Comparison of Evolutionary Algorithms for Optimal Design of Broadband Multilayer Microwave Absorber for Normal and Oblique Incidence

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Abstract **─** Microwave absorbers have emerged as an indispensable industrial apparatus in today's world, owing to their multitude of uses, both civil as well as military. This paper focuses on the use of three evolutionary algorithms, namely, particle swarm optimization, bat algorithm and cuckoo search algorithm for the purpose of obtaining optimal designs of seven layer microwave absorbers over a wide frequency range, and both cases of normal and oblique incidence. The resultant optimal designs are compared in terms of maximum reflection coefficient and total thickness with those presented in existing literature.

Index Terms **─** Bat algorithm, Chew's recursive formula, cuckoo search algorithm, multilayer microwave absorber, particle swarm optimization, polarization.

I. INTRODUCTION

Right from its conception in the early 20th century, and its subsequent application in Sir J. C. Bose's oscillators [1], electromagnetic absorbers have found their use in a variety of applications, from suppressing radar echoes to reduction of background radiation in cellular telephone applications. Traditionally, three forms of microwave absorbers are available in literature, the multilayer absorber [2], the FSS (frequency selective surface screen)-coated absorber [3] and the textured absorber [4], of which, the multilayer absorber is the more common one [5] and will be taken up in this study.

The problem of creating the perfect magnetic insulator revolves around its capability of suppressing magnetic radiation from a wide spectrum of frequencies, over an extensive range of incident angles, and meanwhile keeping the absorber thin enough to be physically realizable. Over the years, primitive optimization algorithms like the simplex method or the simulated annealing method have been used, but they are notorious for getting trapped in local minima, yielding sub-optimal results [6]. Recently, several nature-inspired metaheuristic algorithms have been used for optimization purposes, most notably the genetic algorithm [5], the particle swarm optimization [6] and the differential evolution [7] and being some of them.

This paper proposes the use of three evolutionary algorithms, viz. particle swarm optimization (PSO) [8], bat algorithm (BAT) [9] and cuckoo search algorithm (CSA) [10] to design optimal wideband seven-layer microwave absorbers for both normal incidence as well as a particular case of oblique incidence (angle of incidence 50°). The results obtained by the three algorithms are contrasted with one another and these are further compared with those demonstrated in literature [7]. Performance of the three different evolutionary algorithms, namely PSO, BAT and CSA is compared in terms of maximum reflection coefficient and statistical parameters like mean, standard deviation, best and worst value of fitness function.

II. PROBLEM FORMULATION

The physical model of a generalized planar stratified microwave absorber with N layers on a substrate of a perfect electric conductor (PEC) has been shown in Fig. 1. The overall reflection coefficient between air and the microwave absorber can be calculated by recursively using Chew's algorithm [2]:

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

where,

For TM (parallel) polarization:

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

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 i^{th} layer, and k_i denotes the wave number of the i^{th} 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.

Mathematically, i = 0 represents air, $i = N + 1$ represents PEC for an ideal reflection backing, and $R_{0,1}$

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denotes the reflection coefficient at the first interface; i.e., the overall reflection coefficient of the multilayer microwave absorber. The reflection coefficient of the last interface, i.e., $R_{N,N+1}$, is set to +1 and -1 for TM and TE polarizations respectively; a fact blatantly ignored by many papers in existing literature [7].

The primary objective of this paper is to obtain a set of layers of various thicknesses from a predefined database of sixteen different materials with varied electrical properties, which would minimize the overall maximum reflection coefficient (in decibels) of the microwave absorber over a wide band of frequencies, for a particular angle of incidence and polarization. Hence, the following objective function is used for optimization:

$$minimum\ F = 20log_{10}\left(\max\left(\left|R_{0,1}\right|\right)\right). \qquad (5)$$

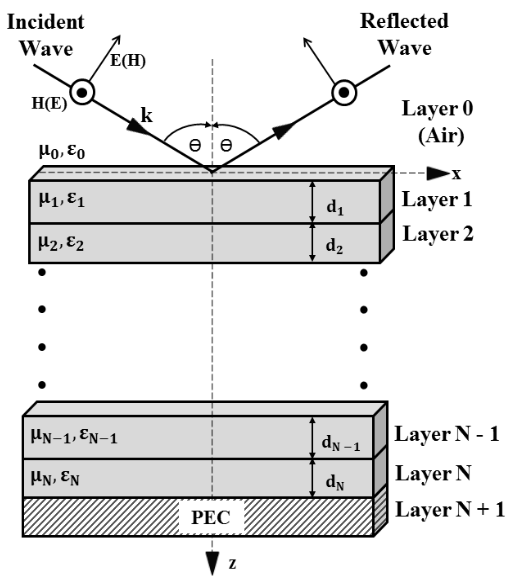


Fig. 1. Physical model of multilayer microwave absorber.

