Progress In Electromagnetics Research C, Vol. 13, 171–185, 2010

ON THE OPTIMAL DESIGN OF MULTILAYER MICROWAVE ABSORBERS

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Abstract—In this paper, some common misconceptions in several papers dealing with the optimal design of multilayer microwave absorbers are indicated. Specifically, it is emphasized that Chew's recursive formula for the reflection coefficient of multilayer media for the TM polarization corresponds to the magnetic field, not the electric field. It is also emphasized that both TM and TE polarizations should have the same magnitude of the reflection coefficient for the case of normal incidence. Numerical optimal results are also presented and compared with those existing in the literature.

1. INTRODUCTION

Multilayer microwave absorbers are important elements in many military and civil applications. The problem of designing these absorbers lies mainly in the minimization of the overall reflection coefficient in a specific frequency band and a specific range of angles of incidence for any polarization (TE and TM). In the last two decades, many papers appeared in which the design of such absorbers has been accomplished using evolutionary techniques [1–7]. Specifically, genetic algorithm (GA) has been used to design optimal microwave absorbers [1–5]. Moreover, a modified particle swarm optimization (PSO) has been used successfully in the design of thin wideband microwave absorbers [6]. Very recently, the self-adaptive differential evolution (SADE) algorithm has been used in the optimal design of multilayer absorbers [7]. It has been shown that SADE gives better results than other evolutionary techniques (PSO and GA). In all of these papers, a fitness (or objective) function (to be minimized) had

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to be formulated. This fitness function is mainly the magnitude of the overall reflection coefficient of the multilayer absorber. Chew's recursive formula [8] for the evaluation of the reflection coefficient has been mainly used in most papers dealing with this problem. This formula can be used to evaluate the overall reflection coefficient for any number of layers for both TE and TM polarizations for any angle of incidence. For the case of normal incidence, the formula gives the same magnitude of the reflection coefficient for both polarizations. Unfortunately, the fact that the expression for the reflection coefficient for the TM polarization corresponds to the magnetic field (not the electric field) has been neglected in several papers [1, 4, 7]. This leads to different values for the magnitude of the reflection coefficient for the case of normal incidence for both polarizations.

In this paper, Chew's recursive formula for the evaluation of the reflection coefficient for multilayer structure is presented in a complete form for an obliquely incident wave (for both TE and TM polarizations). It is emphasized that Chew's recursive formula for the reflection coefficient of multilayer media for the TM polarization corresponds to the magnetic field, not the electric field. Moreover, new designs of multilayer absorbers are presented which give better response in the desired frequency band than those published in the literature. These designs are obtained using the differential evolution (DE) with competitive control-parameter setting technique [9]. For the sake of brevity, the reader may consult [9], and the references therein, for the details of the DE method and description of the used algorithm.

2. FORMULATION OF THE PROBLEM

Figure 1 shows the problem under consideration. The multilayer microwave absorber consists of N layers of different materials backed by a perfect electric conductor (PEC), as the last layer number is $N+1$. The incident wave exists in free-space (layer number 0) and is obliquely incident on the first interface, making an incidence angle θ with the z-axis. In general, the goal is to design a multilayer system (from a specific predefined materials database) that minimizes the overall reflection coefficient in a specific frequency range and a specific range of incidence angles. The generalized reflection coefficient at the interface between layer i and layer $i+1$ can be written as follows [8]:

$$\tilde{R}_{i,i+1} = \frac{R_{i,\,i+1} + \tilde{R}_{i+1,\,i+2} e^{-j2k_{i+1,\,z} d_{i+1}}}{1 + R_{i,\,i+1} \tilde{R}_{i+1,\,i+2} e^{-j2k_{i+1,\,z} d_{i+1}}} \tag{1}$$

