# Comparative Study of Evolutionary Algorithms for the Optimum Design Of Thin Broadband Multilayer Microwave Absorber for Oblique Incidence

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***ABSTRACT***

*With the increasing levels of Electromagnetic pollution almost exponentially in this modern age of Electronics reported and highlighted by numerous studies carried out by scientists from all over the world, inspire engineers to concentrate their research for the optimum design of multilayer microwave absorber considering various parameters which are inherently conflicting in nature. In this paper we mainly focus on the comparative study of different Evolutionary algorithms for the optimum design of thin broadband (2-20GHz) multilayer microwave absorber for oblique incidence ($30^0$) considering arbitrary polarization of the electromagnetic waves. Different models are presented and synthesized using various Evolutionary algorithm namely Firefly algorithm (FA), Particle swarm optimization (PSO), Artificial bee colony optimization (ABC) and the best simulated results are tabulated and compared with each others.*

***KEYWORDS***

*Multilayer microwave absorber, oblique incidence, TE polarization, TM polarization, Particle swarm optimization (PSO), Firefly algorithm (FA), Artificial bee colony optimization (ABC).*

## INTRODUCTION

In today's world as electromagnetic pollution levels are reaching an alarming proportions increasing almost exponentially microwave absorber find its wide range of applications in almost all military and civil electronics systems for their properties to attenuate energy in an electromagnetic wave and can capable to eliminate stray or unwanted radiation that may interfere with the system operation and can degrade its performance .Earlier single layer absorber have been studied for many years but they find their limitations of narrow frequency band and thick structure. Hence recently more and more attention has been given for the optimum design of multilayer microwave absorber such that they must have minimum reflection coefficient of the electromagnetic wave in a specific band of frequencies for any angle of incidence and arbitrary polarization of the electromagnetic waves at the same time the absorber should be thin and light

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weight as well which makes the above problem a multi objective optimization problem to find out a proper trade-offs between various parameters of the microwave absorber such as choice of materials from a predefined database of existing materials, frequency range, incidence angle , number of layers, type of polarization, permittivity, permeability. However it has been solved successfully in many papers by applying various evolutionary optimization algorithm such as Genetic algorithm(GA)[1-3,6],Central force optimization (CFO)[7], Differential evolution(DE)[8],particle swarm optimization(PSO)[4-5,13-21],Firefly algorithm(FA)[22-24]and many more. In this paper we mainly focus on the comparative study of three most popular evolutionary optimization algorithms namely Firefly algorithm(FA),Particle swarm optimization(PSO),and Artificial bee colony optimization(ABC)[25,26] algorithm for the optimum design of multilayer microwave absorber for oblique incidence($30^0$)in the wide frequency band (2-20GHz) considering arbitrary polarization of the electromagnetic waves. The total thickness of the absorber is also included with the reflection coefficient while formulating the cost function to make our design more convenient for practical use. In this paper our study is organized as follows: Section 2 gives the brief overview of the physical model of multilayer microwave absorber. Section 3 describes the cost function or fitness function to be optimized using evolutionary optimization algorithms. A brief overview of particle swarm optimization (PSO), Firefly algorithm (FA), Artificial bee colony optimization (ABC) to solve the above mentioned problem is described in section 4. Simulation results and subsequent discussions are described in section 5, while the concluding arguments are explained in section 6.

## 2. GENERALIZED MODEL OF MULTILAYER MICROWAVE ABSORBER

The generalized structure of multilayer microwave absorber illustrated in Fig.1 is formed by cascading N number of layers of different materials with frequency dependent permittivity and permeability available from specific predefined material database and is backed by perfect electric conductor (PEC) which acts as an ideal reflection object and consider as the last layer (layer number N+1) of the multilayer structure of the microwave absorber. The electromagnetic wave travel through the free space(air) which is consider as layer number 0 and incident obliquely at the first surface of the multilayer structure making an incident angle θ with the Z axis (normal) at the point of incidence. When this electromagnetic wave is travelled through the multilayer structure certain parts of its energy is being absorbed in each layer , and is reflected back by the last layer (layer number N+1) formed by perfect electric conductor(PEC). Now from the concept of transmission line theory [9] the generalized reflection coefficient between any two layers of the multilayer structure can be determined using the following algorithm:

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

Where,

For TM (parallel) polarization:

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

For TE (perpendicular) polarization:

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

In the above equations,

$\varepsilon_i$ = frequency dependent complex permittivity of i^th layer.

