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Particle Swarm Optimization for Optimal Design of Broadband Multilayer Microwave Absorber for Wide Angle of Incidence

Subhanwit Roy, Souptik D. Roy, Jyotirmay Tewary, Ananya Mahanti, and Gautam K. Mahanti*

Abstract—Microwave absorbers find a plethora of applications in the modern-day military and civil industries. This paper compares the performances of different variations of the Particle Swarm Optimization (PSO) algorithm to obtain optimal designs for multilayer microwave absorber over different frequency ranges, angles of incidence and polarizations. The goal of this optimization is to minimize maximum overall reflection coefficient of the absorber by choosing suitable layers of materials from a predefined database and simultaneously make the overall thickness the least practically possible. Numerical optimal results for each variation of the PSO are presented and the best results are compared with those existing in literature.

1. INTRODUCTION

In today's world, zero-reflecting electromagnetic absorbers find their use in a multitude of applications, both military and civil. Militarily, they are often used to suppress radar echoes, muffle radiation from electronic sources and other stealth applications. On the other hand, microwave absorbers have been used to diminish electromagnetic interference between microwave components and electronic components. They also find exciting applications in satellite and mobile phone applications and to reduce background radiation [1]. Historically, one of the earliest implementations of microwave absorbers can be traced back to Sir J. C. Bose who used certain materials to coat the insides of the oscillator tube to avoid unwanted reflections from the inside. He found that blotting paper dipped in electrolyte served as the most effective absorbing material [2, 3]. From such humble origins, the research on microwave absorbers has come a long way, experiencing a paradigm shift toward the latter quarter of the twentieth century, owing to the advent of evolutionary optimization algorithms.

Historically, two forms of microwave absorbers have been developed over the years — the multi-layer absorber and absorbers with frequency selective surface screens (FSSs) [4–6]. Of these, the multi-layer absorber, composed of planar layers of different lossy materials is the more common type [7] and will be taken up in the present research. A third-type of planar absorber was proposed [8], created by texturing on or within the coating of the material, formally called the textured absorber. Ideally, a thin, wide-band microwave absorber with a wide angle of incidence is the optimal design. But these attributes are characteristically conflicting. For instance, it may be possible to develop a low-reflecting absorber having a high thickness and a thin absorber with low reflection suppression.

A large number of factors, such as the frequency of operation, angle of incidence, wave polarization, dielectric constants and permeabilities of the materials, thickness of the layers, have to be taken into consideration when designing an optimum wide-band microwave absorber [9]. The microwave engineer is forced to seek out proper trade-offs between contradictory goals whilst keeping the absorber physically

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* Corresponding author: Gautam Kumar Mahanti (gautammahanti@yahoo.com).
The authors are with the Department of Electronics and Communication Engineering, National Institute of Technology, Durgapur, India.

realizable. Extensive experiments on double-layer microwave absorbers have been carried out in earlier research [10, 11]. But the increase in the number of layers and subsequent advancements in material science have made it difficult to obtain an optimal result using conventional means of optimization. Subsequent research considering a higher number of layers has modeled the subject as an n-dimensional optimization problem for minimizing the reflection coefficient of an incident wave for a large range of frequencies and angles of incidence [12, 13]. Older optimization algorithms, like the simplex method or the simulated annealing method, is known to have a large convergence time, and a tendency to get trapped in local optimization, often resulting in sub-optimal designs [14]. A host of newer, more sophisticated algorithms have been developed, and used in the synthesis of the multi-layer wideband absorber, including the Genetic Algorithm (GA) and its many derivatives [7, 8, 14, 15], Central force Optimization (CFO) [16] and the Self-Adaptive Differential Evolution [17, 18] algorithms. A Modified Multi-Objective Particle Swarm Optimization has found some success in multi-layer microwave absorber design [19, 21], but the study was conducted for normally incident waves on five-layer absorbers.

Chew's recursive formula [12] is used in the estimation of the reflection coefficient of multi-layer structures in some studies for any angle of incidence [14, 18]. Reflection coefficients for both TE and TM polarizations can be evaluated using this formula. For normal incidence, the formula yields the same magnitude for both polarizations, but the fact that a TM polarization corresponds to a magnetic and not an electric field has been disregarded in many studies [14, 17, 20]. Additionally, a large number of investigations only consider normally incident electro-magnetic waves [16, 19, 21] or narrow incident angles [18], which may lead to a synthesis of a sub-optimal absorber for other incident angles. Furthermore, authors of the articles [22–30] discuss the Particle Swarm Optimization (PSO) in details, besides analyzing miscellaneous variations and applications pertaining to the performance of the algorithm.

Optimal designs for five-layer microwave absorbers have been proposed in the present study. The layers were optimized over a wide range of frequencies and incident angles by modified forms of the Single Objective Particle Swarm Optimization algorithm for both TE and TM polarization. A weighted form of the total thickness of the absorber was amalgamated with the reflection coefficient to formulate the objective or cost function to penalize girth in the design. The results obtained are contrasted with the results demonstrated in literature [14] and this comparison proves the efficacy of the proposed technique.

The study is organized as follows. Section 2 illustrates a physical model for the Multilayer Absorber. Section 3 formulates the objective function to be optimized by Particle Swarm Optimization (PSO). A theoretical background on PSO is presented in Section 4, and its application on optimal design of microwave absorbers is given in Section 5. Section 6 delves into the results and subsequent discussions and the concluding arguments are presented in Section 7.

2. PHYSICAL MODEL FOR MULTILAYER ABSORBER

The physical model of a generalized planar stratified microwave absorber with N layers on a substrate of a Perfect Electric Conductor (PEC) has been illustrated with Figure 1. An electromagnetic wave of a particular frequency is obliquely incident from air (mathematically, layer 0) to the first interface of the N-layer absorber at an angle θ with the normal at the point of incidence. The incident wave travels through the N layers of the multilayer absorber; a part of its energy being absorbed by each layer, and is reflected back by the PEC (mathematically, layer $N+1$) which provides an ideal reflection backing.