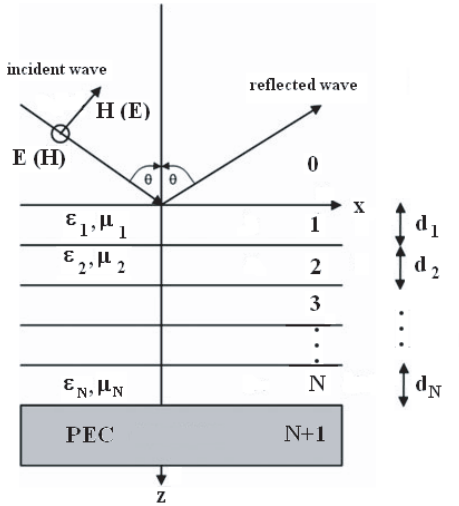

Figure 1. General structure of multilayer microwave absorber with an obliquely incident TE (or TM) polarized wave.

where for TE (i.e., perpendicular) polarization:

$$R_{i,\,i+1} = \frac{\mu_{i+1}\,k_{i,z} - \mu_i\,k_{i+1,z}}{\mu_{i+1}\,k_{i,z} + \mu_i\,k_{i+1,z}} \tag{2}$$

while for TM (i.e., parallel) polarization:

$$R_{i,\,i+1} = \frac{\varepsilon_{i+1}\,k_{i,z} - \varepsilon_i\,k_{i+1,z}}{\varepsilon_{i+1}\,k_{i,z} + \varepsilon_i\,k_{i+1,z}} \tag{3}$$

ε_i and μ_i are the complex permittivity and permeability, respectively, for the ith layer, and $k_{i,z} = k_i\cos(\theta_i)$ where θ_i is the angle of transmission (or refraction) in the ith layer. Using Snell's law, $k_{i,z}$ can be written in terms of the incidence angle θ as follows:

$$k_{i,z} = \omega\sqrt{\mu_i\varepsilon_i - \mu_0\varepsilon_0\sin^2(\theta)} \tag{4}$$

The above equations are recursive relations that express $\tilde{R}_{i,\,i+1}$ in terms of $\tilde{R}_{i+1,\,i+2}$. The total reflection coefficient of the multilayer structure, shown in Figure 1, is obtained by evaluating Equation (1) recursively starting from $\tilde{R}_{N-1,\,N}$ to $\tilde{R}_{0,\,1}$. Because of the existence of the perfect electric conductor, one has to set: $\tilde{R}_{N,\,N+1} = -1$ for TE polarization and $\tilde{R}_{N,\,N+1} = +1$ for TM polarization. Here, it should be emphasized that Equations (1)–(3) correspond to the reflection coefficient for the electric field for the TE case, while they correspond to the reflection coefficient for the magnetic field for the TM case [8]. This leads to the setting of $\widetilde{R}_{N,N+1} = +1$ (not -1) for TM polarization. Alternatively, one can set $\widetilde{R}_{N,N+1}$ to -1 for the TM case, while multiplying Equation (3) with a negative sign. It seems that this fact has been neglected in many papers and $\widetilde{R}_{N,N+1}$ was set to -1 for both TE and TM polarizations [1, 4, 7]. This has led to different values for the magnitude of the reflection coefficient for *normal incidence* for both polarizations, which should not be the case. Both polarizations should have the same magnitude of the reflection coefficient for the case of normal incidence. It should be mentioned that for normal incidence case, one can use transmission line theory to obtain an expression for the overall reflection coefficient of the multilayer absorber. This option has been checked and it gives the same results as Chew's recursive formula with $\theta = 0$, whether TE or TM formulas are used in the calculations.

Generally, the goal of the absorber design is to find a set of layers that minimizes the reflection coefficient for a set of frequencies and incidence angles for both polarizations. The materials for the different layers are usually selected from a predefined database of available materials whose constitutive parameters may vary arbitrarily with frequency. This can be expressed as minimizing the overall reflection coefficient of the multilayer absorber $\widetilde{R}_{0,1}$ (within a specific range of frequencies and incidence angles) [1–7]. Moreover, a condition on the total thickness of the absorber can be set while searching for the optimum solution [1–7]. Here, the differential evolution (DE) with competitive control-parameter setting technique (debr18. m) [9] is used to perform the optimization. This is a self-adaptive DE in which the setting of the control parameters is made adaptive through the implementation of a competition into the DE algorithm.