III. APPLICATION OF EVOLUTIONARY ALGORITHMS FOR OPTIMAL MULTILAYER ABSORBER DESIGN

In this paper, two different seven layer microwave absorber design problems have been considered, one for oblique incidence at an angle of incidence 50° with the normal at the point of incidence (Model 1) for TE polarization, and another for normal incidence (Model 2). By the theory of transmission lines, both TM and TE polarizations yield the same value of reflection coefficient for normal incidence [7]. As discussed in Section I, the following three evolutionary algorithms have been used for the above optimization problem.

A. Particle swarm optimization (PSO)

Introduced in 1995, particle swarm optimization emulates the swarm intelligence of bees for finding food sources in order to solve optimization problems of interest. Details about the algorithm can be found in literature [8].

For this study, an initial population of 30 particles with 14 dimensions has been considered. The two acceleration constants are linear decreased and increased respectively between 2.5 and 1.5 and vice versa. The inertia weight is linearly damped from 0.9 to 0.2 over 80% of maximum iterations and then sustained at a value of 0.2. Maximum particle velocity remains unchanged over all iterations.

B. Bat algorithm (BAT)

Bat algorithm is another evolutionary optimization algorithm motivated by the echolocation of bats. Article [9] provides an insight into this algorithm and its applications.

This research has used an initial population of 100 microbats with 14 dimensions. Loudness and pulse rate parameters are both fixed to 0.5.

C. Cuckoo search algorithm (CSA)

Cuckoo search is yet another nature-inspired optimization algorithm based on the cuckoo breeding behavior. Its uses in engineering optimization can be found in paper [10].

For this work, an initial population of 25 nests with 14 dimensions has been used. The discovery rate of alien eggs parameter is set to 0.25.

The predefined database of sixteen different fictitious materials with frequency dependent electrical permeabilities and permittivities used for this research is presented in Table 1. The database consists of four classes of materials, viz. lossless dielectric materials, lossy magnetic materials, lossy dielectric materials and relaxation-type magnetic materials. The material properties, in spite of being fictitious, are exemplary of a wide class of materials typically used in literature for microwave absorber design [7].

With reference to Table 1, the reader may consult paper [7] for the relevant equations for calculating the complex frequency dependent permittivity and permeability of each of the sixteen materials.

IV. RESULTS AND DISCUSSIONS

In this section, the optimal results for the problems under consideration are presented and discussed. For all three optimization algorithms a total number of 20 trials have been considered, with each trial consisting of 1000 iterations and a wideband frequency range of 0.1-20 GHz is swept at a step of 0.5 GHz. For each of the seven layers, the minimum and maximum thicknesses are set to 0.1 mm and 2.0 mm respectively. All calculations are executed on a personal computer with Intel® Core™ i5-3210M processor (CPU 2.50 GHz) and 8.0 GB RAM.

Table 2 compares the performance of the three algorithms for optimizing the two designs under inspection in terms of best fitness value (gbestval), worst fitness value, standard deviation of fitness values, mean best fitness value and computational time. For all three evolutionary algorithms, Figs. 2 (a)-(b) illustrate the reflection coefficient versus frequency graphs for Models 1 and 2 respectively; whereas, the variation of the mean of best fitness value (gbestval) with iterations for both models are shown in Figs. 3 (a)-(b). The details of the optimal designs obtained for Model 1 by the three evolutionary algorithms under consideration are manifested in Table 3. Similarly, Table 4 presents the details of the optimal designs for Model 2. Tables 3 and 4 further compare these models with those obtained by differential evolution (DE), present in literature [7].