By the theory of transmission lines [12], the generalized reflection coefficient [16, 18] between any two layers of the absorber can be calculated using the following algorithm:

$$R_{i,i+1} = \frac{\rho_{i,i+1} + R_{i+1,i+2} \exp\left(-2jk_{i+1}d_{i+1}\right)}{1 + \rho_{i,i+1} R_{i+1,i+2} \exp\left(-2jk_{i+1}d_{i+1}\right)} \tag{1}$$

where,
For TM (parallel) polarization:

$$\rho_{i,i+1} = \frac{\varepsilon_{i+1}k_i - \varepsilon_i k_{i+1}}{\varepsilon_{i+1}k_i + \varepsilon_i k_{i+1}}, \quad i < N \tag{2}$$

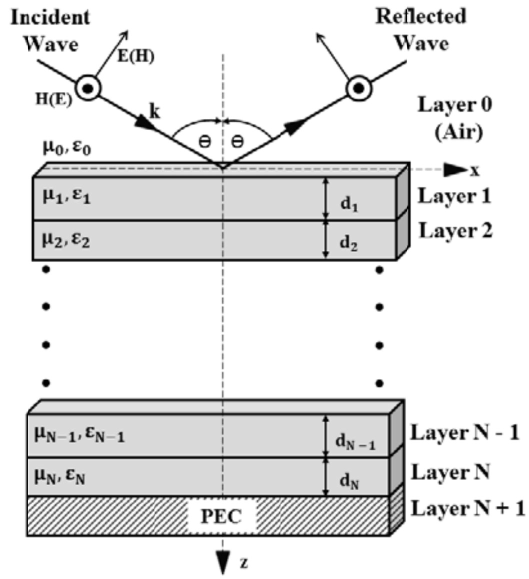


Figure 1. Generalized physical model of multilayer microwave absorber.

For TE (perpendicular) polarization:

$$\rho_{i,i+1} = \frac{\mu_{i+1}k_i - \mu_i k_{i+1}}{\mu_{i+1}k_i + \mu_i k_{i+1}}, \quad i < N \tag{3}$$

In the above equations, ε_i and μ_i, respectively represent the frequency dependent complex permittivity and permeability of the ith layer, and k_i denotes the wave number of the ith layer, given by Snell's law as follows:

$$k_i = \omega\sqrt{\mu_i\varepsilon_i - \mu_0\varepsilon_0\sin^2\theta} \tag{4}$$

In Equation (4), ω symbolizes the frequency of the incident wave whereas ε_0 and μ_0 denote the permittivity and permeability of free space respectively, i.e.,

$$\varepsilon_0 = 8.854 * 10^{-12}\frac{F}{m} \tag{5}$$

and

$$\mu_0 = 4\pi * 10^{-7}\frac{H}{m} \tag{6}$$

The reflection coefficient of the last interface, i.e., the reflection coefficient between the last layer of the multilayer absorber and the PEC ($R_{N,N+1}$), is set to +1 for TM polarization whereas it is set to −1 for TE polarization. This is done in agreement with the fact that for normal incidence, both TE as well as TM polarizations yields the same magnitude of the reflection coefficient [18]. Several papers [14, 17, 20] have wrongfully set the $R_{N,N+1} = -1$ for both types of polarization, leading to two different values for the magnitude of the absorber reflection coefficient.

Having the knowledge of the reflection coefficient of the last interface ($R_{N,N+1}$), the material permittivity (ε_i), permeability (μ_i) and the thickness (d_i) in millimeters of each layer, the total reflection coefficient of the multilayer absorber, i.e., the reflection coefficient of the first interface ($R_{0,1}$) can be computed recursively, using Equations (1)–(6).

3. PROBLEM FORMULATION

The primary objective of this paper is to obtain a set of layers from a predefined database of various materials with varied electrical properties, which would minimize the overall maximum reflection coefficient ($R_{0,1}$) of the microwave absorber over a wide band of frequencies, for a particular angle of incidence and polarization. Simultaneously, it is desired that the total thickness of the absorber be as less as possible. These two design considerations are incorporated in the form of the following objective function for the purpose of optimization:

$$\text{minimum } F = \zeta_1 * 20\log_{10}\left(\max\left(|R_{0,1}|\right)\right) + \zeta_2 * \sum\nolimits_{i=1}^{N} d_i \tag{7}$$

Mathematically, the above objective function attempts to minimize the weighted sum of overall maximum reflection coefficient of the microwave absorber over a particular frequency range, for a given angle of incidence and polarization, with the sum of all the individual layer thicknesses in meters. In Equation (7), ζ_1 and ζ_2 are weighting constants emphasizing each of the term associated with it.

In our study, different variations of the Particle Swarm Optimization (PSO) have been implemented in order to obtain optimal designs for wideband multilayer absorbers for different angles of incidence and TM or TE polarization.

4. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization [22–30] is an evolutionary algorithm which is based on the collaborative manner in which a swarm of insects, a herd of animals, a flock of birds, or a school of fish search for food. Each member in a swarm alters its pattern for search of food not only by using its own experience but also taking into account the experiences of fellow swarm members. In the subsequent mathematical modeling of the phenomenon, each member in a swarm is referred to as a particle and it denotes a potential solution, a point in the D-dimensional search space. The model further manifests the location of food as the global optimum. The flying direction of a particle is adjusted by its fitness value and velocity which are, according to the algorithm, determined by the best experiences of the entire swarm. The PSO algorithm [28] is easy to execute and it has been seen to perform well on a plethora of optimization problems.

An eclectic mix of difficult multidimensional optimization problems can be solved efficiently by using the PSO algorithm. Introduced by Kennedy and Eberhart [22] in 1995, the PSO has experienced a burgeoning popularity as an effective alternative to more inveterate algorithms like GA, ACO, SA, etc. for solving optimization problems in antenna arrays and microwave engineering.

The PSO algorithm used in this research is a real-coded one. The fundamental steps involved in this algorithm [28] are given below. Some texts and equations in regard to PSO are taken from [28] and reproduced above and below.