3. NUMERICAL RESULTS

In this section, the differential evolution (DE) with competitive control-parameter setting technique [9] is applied to find optimal designs for multilayer microwave absorbers. In the illustrative examples, the materials database shown in Table 1 is used [1, 2, 6, 7]. This database consists of 16 different materials: lossless dielectrics, lossy magnetic materials, lossy dielectrics, and relaxation-type magnetic materials. Although these material characteristics are fictitious, they are representative of a wide class of available microwave absorbers and have been widely used in the literature. The maximum thickness for each layer is set to 2 mm. The algorithm is run for 20 independent trials although only the best solution is presented. In the DE simulation, the number of iterations is set to 1000. The obtained results are compared with those published in the literature obtained using different optimization methods.

3.1. First Example (Designs HF1 and HF2)

In this example, a five layers absorber ($N = 5$) is optimized (for normal incidence) to minimize the reflection coefficient in the frequency range of 2–8 GHz, with a frequency increment of 0.5 GHz. In this case, the optimization involves 10 design parameters: the thicknesses and the materials numbers. As mentioned above, in the case of normal incidence, one does not have to specify the type of polarization since both polarizations have the same reflection coefficient. Tables 2 and 3 show the obtained results along with those presented in the literature [7]. In Table 2 (HF1 design), the maximum total thickness of the absorber was set to 5 mm, while it was set to 2.57 mm in Table 3 (HF2 design). Figure 2 shows the reflection coefficient as a function of frequency for both designs. The obtained HF1 design offers slightly less total thickness than that found in the literature [7]. For the HF1 design, the maximum reflection coefficient in the desired frequency band is −25.485 dB as compared to −24.75 dB in the literature [7]. It is also interesting to note that the results for the HF1 design have three layers (layers 2, 3, 4) of the same material which is practically attractive. For the HF2 design, the maximum reflection coefficient in the desired frequency band is −20.9104 dB as compared to −20.03 dB in [7].

3.2. Second Example (Design DES2)

In this example, a five layers absorber ($N = 5$) is optimized (for normal incidence) to minimize the reflection coefficient in the frequency range of 0.5–8 GHz. The maximum total thickness of the absorber was set to 5 mm and the frequency step was taken as 0.5 GHz. Table 4 shows the obtained results compared with those presented in the literature [7], while, Figure 3 shows the frequency response of the DES2 design compared to that mentioned in the literature [7]. It can be seen that the proposed design gives somewhat a better response than the literature one [7] in the desired frequency range. Specifically, the maximum reflection coefficient in the desired frequency band is −20.8 dB as compared to −20.26 dB [7].

For the same proposed DES2 design, Figures 4 and 5 show the frequency response for obliquely incident TE and TM polarized waves,

Table 1. Pre-defined materials database.