The results suggest that cuckoo search algorithm performs the best among the three discussed algorithms for obtaining a seven layer microwave absorber for both conditions of normal as well as oblique (angle of incidence 50°) incidence as far as obtaining the most optimal designs are concerned. Particle swarm optimization is also successful in obtaining a good design. The graphs indicate that bat algorithm performs well for lower values in the frequency range for oblique incidence but not so much for other cases. For both instants of normal and oblique incidence, CSA and PSO outperform DE [7] in terms of overall reflection coefficient as well as total thickness of the seven layer coating. It can also be discerned from the graphs, that CSA also has a high convergence rate along with the ability to obtain the best fitness values for both instances of normal as well as oblique incidence.

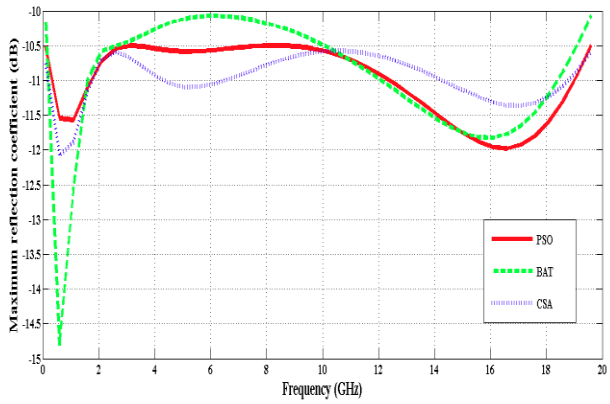
As far as computational time is concerned, it is observed that PSO is computationally the fastest and it also yields satisfactory results. CSA in spite of giving the most optimum designs, takes up the maximum run time.

Table 1: Predefined database of materials [7]

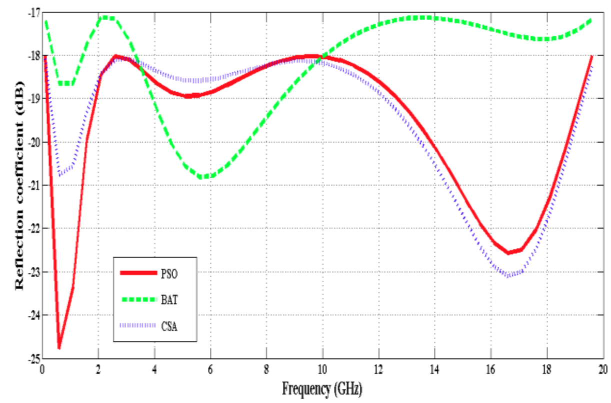
Lossless Dielectric Materials						
Material No.	μ´	μ´´	ε´	ε´´		
1	1	0	10	-		
2			50	-		
Lossy Magnetic Materials						
Material No.	μ´(1 GHz)	μ´´(1 GHz)	ε´	ε´´	a	b
3	5	10	15	0	0.974	0.961
4	3	15			1.000	0.957
5	7	12			1.000	1.000
Lossy Dielectric Materials						
Material No.	μ´	μ´´	ε´(1 GHz)	ε´´(1 GHz)	a	b
6	1	0	5	8	0.861	0.569
7			8	10	0.778	0.682
8			10	6	0.778	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				

Table 2: Comparison of PSO, BAT and CSA for optimal multilayer microwave absorber design based on 20 trials

Statistical Parameters	PSO		BAT		CSA		Winner	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Best fitness value	-10.50	-18.02	-10.07	-17.13	-10.57	-18.09	CSA	CSA
Worst fitness value	-3.96	-5.63	-4.12	-6.05	-2.87	-5.62	BAT	BAT
Standard deviation of fitness values	0.30	0.72	0.65	1.32	0.22	0.75	CSA	PSO
Mean best fitness value	-10.03	-16.35	-8.59	-13.43	-10.27	-16.91	CSA	CSA
Computational time (s)	978	980	1264	1307	1551	1523	PSO	PSO

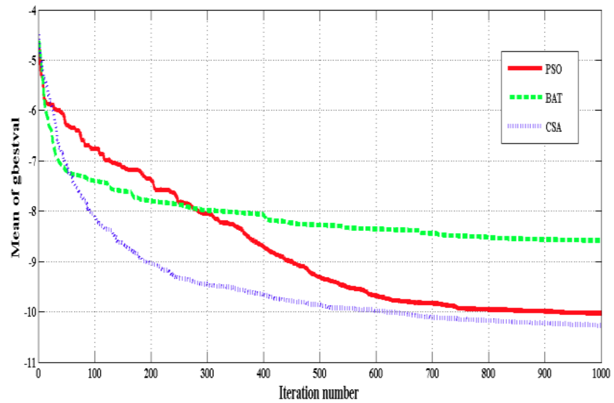


(a)

