Design of Wideband Planar Absorbers using Composite Materials

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Abstract **–** Design of planar microwave absorbers usually incorporates the use of either magnetic or electric lossy materials. In this study, chiral materials are included in the design process of these absorbers. The genetic algorithm is used to obtain suitable solutions satisfying the design requirements. Wideband absorbers are designed using different configurations and presented in this paper. It is shown that the inclusion of chiral materials in the design process leads to more efficient absorbers.

Keywords: Electromagnetic absorbers, chiral materials, composite materials.

I. INTRODUCTION

Wideband microwave absorbers are of great interest for their important applications. These applications include radar cross section reduction of a wide range of objects, suppression of unwanted radiation and development of anechoic chambers [1-3]. Different designs of such absorbers are presented for various configurations including single layer [4-8], two layers [9-12] and multilayer absorbers [3, 13-16]. The design techniques of these absorbers are based on graphical methods [4, 7], local optimization methods [13], global optimization methods [3, 14, and 15] and analytical methods [9-11]. All of the above designs utilize layers of absorber materials which are of simple lossy electric or lossy magnetic types.

In this paper, chiral materials are used in the design process in addition to the above materials to construct the absorber. Design of wideband absorbers with different layer configurations is performed with the aid of the genetic algorithm as a global optimization technique. Better performance is expected when chiral materials are included in the design procedure of these absorbers, by virtue of the extra degree of freedom provided by the chirality parameter.

II. FORMULATION OF THE PROBLEM

Consider a planar absorber that is composed of N layers of lossy materials backed by a perfectly conducting surface as shown in Fig. 1. Each layer is defined by its complex permittivity ε_n, complex permeability μ_n, thickness d_n, in addition to chiral admittance ξ_n where $1 \leq n \leq N$. The time variation of the electromagnetic fields is assumed sinusoidal with the factor $e^{j\omega t}$. The electromagnetic fields inside any layer is controlled by the equations [16],

$$\underline{D}_n = \varepsilon_n \underline{E}_n - j\,\xi_n \underline{B}_n \tag{1}$$

$$\underline{B}_n = \mu_n (\underline{H}_n + j\,\xi_n \underline{E}), \tag{2}$$

where ε_n, μ_n are the usual electric permittivity and magnetic permeability, and ξ_n is the chiral admittance.

Let a uniform plane wave be normally incident to the absorber interface with the air.

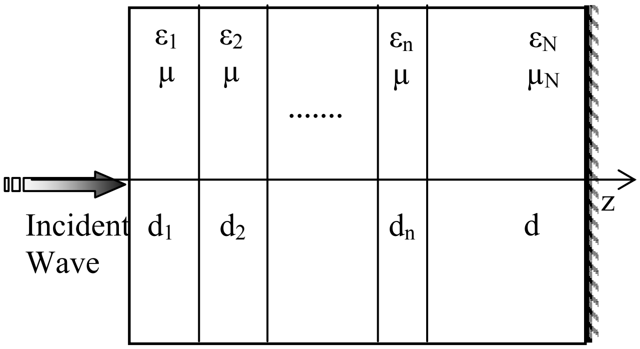

Fig. 1. N-layer planar absorber.

Because of the chirality, there are two normal propagating modes in each layer; one is having right circular polarization (RCP) with $\exp(-jk_n^+z)$ propagation factor and the other left circular polarization (LCP) with $\exp(-jk_n^-z)$ propagation factor where [17,18],

$$k_n^\pm = \sqrt{\omega^2 \mu_n \varepsilon_n + \omega^2 \mu_n^2 \xi_n^2} \pm \omega \mu_n \xi_n \tag{3}$$

writing ξ_n in the form,

$$\xi_n = \sqrt{\frac{\varepsilon_0}{\mu_0}}\,\chi_n \tag{4}$$

where χ_n is a dimensionless chirality factor, we re-express $k_n^{\pm}$ as,

$$k_n^{\pm} = k_n \left[\sqrt{1 + \left(\frac{\eta_n}{\eta_0}\right)^2 \chi_n^2} \pm \frac{\eta_n}{\eta_0}\chi_n \right] \tag{5}$$

where

$$k_n = \omega\sqrt{\mu_n\,\varepsilon_n} \tag{6}$$

and

$$\eta_n = \sqrt{(\mu_n / \varepsilon_n)}\ , \tag{7}$$

with η_0 is the free space wave impedance.