Lossless dielectric Materials ($\mu' = 1$, $\mu'' = 0$)				
No.				ϵ'
1				10
2				50
Lossy Magnetic Materials ($\epsilon' = 15$, $\epsilon'' = 0$) $\mu = \mu' - j\mu''$ $\quad \mu'(f) = \frac{\mu'(1\ \text{GHz})}{f^a}$ $\quad \mu''(f) = \frac{\mu''(1\ \text{GHz})}{f^b}$				
No.	μ' (1 GHz)	a	μ'' (1 GHz)	b
3	5	0.974	10	0.961
4	3	1.000	15	0.957
5	7	1.000	12	1.000
Lossy Dielectric Materials ($\mu' = 1$, $\mu'' = 0$) $\epsilon = \epsilon' - j\epsilon''$ $\quad \epsilon'(f) = \frac{\epsilon'(1\ \text{GHz})}{f^a}$ $\quad \epsilon''(f) = \frac{\epsilon''(1\ \text{GHz})}{f^b}$				
No.	ϵ' (1 GHz)	a	ϵ'' (1 GHz)	b
6	5	0.861	8	0.569
7	8	0.778	10	0.682
8	10	0.778	6	0.861
Relaxation-Type Magnetic Materials ($\epsilon' = 15$, $\epsilon'' = 0$) $\mu = \mu' - j\mu''$ $\quad \mu'(f) = \frac{\mu_m f_m^2}{f^2 + f_m^2}$ $\quad \mu''(f) = \frac{\mu_m f_m f}{f^2 + f_m^2}$ ***f and f_m in* GHz**				
No.		μ_m		f_m
9		35		0.8
10		35		0.5
11		30		1.0
12		18		0.5
13		20		1.5
14		30		2.5
15		30		2.0
16		25		3.5

Table 2. Parameters for the HF1 design.

	Present design		Data from [7]	
Layer	Material	Thickness (mm)	Material	Thickness (mm)
1	16	0.384	14	0.459
2	6	0.433	6	1.817
3	6	1.143	6	1.028
4	6	1.446	5	0.885
5	15	1.454	15	0.809
6	Ground plane		Ground plane	
Total thickness (mm)	4.860		4.998	
Maximum reflection coefficient (dB)	–25.485		–24.75	

Table 3. Parameters for the HF2 design.

	Present design		Data from [7]	
Layer	Material	Thickness (mm)	Material	Thickness (mm)
1	16	0.562	14	0.570
2	7	0.897	6	0.766
3	2	0.408	2	0.722
4	15	0.592	15	0.206
5	15	0.111	15	0.304
6	Ground plane		Ground plane	
Total thickness (mm)	2.57		2.57	
Maximum reflection coefficient (dB)	–20.9104		–20.03	

respectively, with incidence angles of 10°, 20°, 30°, and 40°. It can be seen that although the design was optimized for normal incidence case, the same design gives a reflection coefficient less than -20 dB in the desired frequency range (0.5–8 GHz) for the TM polarization with incidence angles up to 30°. For the TE polarization, the response gets

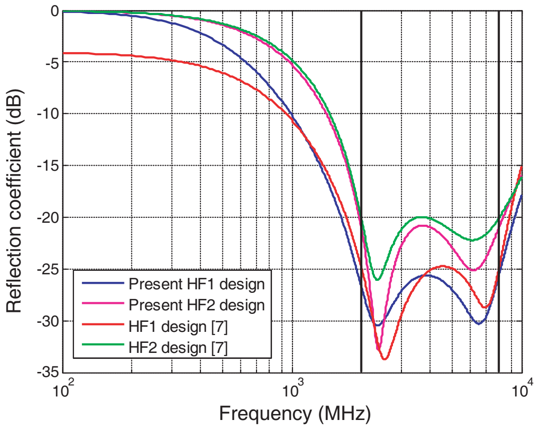

Figure 2. Five-layer absorber optimized for normal incidence for 2–8 GHz frequency range.

Table 4. Parameters for the DES2 design.

	Present design		Data from [7]	
Layer	Material	Thickness (mm)	Material	Thickness (mm)
1	16	0.484	14	0.431
2	6	1.314	6	1.438
3	5	0.517	5	1.143
4	4	1.529	4	0.507
5	5	1.149	4	1.479
6	Ground plane		Ground plane	
Total thickness (mm)		4.993		5.0
Maximum reflection coefficient (dB)	–20.7968		–20.26	

worse as the incidence angle increases. This is in contrary to what was found in [7] for the same design. Specifically, it was shown in Figure 8 in [7] that, for TE polarization, DES2 design has a reflection coefficient less than -20 dB in the desired frequency range for incidence angles from 10° to 40°.