$\mu_i$ = frequency dependent complex permeability of i^th layer.

$k_i$ = wave number of the i^th layer and according to Snell's law it is related with the incident angle θ as follows:

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

In equation (4), ω represents the frequency of the incident wave whereas $\varepsilon_0$ and $\mu_0$ denote the permittivity and permeability of free space respectively, i.e.

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

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

In this paper while designing the multilayer structure of the microwave absorber the misconception that for normal incidence both TM and TE polarization don't have the same magnitude of the reflection coefficient [8] and wrongfully set the reflection coefficient between the last layer of the multilayer structure and the PEC($R_{N,N+1}$)to -1 for both TE and TM polarizations deals with the same problem in several papers [10,11,12] has been traced out and it has been emphasized that it should be set to +1 for TM polarization where as it set to -1 for TE polarization of the electromagnetic wave otherwise it results in different values for the magnitude of the reflection coefficient for normal incidence but which is not the case actually. Taken this above concept under consideration the overall reflection coefficient of the multilayer microwave absorber is now computed recursively using the equations (1)-(6).

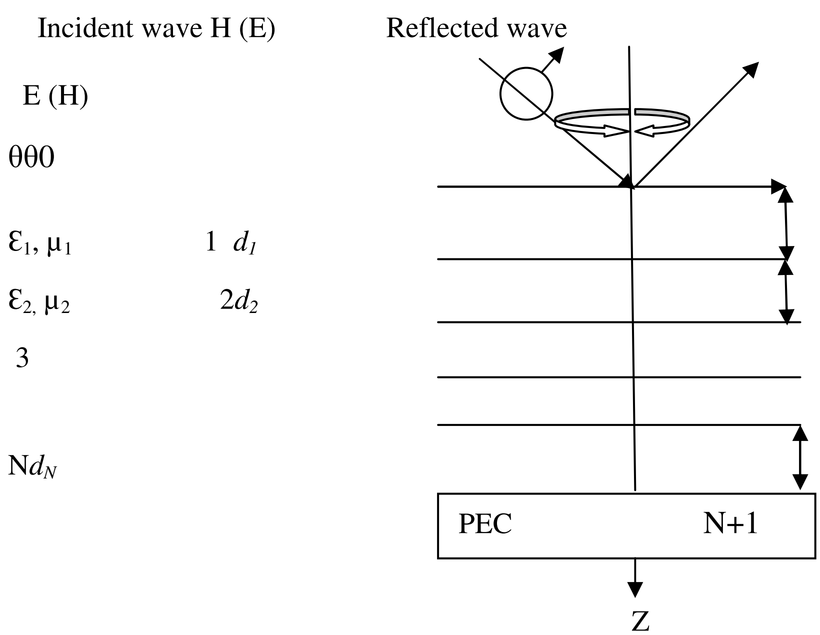


Fig 1.Generalized Physical Model of Multilayer Microwave Absorber.

# 3. PROBLEM FORMULATION

The primary objective of our design is to obtain a multilayer structure of the microwave absorber which is formed by cascading of N different materials having frequency dependent permittivity and permeability choosing from predefined database of the existing materials that minimize the overall reflection coefficient of the microwave absorber for wide band of frequency (2-20 GHz) and a particular incidence angle of $30^0$ considering both TE and TM polarizations of the electromagnetic wave. It is also required that the thickness of the multilayer structure of the absorber should be least practically possible therefore both these design considerations are incorporated in the form of following objective function for the purpose of optimization.

Minimum $F=K_1*20\log_{10}(\max(|R_{01}|)) + K_2\sum_{i=1}^{N} d_i$ (7)

Where the sum of all the individual layer thickness in meter is also optimized along with the weighted sum of overall maximum reflection coefficient of the multilayer microwave absorber$K_1$, $K_2$ are weighting constants emphasizing each of the term associated with the fitness function and has been set to $K_1=1$ and $K_2= 3000$ respectively for all the models studied in our design consideration optimized using three different evolutionary optimization algorithm namely particle swarm optimization(PSO), Firefly algorithm(FA), Artificial bee colony optimization(ABC) in this paper.