It can be shown that the reflection coefficient Γ of a circularly polarized plane wave, which is normally incident on the absorber, is given by,

$$\Gamma = \frac{z_1 - \eta_0}{z_1 + \eta_0} \tag{8}$$

where,

$$z_n = \zeta_n\,\frac{\zeta_n \tanh(\gamma_n d_n) + z_{n+1}}{\zeta_n + z_{n+1}\tanh(\gamma_n d_n)}\ , \tag{9}$$

with

$$\zeta_n = \frac{\eta_n}{\sqrt{1 + \left(\eta_n/\eta_0\right)^2 \chi^2}}\ , \tag{10}$$

$$z_N = \zeta_n \tanh(\gamma_n d_n)\,, \tag{11}$$

and

$$\gamma_n = j\,\frac{\left(k_n^{+} + k_n^{-}\right)}{2} = jk_n\ , \tag{12}$$

where γ_n is the average propagation constant of the forward and backward plane waves in the chiral medium, which have opposite circular polarization. We note here that equation (8) applies to either an RCP or LCP incident wave. Hence it is also valid for a linearly polarized incident wave. On the other hand, the case when $\chi_n = 0$ represents either an ordinary lossy electric or lossy magnetic material, with no chirality.

It is worth noting that in the design process of chiral absorbers, only magnetic materials are considered as chiral materials while electric materials are still non-chiral. In other words, the chirality is imposed on magnetic materials only and this is quite sufficient to achieve good performance for the designed absorbers. Moreover, all the materials that are used to construct the absorbers are assumed to be dispersive. This dispersion is imposed such that the complex relative permittivity of the electric layers and the complex relative permeability of the magnetic layers are inversely proportional to square root of the operating frequency. In such case, the electric and magnetic parameters of these layers ε_n and μ_n are expressed as,

$$\begin{gathered} \varepsilon_n = \varepsilon_0\,\varepsilon_{rn}\,(1 - \tan\delta_{en})\sqrt{f\ / f_0} \\ \mu_n = \mu_0 \end{gathered} \tag{13}$$

for the electric layers, and,

$$\begin{gathered} \varepsilon_n = 10\varepsilon_0 \\ \mu_n = \mu\,\mu_{rn}\,(1 - \tan\delta_{mn})\sqrt{f\ / f_0} \end{gathered} \tag{14}$$

for the magnetic layers. This frequency dependence is satisfied by most materials.

The depth of each layer d_n is normalized with respect to the wavelength of the wave inside this layer.

III. APPLICATION OF THE GENETIC ALGORITHM

A conventional genetic algorithm is built to solve the optimization problem, whose objective is to minimize the total reflected power from the layered structure, over a wide frequency range. We choose to maximize the total power transmitted to the absorber and at the same time minimize the maximum power reflected over the frequency band. A set of constraints is used to impose limitations or specifications on the system parameters. The variables (genes) in the fitness function are the intrinsic electric and magnetic parameters, the chirality factor as well as the thickness of the layers.

The genetic algorithm is applied for 100 design experiments in each layer configuration of chiral and non chiral absorbers with 6000 iterations in each experiment. In each design experiment, the fitness criterion is examined over a normalized frequency range from 0.1 to 9.0 with five samples in the range. Of course, larger number of samples within the range can be considered; however, this would cost more computational time without guarantee of much better results. The fitness criterion is defined as,

$$\begin{gathered} fitness = \frac{1}{2} Q \left\{ \sum_{i=1}^{N_s} (1 - \left|\Gamma_i^2\right|) \right\} \\ + (1 - Q)\left\{ 1 - \left|\Gamma_{\max}^2\right| \right\} \end{gathered} \tag{15}$$

where Q is a factor ranging from 0 to 1 and it is set to 0.5 in these experiments, N_s , is the number of applied samples through the frequency range, Γ_i is the reflection coefficient at any sampling frequency, Γ_{max} is the maximum reflection coefficient amplitude among the samples.

IV. RESULTS

The best four designs in the above experiments are chosen for each layer configuration of the absorber based on the fitness criterion equation (15). The parameters of these designs are given in Tables 1 to 3 for two, three and four layer chiral absorber models. Examination of the fitness criteria in these leads to the conclusion that the absorber performance improves with the increased number of layers. The frequency responses of these chiral absorbers are presented in Figs. 2 to 4. The best design of each layer configuration exhibits reflection level below than -20 dB all over the frequency range. This level decreases obviously as the number of layers increases. The frequency response of the best four design experiments of the five layer nonchiral absorber is shown in Fig. 5. It is clear that the frequency response of these designs has much lower performance than those of the chiral absorbers.

Table 1. Design parameters for a two layer chiral absorber.