Step 1: The algorithm is run for N independent trials and each time a different initial population (potential solutions) is used. At the commencement of each trial, the algorithm randomly generates an initial population ($P * D$) of P particles (individuals) and D dimensions with every particle within the variable constraint range.

Step 2: For each particle in the population, the position and associated velocity are randomly initialized in the D-dimensional search space.

Step 3: The fitness value is evaluated for each particle in the D-dimensional search space.

Step 4: The personal best (*pbest*) of each particle is compared with its current fitness value. If the current fitness value is found to be better, then the current fitness value is assigned to *pbest* and the current coordinates are allocated to *pbest* coordinates.

Step 5: The current best fitness value in the entire population and its coordinates are determined. If the current best fitness value is found to be better than global best (*gbest*), the current fitness value is assigned to *gbest* and the current coordinates are allocated to *gbest* coordinates.

Step 6: Velocity (V_{id}) and position (X_{id}) of the d-th dimension of the i-th particle are updated using the following set of equations:

$$V_{id}^{t} = w * V_{id}^{t-1} + c_1 * rand1_{id}^{t} * \left(pbest_{id}^{t-1} - X_{id}^{t-1}\right) + c_2 * rand2_{id}^{t} * \left(gbest_{d}^{t-1} - X_{id}^{t-1}\right) \tag{8}$$

$$V_{id}^{t} = \min\left(V_{\max}^{d}, \max\left(V_{\min}^{d}, V_{id}^{t}\right)\right) \tag{9}$$

$$X_{id}^{t} = X_{id}^{t-1} + V_{id}^{t} \tag{10}$$

If $X_{id}^t > X_{\max}^d$, then,

$$X_{id}^t = X_{\min}^d + rand3_{id}^t * \left(X_{\max}^d - X_{\min}^d\right) \tag{11}$$

If $X_{id}^t < X_{\min}^d$, then,

$$X_{id}^t = X_{\min}^d + rand4_{id}^t * \left(X_{\max}^d - X_{\min}^d\right) \tag{12}$$

where c_1, c_2 = acceleration constants, w = inertia weight, *rand1*, *rand2*, *rand3* and *rand4* denote uniform random numbers [23] between 0 and 1, different value in different dimension, and t represents the current iteration number.

Equations (9), (11) and (12) have the functions of clamping the velocity and position along each dimension to ($V_{\max}^d$, X_{id}^t) and ($V_{\min}^d$, X_{id}^t) value if they attempt to cross the desired domain of interest. These clipping techniques also help prevent the particles from explosion. The maximum velocity is set to the upper limit of the dynamic range of the search ($V_{\max}^d = X_{\max}^d$), whereas the minimum velocity ($V_{\min}^d$) is set to ($-V_{\max}^d$).

Step 7: Steps 3–6 are repeated until a stop criterion is satisfied or a predefined maximum number of iteration is completed. The latter usually happens when there is no further update of the best fitness value.

Step 8: Steps 1–7 are repeated until the stopping criterion, i.e., a predefined number of maximum trials (N) being completed, is satisfied. The best scoring individual among the N_{gbest} individuals (one *gbest* individual for each trial) considering all the trials is taken as the final answer. The mean, standard deviation and worst scoring individual of all N_{gbest} values are finally computed.

5. APPLICATION OF PSO FOR OPTIMAL DESIGN OF MICROWAVE ABSORBER

For this research, three different variations of the Particle Swarm Optimization (PSO) algorithm have been considered, namely Case 1, Case 2 and Case 3, based on the strategies determining the variation of acceleration constants, inertia weight and maximum particle velocity with iteration. An initial population of 30 particles with 10 dimensions has been considered.

- **Case 1**
  Both the acceleration constants c_1 and c_2 are set to a value of 1.4945 and it is kept fixed over every iteration. The inertia weight, w is fixed at a constant value of 0.8 [28]. Maximum particle velocity is also kept constant for all iterations.
- **Case 2**
  The acceleration constant c_1 is made to decrease linearly from 2.5 to 1.5 over the span of maximum number of iterations, while, the acceleration constant c_2 is made to increase linearly from 1.5 to 2.5. The inertia weight, w is made to damp linearly from a value of 0.9 to 0.2 with iterations [29], over the first 80% of the total number of iterations and is sustained at 0.2 for the remaining number of iterations. Similar to Case 1, maximum particle velocity is kept constant for all iterations.
- **Case 3**
  This case follows similar strategies to Case 2 as far as varying acceleration constants c_1 and c_2, and inertia weight w are concerned. In this modified PSO, velocity clipping technique is applied withtime-varying maximum velocity, which decreases linearly from $V_{\max}^d$ to $0.1 * V_{\max}^d$ over the full range of search, because as the particles approach the optimal result it is preferred to have them move with lower velocities [30].

The above three modified PSO algorithms are separately applied to minimize the objective function (7), and thus arrive at an optimal design of a microwave absorber, for arbitrary angle of incidence and polarization, using materials from a predefined database, whose electrical properties are listed in Table 1. The database contains 16 different materials: lossless dielectric materials, lossy magnetic materials, lossy dielectric materials and relaxation-type magnetic materials, which are exemplary of a wide class of materials typically used in literature for microwave absorber design [18]. With reference to Table 1, the following formulae apply for the calculation of real and imaginary parts of the complex permeabilities and permittivities for different types of materials:

Table 1. Predefined database of materials [18].

