2 - j\omega\omega_{10}\Gamma_1} - \dfrac{\Omega_{\mu 2}\omega^2}{\omega^2 - \omega_{20}^2 - j\omega\omega_{20}\Gamma_2} \\ \kappa = -\dfrac{\Omega_{\kappa 1}\omega_{10}\omega}{\omega^2 - \omega_{10}^2 - j\omega\omega_{10}\Gamma_1} - \dfrac{\Omega_{\kappa 2}\omega_{20}\omega}{\omega^2 - \omega_{20}^2 - j\omega\omega_{20}\Gamma_2} \end{cases} \tag{16}$$

where ω_{10}, ω_{20}, ε_b and μ_b are resonant frequencies and effective background relative permittivity and permeability, respectively. Other parameters are coefficients which depend on the geometrical properties of chiral particles and describe the strength of resonances.

Using a PEC backed (assuming $t = 0$) dispersive chiral layer, we intend to design a typical dual-band absorber with the thickness of $d = 1.6\,\mathrm{mm}$ for the both TE and TM polarizations at frequencies 9 GHz and 11 GHz, and a wide interval of incidence angles. Using GA method to optimally design the desired dispersive microwave absorber, the optimized value for the unknown parameters in the dispersion relations of relative permittivity, relative permeability, and chirality parameter are obtained and presented in Table 1. The absorption of the structure as a function of frequency for the structure is presented in Figure 4 for both TE and TM polarizations at various angles of incidence. Observe that the absorber has a good performance of very low reflection for both TE and TM incidence in the desired frequencies and angles of incidence, so that at normal incidence two perfect absorptivity peaks operating at 9 GHz and 11 GHz are obtained; whose absorptivity ratios come up to 99%. With increasing angle of incidence, the absorption for both TE and TM incidence remains up to 90%.

Table 1. Optimization results for the unknown parameters of relative permittivity, relative permeability, and chirality parameter of PEC backed chiral layer.

m	ω_{m_0}	Γ_m	$\Omega_{\kappa m}$	$\Omega_{\varepsilon m}$	$\Omega_{\mu m}$
1	$2\pi \times 9.249\,\mathrm{GHz}$	0.017	0.094	0.949	0.007
2	$2\pi \times 11.317\,\mathrm{GHz}$	0.022	0.137	0.578	0.023
$\varepsilon_b = 8.728 \qquad \mu_b = 0.846$					

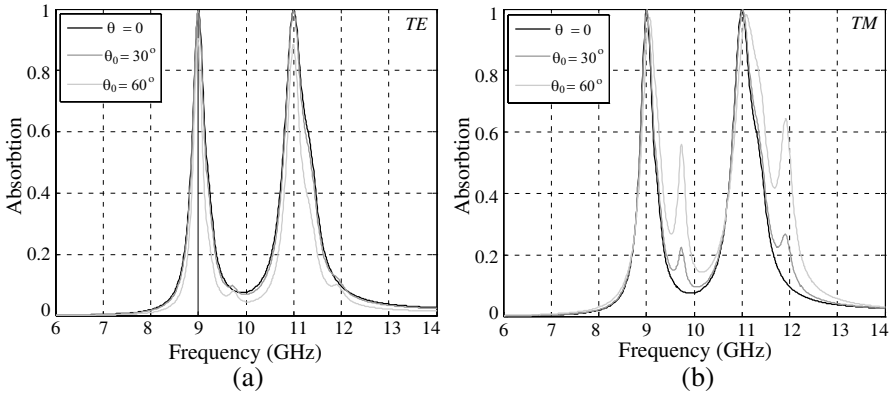

Figure 4. Absorption of a PEC backed dispersive chiral layer as a function of frequency for (a) TE and (b) TM polarization at various angles of incidence.

4. APPLICATION OF SEMI-PLANAR CHIRAL METAMATERIAL STRUCTURES AS MICROWAVE ABSORBERS

In this section, we investigate the application of semi-planar CMMs as the radar absorber structures. The proposed structure [17] is periodic in x-y plane and its unit cell is shown in Figure 5. The unit cell of this structure constructed by two copper double arms conjugated gammadion patterned on the opposite sides of an FR-4 board with dielectric constant of 4.2 and loss tangent of 0.02. The dispersion frequency form of the constitutive parameters of such CMM structures has been presented in [18].