# 4. ALGORITHM OVERVIEWS AND PARAMETRIC SETUP

## 4.1. Overview of firefly algorithm (FA)

FA is a Swarm based optimization algorithm and the concept was first developed by Xin-SheYang .The flashing characteristics of the fireflies is related with the objective function to be optimized by the algorithm and the concept was developed from the study of social behaviour of the fireflies that how they communicate with each other. In this algorithm the glowing fireflies is considered as the search agents and characterized by two parameters such as the location of the fireflies in the *d*-dimensional search space and the light intensity or brightness of the fireflies, asthe brightness or light intensity of the fireflies changes the fireflies also changes their location accordingly and the algorithm approaches towards its optimum solution. The algorithm can be summarized as per the flowchart given in fig2.

## 4.2. Overview of Artificial bee colony optimization (ABC) algorithm

ABC algorithm is also a swarm based optimization algorithm which was first introduced by Basturk and Karaboga. In ABC algorithm there are three groups of bees namely employed bees, onlookers and scouts where the searching ability of ABC algorithm lies on different behaviours of these three groups of bees whereas the positions of the food sources around a colony of artificial bees denoted the solutions of an optimization problem. The algorithm can be summarized as per the flowchart given in the fig3.

### 4.3. Overview of particle swarm optimization (PSO) algorithm

The PSO algorithm is easy to implement and has been empirically shown to perform well on many optimization problems whose basic concept was first developed and introduced by Kennedy and Eberhart in 1995 which is based on the swarm behaviour of insects, animals herding, birds flocking and fish schooling where the search for the food is carried out by the swarm in a collaborative manner. In this concept the searching pattern of each swarm is adapted from its own as well as other member's experience. In PSO each members of the swarm also called particle represents the potential solution which is a point in the search space and the location of the food is the global optimum. The flying direction of each particle has been adjusted by its fitness value and a velocity corresponding to the best experiences of the swarm to search for the Global optimum in the D-dimensional search space. The algorithm can be summarized as per the flowchart given in the fig4.

Table 1. Parametric Setup ofthePSO, FA andABC Algorithms

| **PSO** | | **FA** | | **ABC** | |
|---|---|---|---|---|---|
| **Parameters** | **Values** | **Parameters** | **Values** | **Parameters** | **Values** |
| Particle number | 40 | Number of fireflies | 40 | colony size (NP) | 40 |
| Acceleration constant $c_1$<br>Acceleration constant $c_2$ | 1.4945<br>1.4945 | $ß_0$ | 0.20 | limit for abandonment | 5 |
| Inertia weight w | damp linearly from 0.9 to 0.2 with iterations | γ | 1 | Food number | NP/2 |
| VR min<br>VR max | 0<br>1 | α | 0.9 | - | - |
| Search space dimension | 10 | Search space dimension | 10 | Search space dimension | 10 |
| Run no | 20 | Run no | 20 | Run no | 20 |
| Termination condition | 1000 iterations max | Termination condition | 1000 iterations max | Termination condition | 1000 Iterations max |

Table 2. Predefined Database of Existing Materials [7, 8]

| | | | | |
|---|---|---|---|---|
| **Lossless Dielectric Materials**($\mu_r = 1 + j0$) | | | | |
| # | $\varepsilon_r$ | | | |
| 1 | 10+ j0 | | | |
| 2 | 50+j0 | | | |
| | **Lossy Magnetic Materials** ($\varepsilon_r = 15 + j0$) $\mu = \mu_r - j\mu_i$ $\mu_r(f) = \frac{\mu_r(1GHz)}{f^{\alpha}}$ $\mu_i(f) = \frac{\mu_i(1GHz)}{f^{\beta}}$ | | | |
| # | $\mu_r(1GHz)$, | $\alpha$ | $\mu_i(1GHz)$, | $\beta$ |
| 3 | 5 | 0.974 | 10 | 0.961 |
| 4 | 3 | 1.000 | 15 | 0.957 |
| 5 | 7 | 1.000 | 12 | 1.000 |
| **Lossy Dielectric Materials** ($\mu_r = 1 + j0$) $\varepsilon = \varepsilon_r - j\varepsilon_i$ $\varepsilon_r(f) = \frac{\varepsilon_r(1GHz)}{f^{\alpha}}$ $\varepsilon_i(f) = \frac{\varepsilon_i(1GHz)}{f^{\beta}}$ | | | | |
| # | $\varepsilon_r(1GH)$ | $\boldsymbol{\alpha}$ | $\varepsilon_i(1GHz)$ | $\beta$ |
| 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** $\mu = \mu_r - j\mu_i$ $\mu_r = \frac{\mu_m f_m^2}{f^2 + f_m^2}$ $\mu_i = \frac{\mu_m f_m f}{f^2 + f_m^2}$ **(f and $f_m$ in GHz)** | | | | |
| # | $\mu_m$ | | $f_m$ | |
| 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 | |

Fig 2.