Lossless dielectric materials				
Material No.	μ'	μ''	ε'	ε''
1	1	0	10	-
2			50	-

Lossy magnetic materials						
Material No.	μ' (1 GHz)	μ'' (1 GHz)	ε'	ε''	a	b
3	5	10	15	0	0.974	0.961
4	3	15			1.000	0.957
5	7	12			1.000	1.000

Lossy dielectric materials						
Material No.	μ'	μ''	ε' (1 GHz)	ε'' (1 GHz)	a	b
6	1	0	5	8	0.861	0.569
7			8	10	0.878	0.682
8			10	6	0.878	0.861

Relaxation-type magnetic materials				
Material No.	μ_m	f_m	ε'	ε''
9	35	0.8	15	0
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		

1) Lossy Magnetic Materials:

$$\mu'(f) = \frac{\mu'(1\,\text{GHz})}{f^a} \tag{13}$$

$$\mu''(f) = \frac{\mu''(1\,\text{GHz})}{f^b} \tag{14}$$

2) Lossy Dielectric Materials:

$$\varepsilon'(f) = \frac{\varepsilon'(1\,\text{GHz})}{f^a} \tag{15}$$

$$\varepsilon''(f) = \frac{\varepsilon''(1\,\text{GHz})}{f^b} \tag{16}$$

3) Relaxation-Type Magnetic Materials:

$$\mu'(f) = \frac{\mu_m f_m^2}{f^2 + f_m^2} \tag{17}$$

$$\mu''(f) = \frac{\mu_m f_m f}{f^2 + f_m^2} \tag{18}$$

Finally, the complex permeabilities and permittivities can be calculated as:

$$\mu = \mu' - j\mu'' \tag{19}$$

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{20}$$

where j stands for the imaginary number $\sqrt{-1}$; f denotes frequency; a and b are the decay coefficients.

The performance of each of the three cases for the optimization problem in hand is compared, and these results are further compared with those presented in [14].

6. RESULTS AND DISCUSSIONS

For each layer, the maximum thickness is set to 1.5 mm. For every case, the PSO is run for 20 independent trials, and each time, the maximum number of iterations is set to 700. A population of 30 particles with 10 dimensions is considered. All calculations are executed on a personal computer with Intel® Core™ i5-3210M processor (CPU 2.50 GHz) and 8.0 GB RAM.

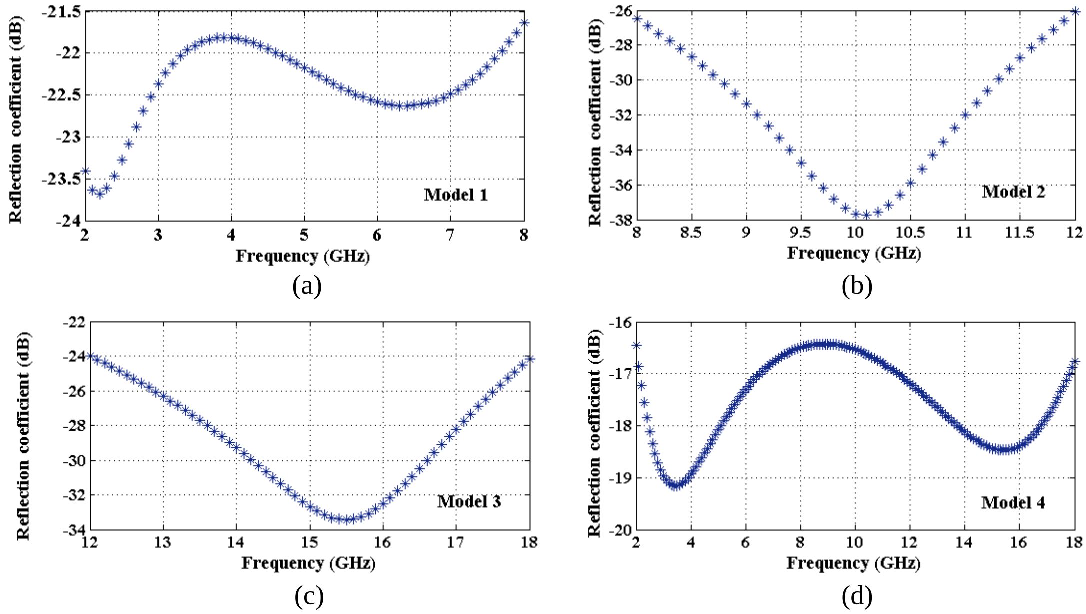


Figure 2. Reflection coefficient vs frequency for normal incidence (Models 1, 2, 3 and 4). (a) Reflection coefficient vs frequency for normal incidence and frequency range 2–8 GHz (S and C bands). (b) Reflection coefficient vs frequency for normal incidence and frequency range 8–12 GHz (X bands). (c) Reflection coefficient vs frequency for normal incidence and frequency range 12–18 GHz (Ku bands). (c) Reflection coefficient vs frequency for normal incidence and frequency range 2–18 GHz (broadband).

Table 2. Parameters for microwave absorber designs for normal incidence (Models 1–4).

Layer	**Model 1 (2–8 GHz)**		**Model 2 (8–12 GHz)**		**Model 3 (12–18 GHz)**		**Model 4 (2–18 GHz)**	
	Material No.	**Thickness in mm**	**Material No.**	**Thickness in mm**	**Material No.**	**Thickness in mm**	**Material No.**	**Thickness in mm**
1	**16**	**0.4254**	**16**	**0.2769**	**16**	**0.2140**	**16**	**0.3038**
2	**8**	**1.4662**	**6**	**1.4678**	**7**	**0.3456**	**6**	**1.0370**
3	**5**	**1.2021**	**6**	**0.8269**	**6**	**1.1166**	**5**	**0.8976**
4	**11**	**0.8465**	**13**	**0.8937**	**5**	**1.2286**	**9**	**0.8011**
Maximum Reflection Coefficient (dB)	−21.6397		−26.1052		−23.9903		−16.4254	
Total thickness (mm)	3.8403		3.3653		2.9048		3.0395	
Data from [14]								
Maximum Reflection Coefficient (dB)	−5.91		−17.02		−13.81		-	
Total thickness (mm)	6.0582		4.1933		3.1387		-	

6.1. Normal Incidence

Keeping in view the various requirements in practical applications, first of all, three four-layer microwave absorbers are optimized using PSO Case 1 for normal incidence (angle of incidence 0°), in order to minimize the overall reflection coefficient for three popular frequency bands; 2–8 GHz (S and C bands), 8–12 GHz (X band), and 12–18 GHz (Ku band), with a frequency increase of 0.1 GHz at each step, named Model 1, Model 2 and Model 3 respectively for convenience. Furthermore, a four-layer absorber is optimized for normal incidence over the wideband range of 2–18 GHz, with a frequency increase of 0.1 GHz at each step (Model 4). As discussed in Section 2, it is not necessary to specify the type of polarization for normal incidence, as both TM as well as TE polarizations yields the same value of maximum reflection coefficient. In the objective function (7), weight constants ζ_1 and ζ_2 are set to 1

Table 3. Parameters for microwave absorber designs for normal incidence (Models 1–4).