To further validate the results in Figures 4 and 5, the overall

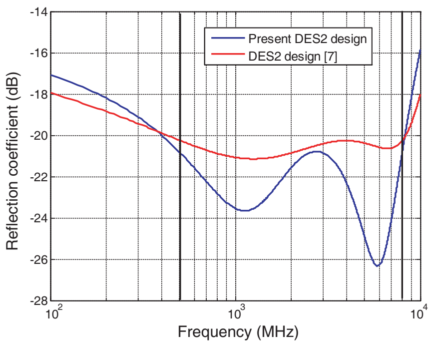

Figure 3. Frequency response of the DES2 design.

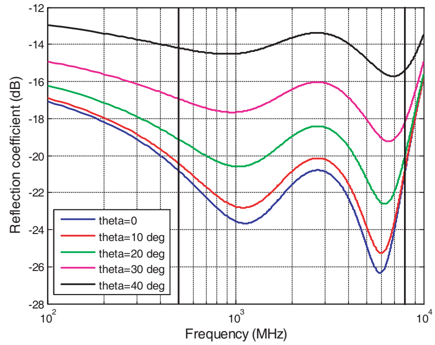

Figure 4. Frequency response of the DES2 design for several angles of incidence for TE polarization.

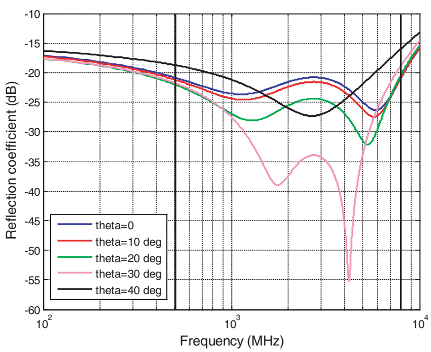

Figure 5. Frequency response of the DES2 design for several angles of incidence for TM polarization.

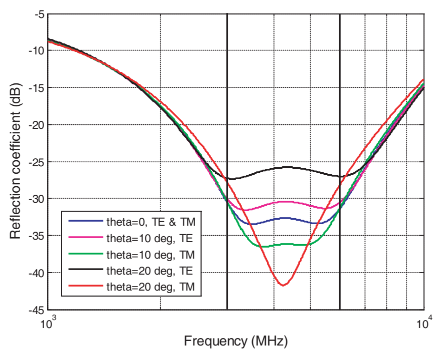

Figure 6. Frequency response of the DES1 design for different angles of incidence for both polarizations.

reflection coefficient has been calculated using the technique presented in [10]. In this technique, the electric and magnetic fields in each layer are expressed as the superposition of forward and backward traveling waves, each with specific unknown amplitude. Then, appropriate boundary conditions (the continuity of tangential electric and magnetic fields components) are enforced at the interfaces between the layers resulting in a set of equations to be solved for the unknown amplitudes. Using this technique, the same results shown in Figures 4 and 5, were obtained.

3.3. Third Example (Design DES1)

In this example, a five layers absorber ($N = 5$) is optimized (for incidence angle $\theta = 10°$) to minimize the reflection coefficient for both polarizations in the frequency range of 3–6 GHz. The maximum total thickness of the absorber was set to 5 mm and the frequency step was taken as 0.5 GHz. Table 5 shows the best results obtained from 20 trials. In addition, for the same design, data from [7] are included in the same table. The obtained maximum reflection coefficient in the desired frequency band is -30 dB as compared to -25.98 dB [7]. Moreover, the present design has a total thickness of 4.3 mm as compared to 6 mm [7]. Figure 6 shows the frequency response of the obtained design for both polarizations for incidence angles of 0, 10°, and 20°. Although the design was optimized for $\theta = 10°$, it also presents very good response for normal incidence and $\theta = 20°$ (reflection coefficient less than -25 dB in the desired frequency range for both polarizations).

Table 5. Parameters for the DES1 design.