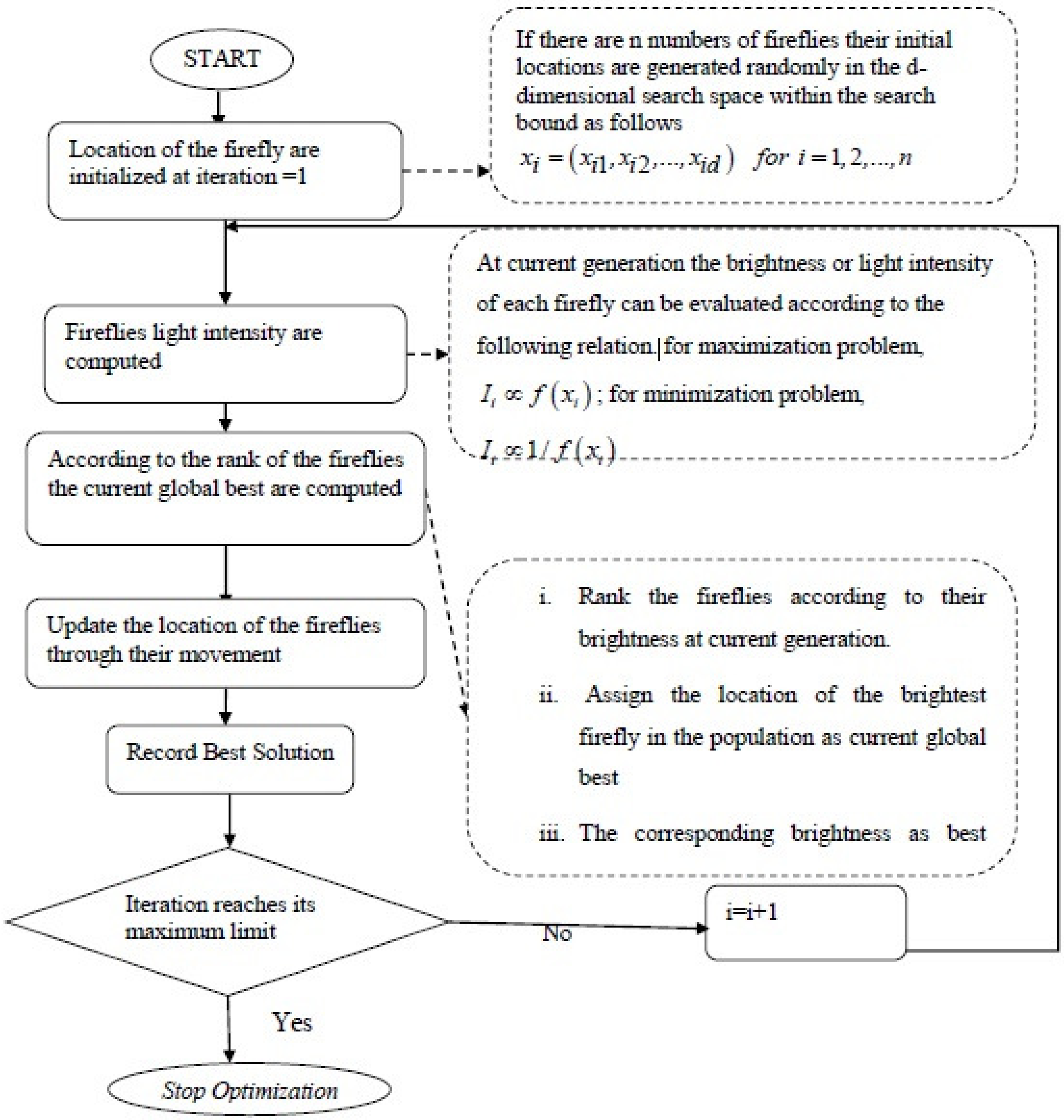


Fig 2. Flowchart Of FA

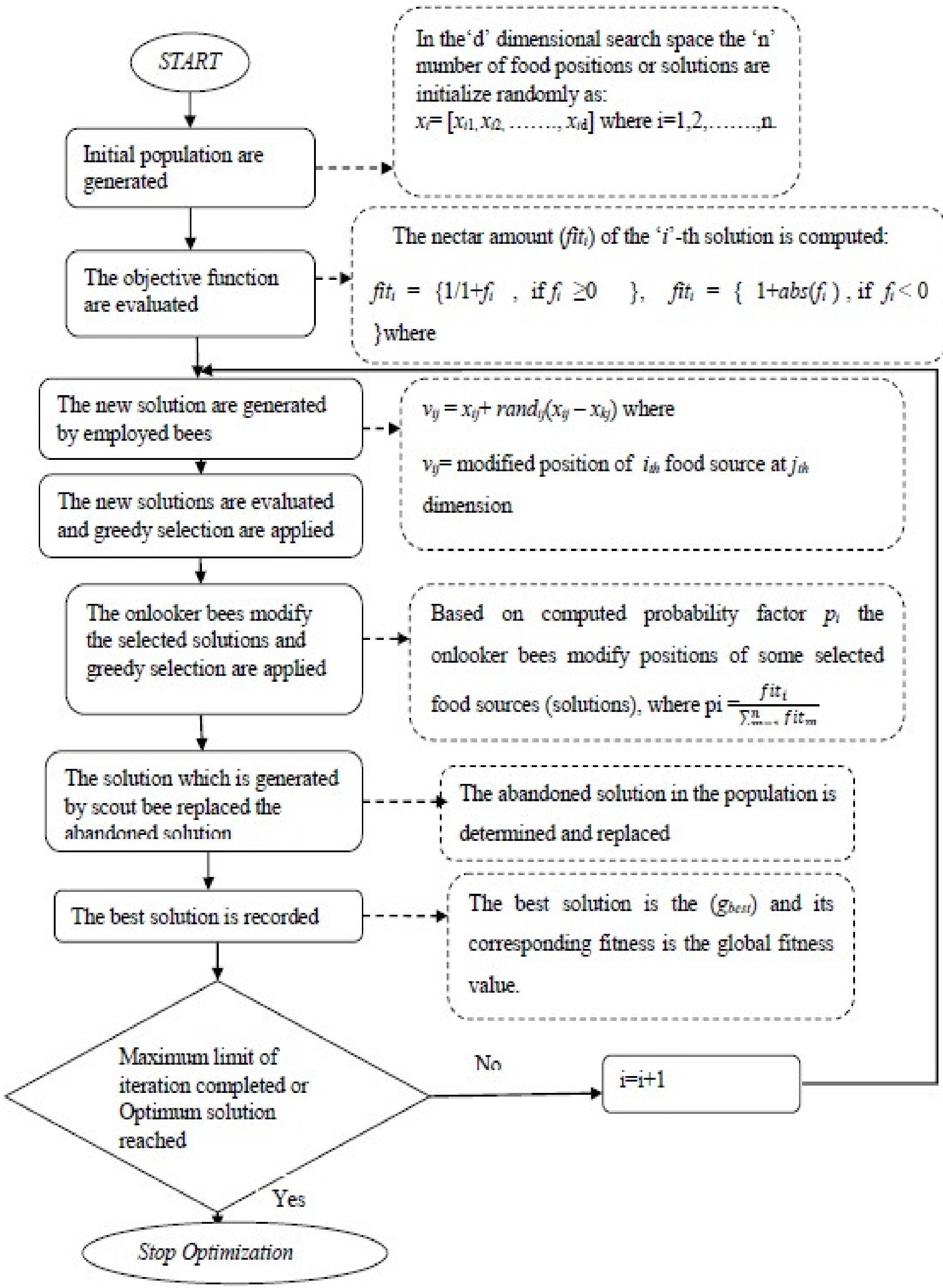


Fig3. Flowchart Of ABC Algorithm

## 5. RESULTS AND DISCUSSION

The comparative study of different evolutionary algorithm such as particle swarm optimization (PSO), firefly algorithm (FA) and artificial bee colony optimization (ABC) are presented in this paper for the optimum design of 5 layer microwave absorber for oblique incidence ($30^0$) considering TE and TM polarization of the electromagnetic wave and for wide range of frequency (2-20GHz) with a frequency increase of 0.1 GHz at each step. 4 different models are presented optimized for overall reflection coefficient and total thickness of the absorber and only for overall reflection coefficient of the absorber without optimized the total thickness. Three different evolutionary algorithms are applied for optimization in each case and there parametric and statistical comparison is tabulated in table 3, 4, 5, 6, 7, 8, 9 and 10 respectively for each model. It has been observed that for model1 (optimized for oblique incidence ($30^0$), TM polarization considering overall reflection coefficient and total thickness of the absorber simultaneously) FA gives the better frequency response for optimizing the overall reflection coefficient of the absorber but PSO results in ultra-thin absorber among all algorithms. Similarly for model 2 (optimized for only overall reflection coefficient of the absorber considering oblique incidence($30^0$) and TM polarization) PSO becomes more effective regarding optimization of the overall reflection coefficient of the absorber but as per as thinner absorber design is concern ABC comes out to be the clear winner over all other situations. Model3 (optimized for overall reflection coefficient and total thickness of the absorber considering TE polarization of the electromagnetic wave and $30^0$ incidence angle) PSO results in much thinner absorber and moderate frequency response over desired frequency band. Similarly for model 4 (considering TE polarization and incidence angle of $30^0$ and optimized for only overall reflection coefficient of the absorber) it has been observed that PSO results in better frequency response over desired frequency band while ABC results in slightly thinner absorber design as compare to other algorithms.fig.5, 6, 7, 8 represents the frequency response for model1, 2, 3, 4 optimized using different evolutionary algorithm while the variation of mean gbest value with iterations for all the above designs are presented in fig.9,10,11 and 12 respectively. For simulation all the three algorithms are run for 20 independent trials and each time the maximum number of iterations is set to 1000.