Model No.	**Case 1**				**Case 2**				**Case 3**				**Winner**
	gbestval	Worst	SD	Mean	gbestval	Worst	SD	Mean	gbestval	Worst	SD	Mean	
5	−15.89	−4.02	0.81	−14.45	−15.41	−3.93	0.46	−14.56	−15.55	−2.33	2.79	−5.83	Case 1
6	−10.47	−1.72	0.27	−10.05	−11.72	−1.87	0.36	−11.15	−11.06	−1.49	2.06	−3.79	Case 2
7	−18.75	−5.77	0.85	−17.03	−22.68	−4.01	1.09	−20.05	−19.89	−2.53	3.66	−7.49	Case 2
8	−8.45	−0.84	0.28	−7.69	−8.81	−0.93	0.36	−8.23	−8.11	−0.58	1.61	−2.61	Case 2
9	−18.44	0.47	1.62	−14.95	−25.11	−6.61	2.32	−24.85	−24.87	−4.54	4.09	−9.25	Case 2
10	−5.08	−0.30	0.31	−4.29	−5.20	0.08	0.23	−4.78	−4.80	0.60	1.15	−1.06	Case 2
11	−19.79	−3.45	0.83	−18.31	−22.24	−1.67	0.85	−20.23	−18.39	−2.35	3.47	−6.53	Case 2
12	−1.24	1.03	0.09	−1.02	−1.53	0.92	0.08	−1.31	−1.40	1.60	0.67	0.63	Case 2

Table 4. Parameters for microwave absorber designs for oblique incidence (Models 5–8).

Layer	**Model 5 (30°, TM)**		**Model 6 (30°, TE)**		**Model 7 (45°, TM)**		**Model 8 (45°, TE)**	
	Material No.	**Thickness in mm**	**Material No.**	**Thickness in mm**	**Material No.**	**Thickness in mm**	**Material No.**	**Thickness in mm**
1	16	0.2229	16	0.2390	16	0.1281	16	0.2658
2	6	1.2227	6	0.9506	6	1.3913	6	0.6955
3	8	0.5835	6	0.8465	14	0.2776	6	0.1495
4	11	0.6624	16	0.2989	4	0.8273	6	1.3844
5	9	0.8230	13	1.3344	4	1.3177	14	0.9434
Maximum Reflection Coefficient (dB)	−19.3096		−15.3938		−26.5192		−12.2444	
Total thickness (mm)	3.4144		3.6694		3.8420		3.4387	
Data from [14]								
Maximum Reflection Coefficient (dB)	−6.92		−6.88		−6.86		−7.14	
Total thickness (mm)	5.0675		4.4097		5.0572		5.2670	

and 1000 respectively.

Figures 2(a)–(d) illustrate the reflection coefficient versus frequency curves for each of the above designs. The obtained results are presented in Table 2 alongside those given in literature [14]. It is apparent from Table 2 that the designs obtained through this experiment are superior to the designs attained in [14] in terms of both overall maximum reflection coefficient and total thickness of absorber coating. The results are indicative of the intrinsic absorbing characteristics of lossy materials.

6.2. Oblique Incidence

Case 1, Case 2 and Case 3 of PSO are separately implemented for optimizing the design of a five-layer microwave absorber over the wideband frequency range of 2–18 GHz, at a step increase of 0.1 GHz, for different angles of incidence and polarizations. For this study, four different angles of incidence, viz. 30°, 45°, 60° and 75° are used for both TM and TE polarizations. In the objective function (7), weight constants ζ_1 and ζ_2 are set to 1 and 1000 respectively for all but two instances.

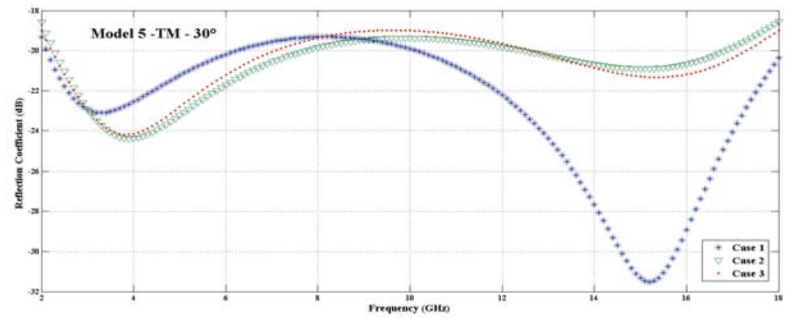
For the purpose of carrying out calculations for angle of incidence 60° and TM polarization, ζ_1 is set to 1 whereas ζ_2 is set to 4000 and 3000 for Case 2 and Case 3, respectively. This is done to somewhat compromise the value of the overall maximum reflection coefficient in order to accommodate for a thinner absorber.

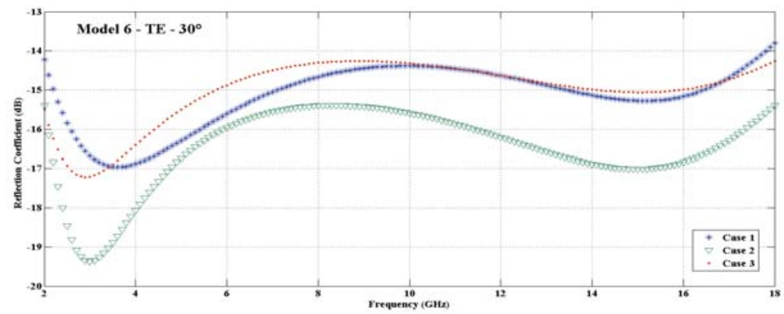
Figures 3(a)–(h) illustrate the reflection coefficient versus frequency curves for each of the above designs. It can be observed that for the same angle of incidence, at a particular frequency, TM and TE polarized waves give very different values of maximum reflection coefficient. Also, diverse characteristics are obtained for incident waves with same polarization but different angles of incidence.