	Layer No.	Type	ε_{rn}, tan(δ_n/2)	μ_{rn}, Tan (δ_n/2)	d_n/λ_n	Chirality
Design 1 Fitness = 99.518%	1	mag.	10.0, 0.0	7.48, .75	099	.779
	2	mag.	10.0, 0.0	29.8, .797	076	.556
Design 2 Fitness = 99.332%	1	mag.	10.0, 0.0	5.86, .75	.099	.691
	2	mag.	10.0, 0.0	35.1, .797	.075	.622
Design 3 Fitness = 99.328%	1	mag.	10.0, 0.0	10.08, .65	.08	.772
	2	mag.	10.0, 0.0	25.0, .80	.09	.694
Design 4 Fitness = 99.202%	1	mag.	10.0, 0.0	20.36, .737	.07	.783
	2	mag.	10.0, 0.0	36.1, .787	.06	.516

A comparison between the chiral and nonchiral absorbers according to the best fitness criterion is given in Fig. 6 for each layer configuration. This comparison shows clearly that the chiral absorbers have much better performance than the nonchiral one. Even, it is evident that the fitness criterion of the two layer chiral absorber is better than the five layer nonchiral one. The conclusion is that less number of chiral layers is needed to achieve a prescribed reflection level over a wide frequency bandwidth.

Table 2. Design parameters for a three layer chiral absorber.

	Layer No.	Type	ε_{rn}, tan (δ_n/2)	μ_{rn}, tan (δ_n/2)	d_n/λ_n	Chirality
Design 1 Fitness = 99.842%	1	mag.	10.0, 0.0	18.04 .7148	.05311	.746
	2	elec.	9.353, .065	1.0, 0.0	.03647	.000
	3	mag.	10.0, 0.0	26.76, .792	.09839	.541
Design 2 Fitness = 99.814%	1	mag.	10.0, 0.0	18.46, .552	.08656	.78
	2	elec.	3.93, .629	1.0, 0.0	.04328	.00
	3	mag	10.0, 0.0	36.53, .796	.08245	.36
Design 3 Fitness = 99.808%	1	mag	10.0, 0.0	22.62, .790	.02281	.78
	2	elec.	9.41, .713	1.0, 0.0	.01375	.00
	3	mag	10.0, 0.0	38.3, .799	.09689	.44
Design 4 Fitness = 99.75%	1	mag	10.0, 0.0	23.7, .769	.03856	.80
	2	elec.	8.89, .054	1.0, 0.0	.02695	.00
	3	mag	10.0, 0.0	36.6, .798	.08868	.62

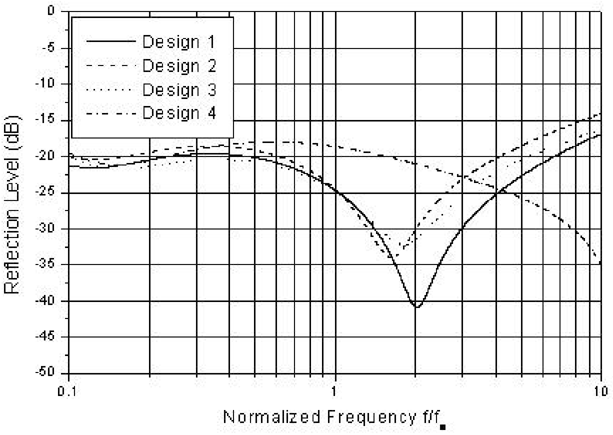

Fig. 2. Power reflection level for a two-layer chiral model.

Table 3. Design parameters for a four layer chiral absorber.

	Layer No.	Type	ε_{rn}, tan $(\delta_n/2)$	μ_{rn}, tan $(\delta_n/2)$	d_n/λ_n	Chirality
Design 1 Fitness = 99.97%	1	elec.	3.43, .448	1.0, 0.0	.001	.00
	2	mag.	10.0, 0.0	14.39, .781	.04	.80
	3	elec.	7.50, .198	1.0, 0.0	.044	.00
	4	mag.	10.0, 0.0	26.16, .793	.097	.45
Design 2 Fitness = 99.99 %	1	mag.	10.0, 0.0	8.50, .707	.055	.70
	2	elec.	3.21, .422	1.0, 0.0	.056	.00
	3	mag.	10.0, 0.0	37.2, .66	.022	.49
	4	mag	10.0, 0.0	32.4, .793	.092	.64
Design 3 Fitness = 99.872%	1	mag.	10.0, 0.0	24.0, .666	.054	.77
	2	elec.	6.15, .387	1.0, 0.0	.025	.00
	3	mag.	10.0, 0.0	30.1, .795	.036	.58
	4	Mag	10.0, 0.0	39.79, .791	.089	.79
Design 4 Fitness = 99.864%	1	Mag	10.0, 0.0	30.40, .486	.089	.77
	2	Mag	10.0, 0.0	25.68, .746	.068	.77
	3	elec.	7.15, .519	1.0, 0.0	.097	.00
	4	Mag	10.0, 0.0	27.59, .784	.098	.49

To simply explain why chiral absorbers surpass the non chiral ones, refer to the layer intrinsic impedance parameter in equation (10).