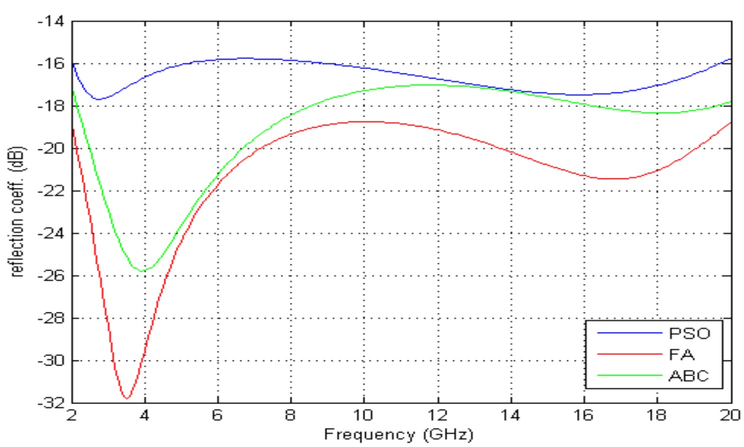


Figure 4. Reflection Coefficient Versus Frequency For Model1

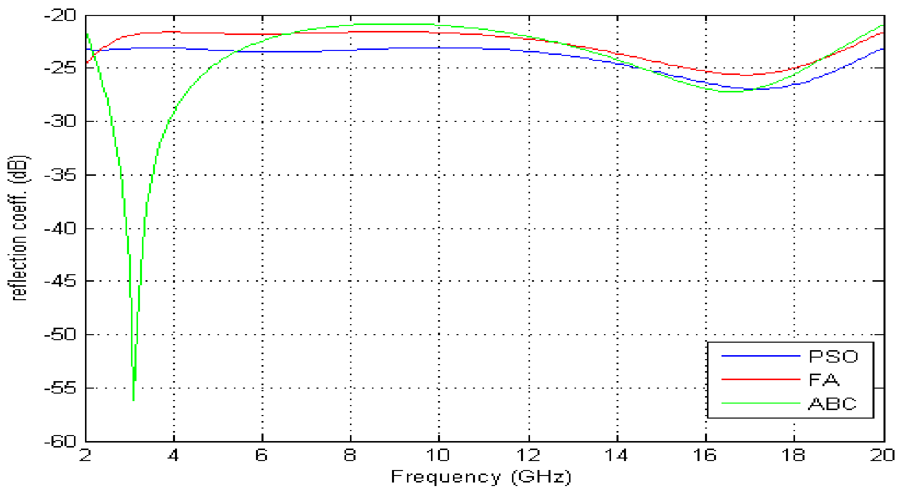


Figure 5. Reflection Coefficient Versus Frequency For Model2

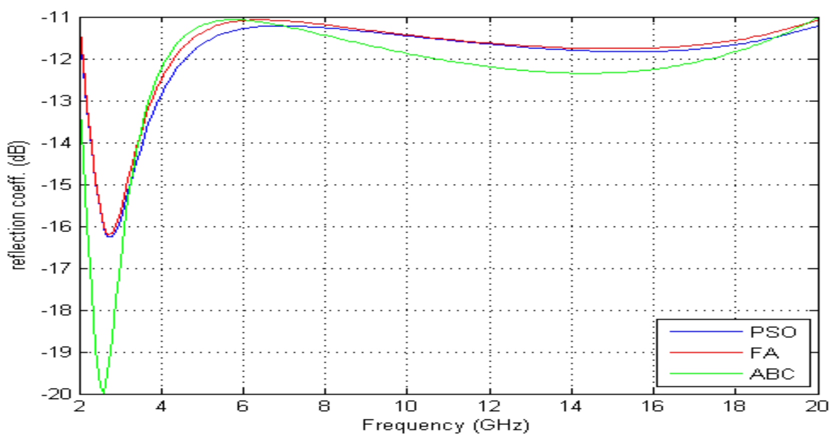


Figure 6.Reflection Coefficient Versus Frequency For Model3

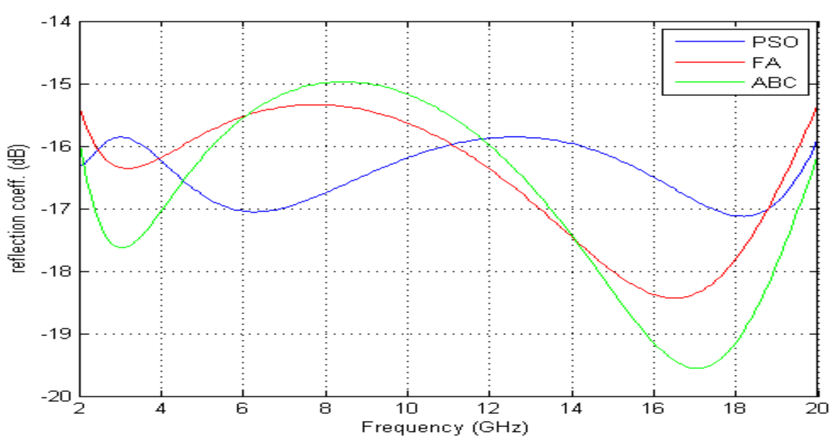


Figure 7. Reflection Coefficient versus Frequency for Model4

Table 3. Parameters for Microwave Absorber Design for Oblique Incidence ($30^0$) TM Polarization Optimized For Overall Reflection Coefficient and Total Thickness of the Absorber (Model1)

| **Layer** | **PSO** | | **FA** | | **ABC** | |
|---|---|---|---|---|---|---|
| | **Material No.** | **Thickness in mm** | **Material No.** | **Thickness in mm** | **Material No.** | **Thickness in mm** |
| 1 | 16 | 0.3323 | 16 | 0.2018 | 16 | 0.2284 |
| 2 | 6 | 0.4414 | 6 | 1.3296 | 6 | 1.0805 |
| 3 | 2 | 0.3648 | 14 | 0.1192 | 9 | 0.5624 |
| 4 | 11 | 0.4656 | 11 | 0.6961 | 12 | 0.1099 |
| 5 | 9 | 0.4220 | 9 | 0.6254 | 9 | 0.6651 |
| **6** | Ground plane | | Ground plane | | Ground plane | |
| **Maximum reflection coefficient in dB** | -15.7872 | | -18.7609 | | -17.0341 | |
| **Total thickness in mm** | 2.0261 | | 2.9722 | | 2.6463 | |

Table 4. Comparative Statistical Analysis After 20 Trials For Model1

| **Algorithm** | **Best** | **Worst** | **Mean** | **Standard deviation** |
|---|---|---|---|---|
| **PSO** | -9.7091 | -8.1827 | -9.0438 | 0.3933 |
| **FA** | -9.8443 | -4.3626 | -7.9062 | 1.4860 |
| **ABC** | -9.0952 | -8.0470 | -8.5155 | 0.2965 |