	Present design		Data from [7]	
Layer	Material	Thickness (mm)	Material	Thickness (mm)
1	16	0.480	14	0.420
2	7	0.486	6	1.881
3	6	1.791	6	1.743
4	5	1.037	14	1.497
5	14	0.497	2	0.456
6	Ground plane		Ground plane	
Total thickness (mm)		4.291		6.0
Maximum reflection coefficient (dB)	–30.0069		–25.98	

3.4. Fourth Example

In this example, a five layers absorber ($N = 5$) is optimized (for incidence angle $\theta = 45°$) to minimize the reflection coefficient for both polarizations in a very wide frequency range of 2–18 GHz. The maximum total thickness of the absorber was set to 5 mm. Table 6 shows the best results obtained out of 20 trials. The maximum reflection coefficient in the desired frequency band is −12.394 dB. Figure 7 shows the frequency response of the obtained design for both polarizations for incidence angles of 0, 30°, 45° and 60°. Although the design was optimized for $\theta = 45°$, it has been found to give a reflection coefficient less than −10 dB (for both polarizations) for angles of incidence less than 55°.

For the same frequency range (2–18 GHz), similar multilayer

Table 6. Parameters for the fourth example.

Layer	Material	Thickness (mm)
1	16	0.2205
2	6	1.8477
3	16	0.5144
4	1	1.0325
5	13	0.9837
6	Ground plane	
Total thickness (mm)		4.6
Maximum reflection coefficient (dB)	−12.394	

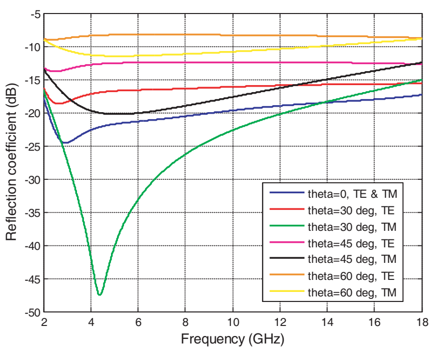

Figure 7. Frequency response for the fourth example for different angles of incidence and polarizations.

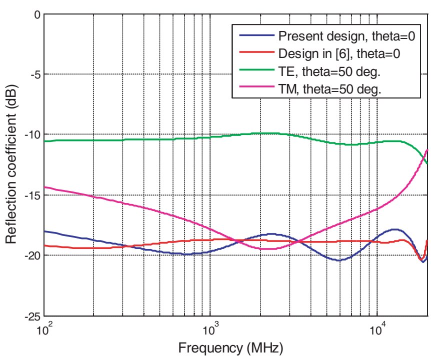

Figure 8. Frequency response for the seven-layer design. For the oblique results, the present design parameters listed in Table 7 are used.

absorbers were designed in reference [4] using the non-dominated sorting genetic algorithm II (NSGA-II). However, a different materials database, which consisted of six lossy materials, was used in [4], and the optimization was performed for angles of incidence ranging from 0 to 89° (i.e., the optimization was not done at a single angle). For an angle of incidence of 60°, some of their designs exhibited a maximum reflection coefficient of −6.75 dB for TE polarization and −8.31 dB for TM polarization in the desired frequency range (2–18 GHz). For the same angle of incidence, within the desired frequency range, the proposed design has a maximum reflection coefficient of −8 dB for TE polarization and −9 dB for TM polarization. According to the literature [4], $\widetilde{R}_{N,N+1}$ was set to −1 for TM polarization which is not in accordance with the value of +1, previously presented in this work (Section 2).