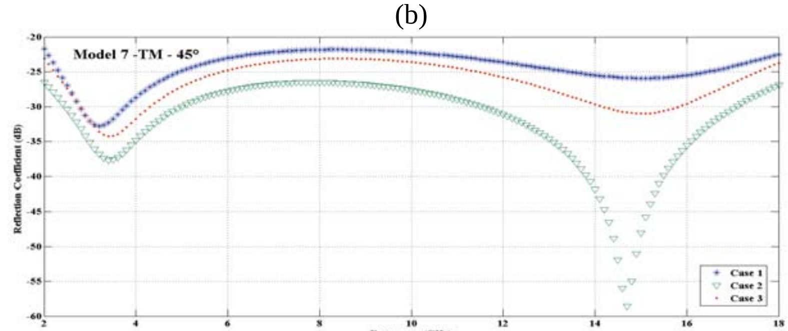
The obtained best fitness value (gbestval), worst fitness value, standard deviation of gbestval and mean gbestval, for each of the eight designs (Models 5–12) are presented in Table 3. It shows that for Model 5, Case 1 of PSO gives the most optimal design whereas Case 2 comes out to be the clear

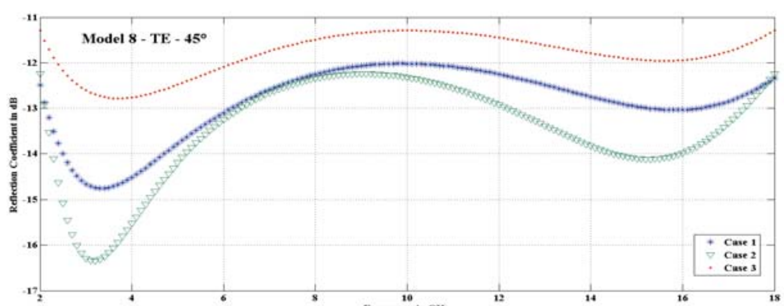
Table 5. Parameters for microwave absorber designs for oblique incidence (Models 9–12).

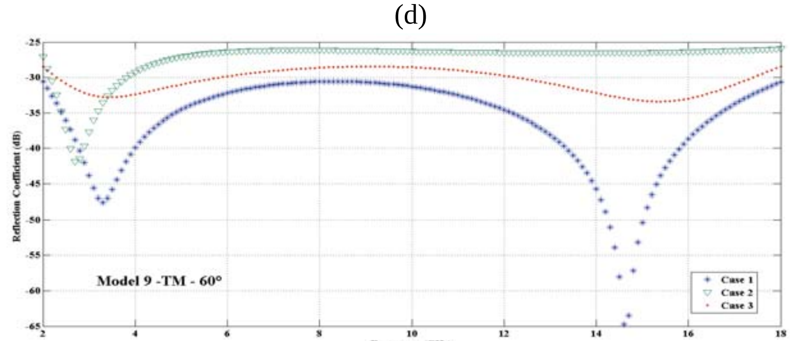
Layer	Model 9 (60°, TM)		Model 10 (60°, TE)		Model 11 (75°, TM)		Model 12 (75°, TE)	
	Material No.	Thickness in mm	Material No.	Thickness in mm	Material No.	Thickness in mm	Material No.	Thickness in mm
1	7	0.8905	16	0.2702	7	0.4359	16	0.4026
2	11	0.2908	8	0.6144	12	0.6174	6	0.4069
3	6	0.9019	6	0.2580	2	1.4350	2	0.4164
4	7	0.5407	6	1.3561	12	0.4009	5	0.1018
5	4	0.4115	14	0.8383	4	0.2459	14	0.3559
Maximum Reflection Coefficient (dB)	−29.1497		−8.5332		−25.3794		−3.2196	
Total thickness (mm)	4.0354		3.3370		3.1351		1.6837	
Data from [14]								
Maximum Reflection Coefficient (dB)	−8.31		−6.75		−9.06		−6.64	
Total thickness (mm)	4.0363		5.4854		4.4675		5.2697	

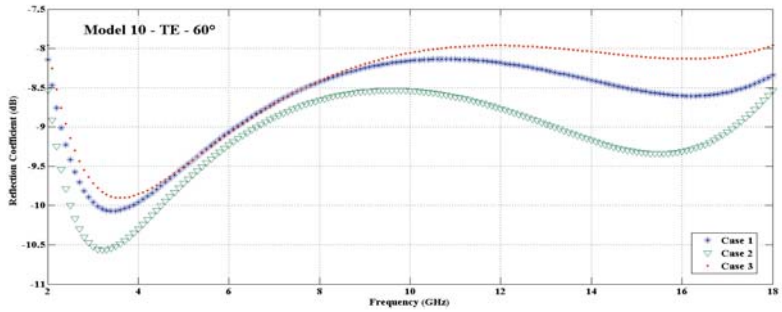

Model 5 -TM - 30°
Reflection Coefficient (dB)
Frequency (GHz)
Case 1
Case 2
Case 3
(a)


Model 6 - TE - 30°
Reflection Coefficient (dB)
Frequency (GHz)
Case 1
Case 2
Case 3
(b)

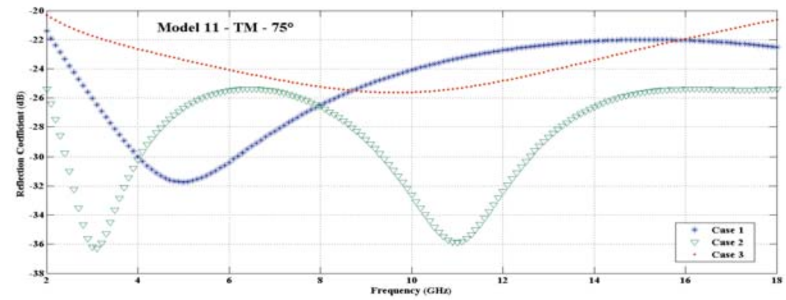

Model 7 -TM - 45°
Reflection Coefficient (dB)
Frequency (GHz)
Case 1
Case 2
Case 3
(c)