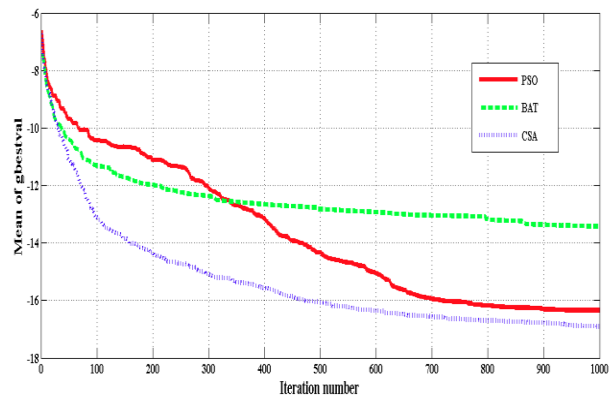


(b)

Fig. 2. (a) Reflection coefficient versus frequency for angle of incidence 50° and TE polarization (Model 1), and (b) reflection coefficient versus frequency for normal incidence and TE/TM polarization (Model 2).



(a)



(b)

Fig. 3. (a) Mean of best fitness value (gbestval) over iterations for Model 1, and (b) mean of best fitness value (gbestval) over iterations for Model 2.

Table 3: Parameters for optimal microwave absorber design for angle of incidence 50º and TE polarization (Model 1)

	PSO		BAT		CSA		Data From [7]	
Layer	Material	Thickness	Material	Thickness	Material	Thickness	Material	Thickness
1	14	0.2544	16	0.2650	16	0.2557	16	0.2282
2	6	0.9796	6	1.9571	6	1.8731	6	1.8034
3	6	1.1676	14	1.5644	14	0.6916	14	0.5566
4	14	0.5550	9	0.4596	5	1.5107	6	0.8822
5	5	1.2927	4	1.9848	5	06469	5	1.3564
6	5	1.2657	5	0.9024	4	1.0798	5	1.9424
7	4	0.6463	7	0.6874	6	0.4594	1	0.0105
	Maximum reflection coefficient (dB) = -10.4986		Maximum reflection coefficient (dB) = -10.4727		Maximum reflection coefficient (dB) = -10.5748		Maximum reflection coefficient (dB) = -10.4	
	Total thickness (mm) = 6.1613		Total thickness (mm) = 7.8207		Total thickness (mm) = 6.5171		Total thickness (mm) = 6.8	

Table 4: Parameters for optimal microwave absorber design for normal incidence and TE/TM polarization (Model 2)

	PSO		BAT		CSA		Data From [7]	
Layer	Material	Thickness	Material	Thickness	Material	Thickness	Material	Thickness
1	16	0.2141	14	0.2108	16	0.2107	16	0.2064
2	6	1.0928	6	1.8910	6	1.1066	6	1.8762
3	6	0.8140	16	0.4632	6	0.7916	14	0.5391
4	14	0.5987	7	0.5737	14	0.5482	6	0.9499
5	5	0.9552	5	1.8523	5	1.3785	5	1.9596
6	5	1.0983	14	0.1007	6	0.5570	4	0.7817
7	4	1.2593	4	1.2121	4	1.7450	5	0.4864
	Maximum reflection coefficient (dB) = -18.0167		Maximum reflection coefficient (dB) = -17.1326		Maximum reflection Coefficient (dB) = -18.0879		Maximum reflection coefficient (dB) = -17.9	
	Total thickness (mm) = 6.0324		Total thickness (mm) = 6.3038		Total thickness (mm) = 6.3376		Total thickness (mm) = 6.8	

V. CONCLUSIONS

This paper has focused on the comparison of particle swarm optimization, bat algorithm and cuckoo search algorithm for the purpose of designing optimal wideband multilayer microwave absorbers for both normal and oblique incidences. The optimization engines have been used to minimize the overall reflection coefficient of the multilayer coating. The results obtained reflect that the design obtained by CSA and PSO are ultrathin and have a superior frequency response compared to the designs presented in literature [7]; whereas BAT produces comparable outputs too. It is seen that CSA outperforms all other algorithms in terms of obtaining the best fitness value, and thus the most optimal absorber design. With respect to computational time, PSO turns out to be the most efficient algorithm of the three, followed by BAT and CSA.

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