3.5. Fifth Example (Seven-layer Design)

In this example, a seven layers absorber ($N = 7$) is optimized (for normal incidence) to minimize the reflection coefficient in the very wide frequency range of 0.1–20 GHz. Table 7 shows the best results obtained from 20 trials. In addition, for the same design, data from [6] are included in the same table. The obtained maximum reflection coefficient in the desired frequency band is −18 dB as compared to −18.5 dB [6]. However, the present design is thinner than the one presented in [6] which makes it more attractive practically. Specifically, the present design has a total thickness of 6.8 mm as compared to 9.6 mm [6]. Figure 8 shows the frequency response of the present design (for normal incidence) along with the frequency response of the design from [6]. In addition, the frequency responses for both polarizations for an incidence angle of 50° are shown in the same figure. It can be seen that a reflection coefficient better than −10 dB is obtained for both polarizations in the desired frequency band with incidence angles up to 50°. Thus, even though the design was performed to have optimal response for normal incidence, it gives good response for angles of incidence up to 50°. It seems that even if the optimization is performed for oblique incidence case, the results will not be much different from those obtained if the optimization is performed for normal incidence. As a proof of concept, the same seven-layer absorber is optimized to minimize the reflection coefficient (for both polarizations) at $\theta = 50°$ in the frequency band of 0.1–20 GHz. Table 8 shows the obtained parameters for this design. Using the data in this table, Figure 9 shows the obtained frequency responses at $\theta = 50°$ and normal incidence. Even though the optimization was performed at $\theta = 50°$, very good

Table 7. Parameters for the seven-layer absorber optimized for normal incidence case.

	Present design		Data from [6]	
Layer	Material	Thickness (mm)	Material	Thickness (mm)
1	16	0.2064	14	0.21267
2	6	1.8762	6	2.1786
3	14	0.5391	14	0.50102
4	6	0.9499	6	1.1592
5	5	1.9596	5	1.7043
6	4	0.7817	6	2.1965
7	5	0.4864	5	1.6561
8	Ground plane		Ground plane	
Total thickness (mm)		6.8		9.6
Maximum reflection coefficient (dB)	−17.9		−18.5	

Table 8. Parameters for the seven-layer absorber optimized for $\theta = 50°$.

Layer	Material	Thickness (mm)
1	16	0.2282
2	6	1.8034
3	14	0.5566
4	6	0.8822
5	5	1.3564
6	5	1.9424
7	1	0.0105
8	Ground plane	
Total thickness (mm)		6.8
Maximum reflection coefficient (dB)	−10.4	

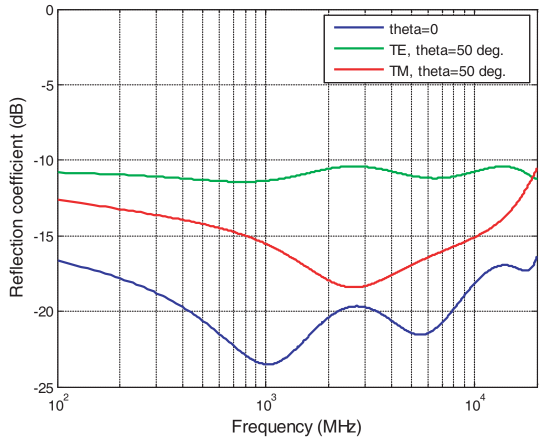

Figure 9. Frequency response for the seven-layer absorber optimized at $\theta = 50°$ (Table 8).

response is still obtained at normal incidence (reflection coefficient less than -16.4 dB in the desired frequency range).

4. CONCLUSIONS

This paper has presented the optimal design of multilayer microwave absorbers using differential evolution (DE) with competitive control-parameter setting technique. It has been emphasized that Chew's recursive formula for the reflection coefficient corresponds to the electric field for the TE case, while it corresponds to the magnetic field for the TM case. A fact that seems to have been neglected in some papers dealing with the same subject. Five different designs have been presented which showed very good frequency response for both polarizations for normal and oblique incidence. The obtained designs are generally better than those published in the literature. Most importantly, a very wideband (0.1–20 GHz), very thin (total thickness of 6.8 mm) seven-layer absorber has been designed with a reflection coefficient better than -10 dB for angles of incidence up to 50° for both TE and TM polarizations.

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