Model 8 - TE - 45°
Reflection Coefficient in dB
Frequency in GHz
Case 1
Case 2
Case 3
(d)

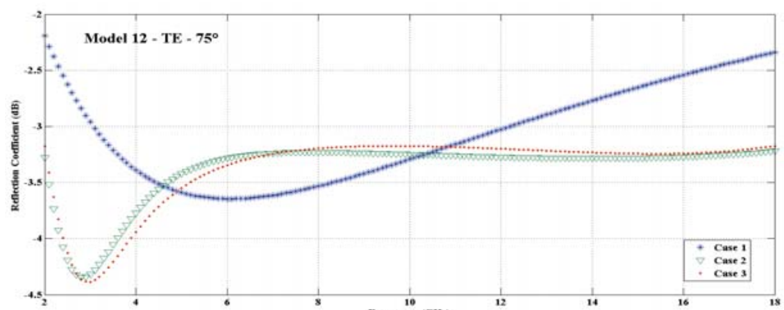

Model 9 -TM - 60°
Reflection Coefficient (dB)
Frequency (GHz)
Case 1
Case 2
Case 3
(e)



(f)



(g)

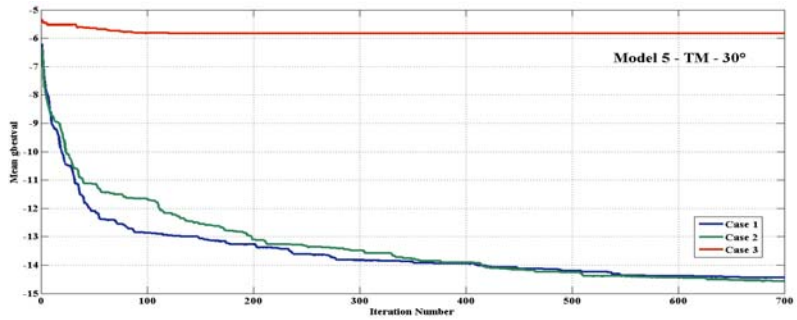


(h)

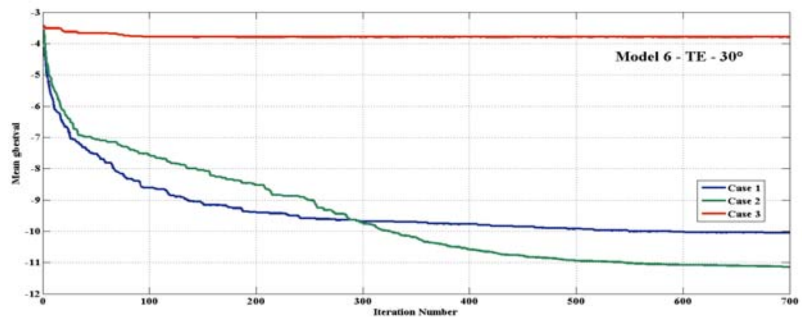
Figure 3. (a) Reflection coefficient vs frequency for angle of incidence 30° and TM polarization (Model 5). (b) reflection coefficient vs frequency for angle of incidence 30° and TE polarization (Model 6). (c) Reflection coefficient vs frequency for angle of incidence 45° and TM polarization (Model 7). (d) Reflection coefficient vs frequency for angle of incidence 45° and TE polarization (Model 8). (e) Reflection coefficient vs frequency for angle of incidence 60° and TM polarization (Model 9). (f) Reflection coefficient vs frequency for angle of incidence 60° and TE polarization (Model 10). (g) Reflection coefficient vs frequency for angle of incidence 75° and TM polarization (Model 11). (h) Reflection coefficient vs frequency for angle of incidence 75° and TE polarization (Model 12).

winner in all other situations. The variation of the mean gbestval with iteration for each case is shown in Figures 4(a)–(h). Tables 4 and 5 compare the best results for each of the models with those in literature [14]. In Tables 3, 4 and 5, Models 5–12 represent the optimal designs for angle of incidence 30° and TM polarization, angle of incidence 30° and TE polarization, angle of incidence 45° and TM polarization, angle of incidence 45° and TE polarization, angle of incidence 60° and TM polarization, angle of incidence 60° and TE polarization, angle of incidence 75° and TM polarization, and angle of incidence 75° and TE polarization respectively.

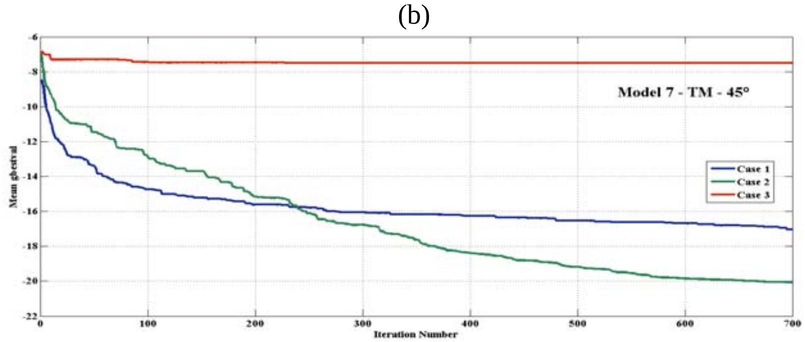
Seven of the eight optimal designs obtained through this work outperform the designs presented in [14] in terms of both maximum reflection coefficient and overall thickness. Only Model 12 fails to better the result of its counterpart in [14].