The assumed CMM structure is located at an optimized distance of $t = 0.4\,\mathrm{mm}$ above a PEC plane, and a fullwave electromagnetic simulation was performed using the commercial program CST Microwave Studio$^{\mathrm{TM}}$ 2010. The simulated absorption as a function

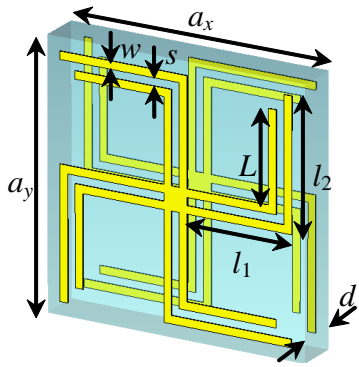

Figure 5. Schematic representation of a unit cell of the CMM structure. The geometric parameters are given by $a_x = a_y = 10\,\text{mm}$, $L = 3.45\,\text{mm}$, $l_1 = 4.05\,\text{mm}$, $l_2 = 4.95\,\text{mm}$, $w = s = 0.3\,\text{mm}$ and $d = 1.6\,\text{mm}$.

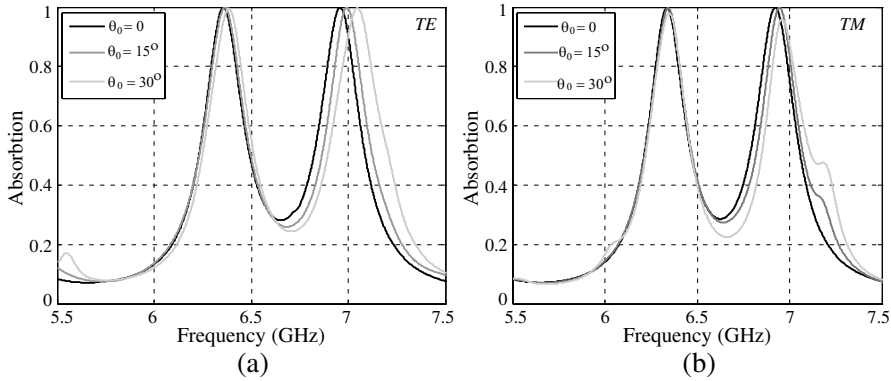

Figure 6. Absorption as a function of frequency for both TE and TM polarizations at various angles of incidence.

of frequency for the structure is presented in Figure 6 for both TE and TM polarizations at various angles of incidence. It can be seen that for the both TE and TM case, at normal incidence there appear two absorbing peaks that are attributed to two resonant modes. Two perfect absorptivity peaks operating at 6.3 GHz and 6.9 GHz can be obtained; whose absorptivity ratios come up to 99%, and with increasing angle of incidence, the absorption remains quite large.

We also study the absorption appearance with different polarization directions under normal incidence. Figure 7 shows the

absorptivity with different angles of polarization direction (φ) deviated from y axis. When the angle is 0°, the polarization is along y direction, two peaks appear in the absorptivity curve. With an increase in the angle, the absorptivity peaks remain almost unchanged. Observe that the absorber structure is almost polarization insensitive.

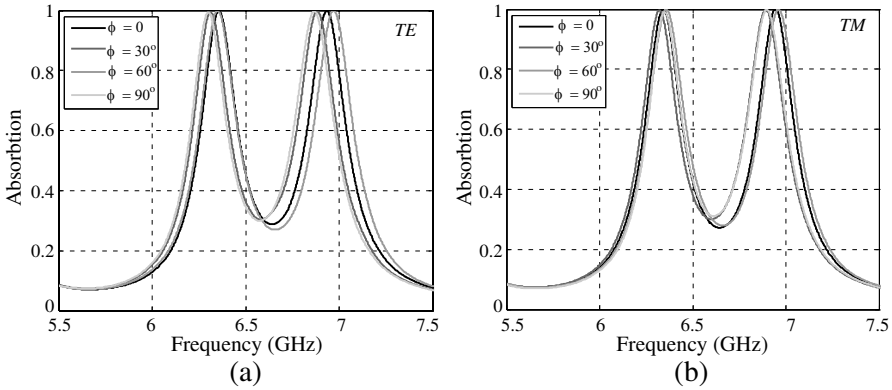

Figure 7. Absorption as a function of frequency for different polarization angles at the normal incidence for (a) TE and (b) TM polarization.

5. CONCLUSIONS

The application of chiral layers and metamaterials for the reduction of reflected power from a PEC plane is investigated. After presenting theory and formulation of the problem, several types of chiral mediums such as chiral nihility, nondispersive, dispersive, and semiplanar CMM structures were used to the design of a zero reflection coating in the desired frequencies and angles of incidence. In some of these designs, the optimization methods and high frequency simulators are utilized as auxiliary tools. The results show that dispersive chiral layers and metamaterials are suitable for application of absorbers. In the future, it is expected that the multi-layer chiral metamaterials can be optimally designed as wideband microwave absorbers.

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