When the layer is magnetic with high loss, such that $|\mu/\mu_0|\chi^2 >> |\varepsilon/\varepsilon_0|$, then $\zeta \approx \eta_0/\chi$. So a highly lossy magnetic layer with chirality parameter χ =1, is a good match to air! (over a wide band) [19]. Of course χ=1 is too much chirality, so it is hard to manufacture. But this shows that adding one or more layers to the one magnetic layer should lead to a practical absorber. This should explain why few numbers of chiral layers could make a wide-band good absorber.

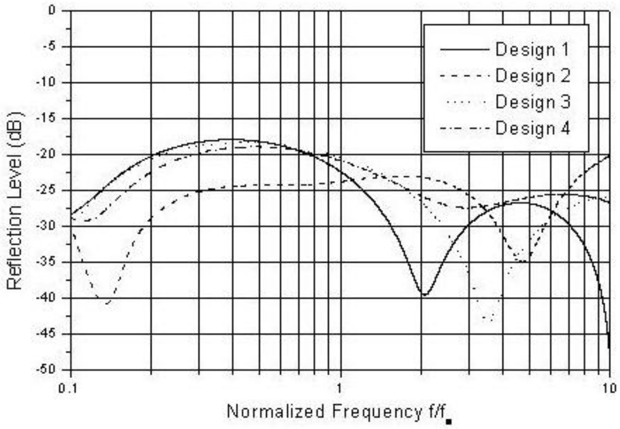

Fig. 3. Power reflection level for a three-layer chiral model.

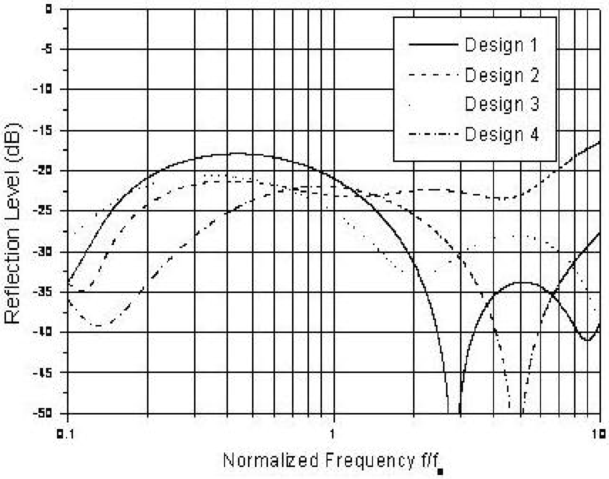

Fig. 4. Power reflection level for a four-layer chiral model.

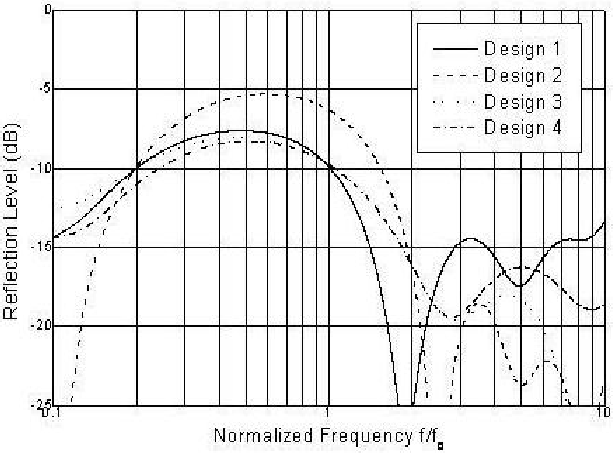

Fig. 5. Power reflection level for a five-layer non-chiral model.

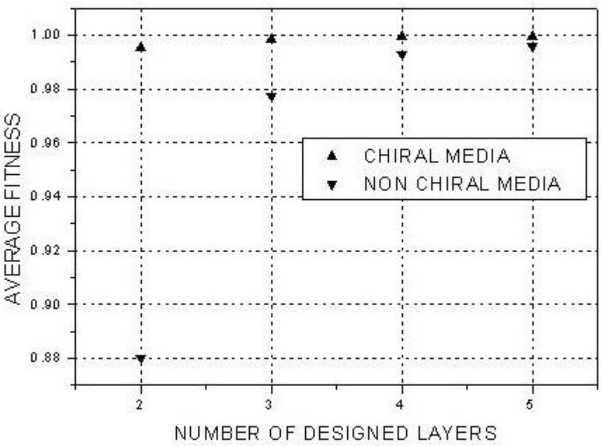

Fig. 6. Maximum fittness versus number of Layers for chiral and non-chiral media.

V. CONCLUSION

In this paper, the analysis of chiral planar absorber is presented. The genetic algorithm is applied to obtain the best four designs over 100 design experiments for each layer configuration of chiral and non-chiral absorbers. Inspection of the fitness criterion of these experiments indicates that the chiral absorbers have much better performance than non-chiral ones. It is concluded that much less number of layers is needed to achieve a prescribed maximum level of the reflection coefficient over a wide frequency range.

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