Model 5 - TM - 30°
Mean gbestval
Iteration Number
Case 1
Case 2
Case 3

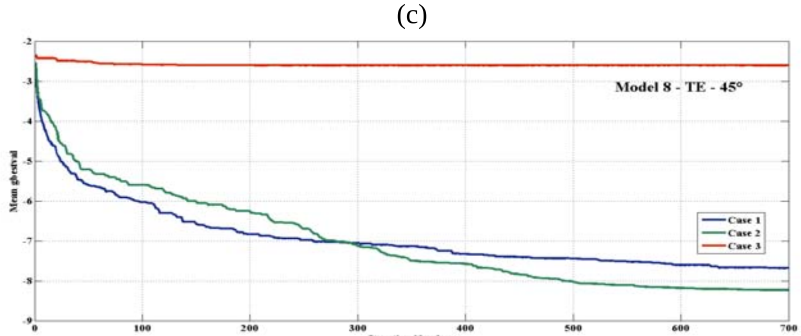
(a)


Model 6 - TE - 30°
Mean gbestval
Iteration Number
Case 1
Case 2
Case 3

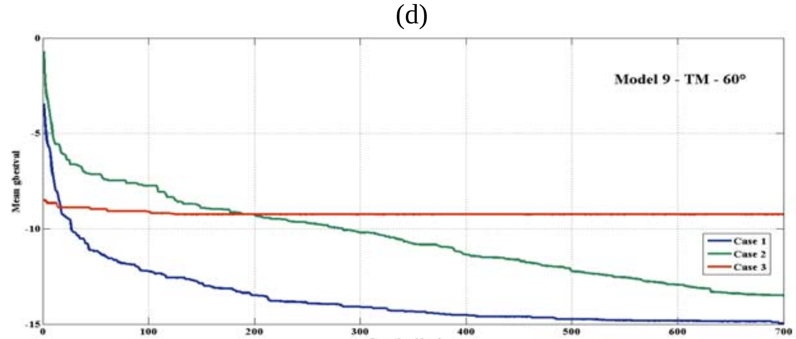
(b)


Model 7 - TM - 45°
Mean gbestval
Iteration Number
Case 1
Case 2
Case 3

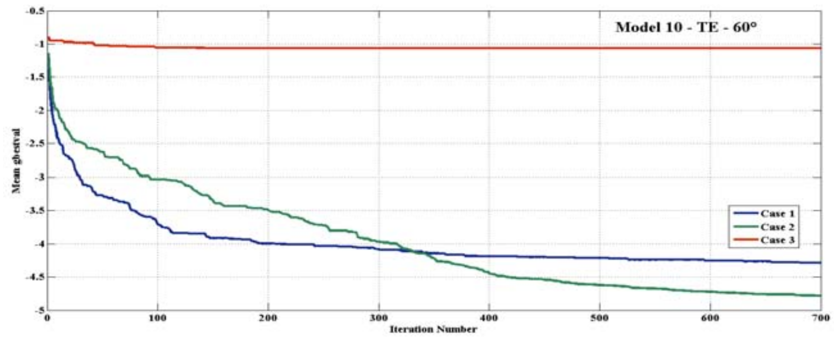
(c)


Model 8 - TE - 45°
Mean gbestval
Iteration Number
Case 1
Case 2
Case 3

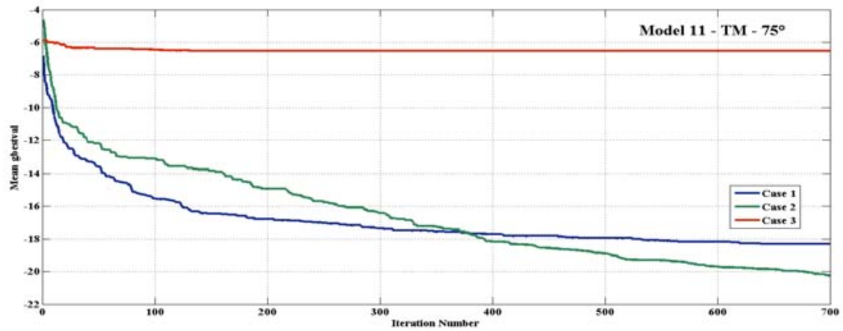
(d)


Model 9 - TM - 60°
Mean gbestval
Iteration Number
Case 1
Case 2
Case 3

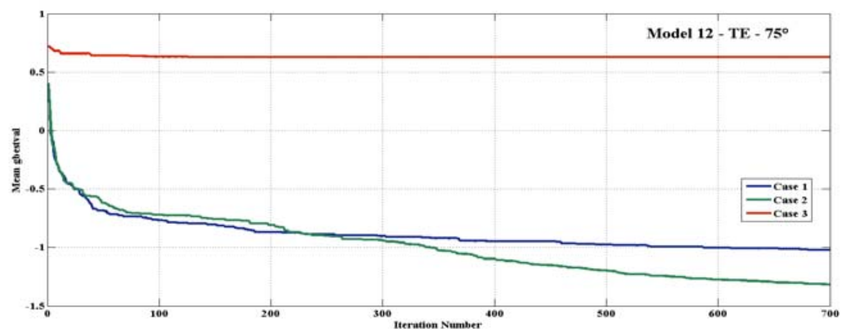
(e)



(f)



(g)



(h)

Figure 4. (a) Mean of best fitness value versus iteration (Model 5). (b) Mean of best fitness value versus iteration (Model 6). (c) Mean of best fitness value versus iteration (Model 7). (d) Mean of best fitness value versus iteration (Model 8). (e) Mean of best fitness value versus iteration (Model 9). (f) Mean of best fitness value versus iteration (Model 10). (g) Mean of best fitness value versus iteration (Model 11). (h) Mean of best fitness value versus iteration (Model 12).

7. CONCLUSIONS

This paper has focused on the use of Particle Swarm Optimization (PSO) for the optimal design of multilayer microwave absorber. It has been emphasized that Chew's recursive algorithm for computing reflection coefficient corresponds to the magnetic field for TM (parallel) polarization, whereas it is consistent with the electric field for TE (perpendicular) polarization, a fact blatantly ignored in many papers dealing with the same problem. Various absorber designs have been obtained for a wideband frequency range, with both normal and oblique incidences and both polarizations. The resultant microwave absorber models have generally been found to be ultrathin and have a better frequency response than those published in literature.

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