Table 5. Parameters For Microwave Absorber Design For Oblique Incidence ($30^0$) TM Polarization Optimized For Overall Reflection Coefficient Only (Model2)

| Layer | PSO | | FA | | ABC | |
|---|---|---|---|---|---|---|
| | Material No. | Thickness in mm | Material No. | Thickness in mm | Material No. | Thickness in mm |
| 1 | 16 | 0.1573 | 14 | 0.1635 | 16 | 0.1685 |
| 2 | 6 | 1.7519 | 6 | 1.8124 | 6 | 1.8329 |
| 3 | 16 | 0.4559 | 16 | 0.4153 | 16 | 0.5201 |
| 4 | 5 | 1.1076 | 5 | 0.7171 | 7 | 0.1529 |
| 5 | 4 | 1.4634 | 10 | 1.8524 | 11 | 1.2277 |
| 6 | Ground plane | | Ground plane | | Ground plane | |
| **Maximum reflection coefficient in dB** | -23.0826 | | -21.5938 | | -20.8239 | |
| **Total thickness in mm** | 4.9361 | | 4.9606 | | 3.902 | |
| | | | | | | |

Table 6. Comparative statistical analysis after 20 trials for model 2

| Algorithm | Best | Worst | Mean | Standard deviation |
|---|---|---|---|---|
| **PSO** | -23.0826 | -17.4886 | -20.1828 | 1.8365 |
| **FA** | -21.5938 | -17.4248 | -18.6764 | 1.1049 |
| **ABC** | -20.8239 | -16.9545 | -18.5162 | 1.1329 |

Table 7. Parameters For Microwave Absorber Design For Oblique Incidence ($30^0$) TE Polarization Optimized For Overall Reflection Coefficient And Total Thickness Of The Absorber (Model3)

| Layer | PSO | | FA | | ABC | |
|---|---|---|---|---|---|---|
| | **Material No.** | **Thickness in mm** | **Material No.** | **Thickness in mm** | **Material No.** | **Thickness in mm** |
| 1 | 16 | 0.3732 | 16 | 0.3742 | 16 | 0.3899 |
| 2 | 8 | 0.1523 | 1 | 0.3992 | 7 | 0.4032 |
| 3 | 7 | 0.2225 | 2 | 0.3902 | 2 | 0.4409 |
| 4 | 2 | 0.4290 | 13 | 0.1006 | 15 | 0.3826 |
| 5 | 15 | 0.4825 | 15 | 0.4063 | 16 | 0.1495 |
| 6 | Ground plane | | Ground plane | | Ground plane | |
| **Maximum reflection coefficient in dB** | -11.2147 | | -11.0730 | | -11.0220 | |
| **Total thickness in mm** | 1.6595 | | 1.6705 | | 1.766 | |

Table 8. Comparative Statistical Analysis After 20 Trials For Model3

| **Algorithm** | Best | Worst | Mean | Standard deviation |
|---|---|---|---|---|
| **PSO** | -6.2362 | -3.9262 | -4.9741 | 0.5123 |
| **FA** | -6.0614 | -2.9609 | -4.6205 | 0.6904 |
| **ABC** | -5.7239 | -4.7002 | -5.1360 | 0.2896 |

Table 9. Parameters For Microwave Absorber Design For Oblique Incidence ($30^0$) TE Polarization Optimized For Overall Reflection Coefficient Only (Model4)

| Layer | PSO | | FA | | ABC | |
|---|---|---|---|---|---|---|
| | **Material No.** | **Thickness in mm** | **Material No.** | **Thickness in mm** | **Material No.** | **Thickness in mm** |
| 1 | 16 | 0.2243 | 16 | 0.2199 | 16 | 0.2156 |
| 2 | 6 | 1.9998 | 6 | 1.8861 | 6 | 1.9705 |
| 3 | 16 | 0.5908 | 14 | 0.4352 | 14 | 0.4966 |
| 4 | 1 | 1.3214 | 5 | 1.1419 | 5 | 1.1380 |
| 5 | 11 | 1.0558 | 10 | 0.8240 | 9 | 0.3961 |
| 6 | Ground plane | | Ground plane | | Ground plane | |
| **Maximum reflection coefficient in dB** | -15.8569 | | -15.3363 | | -14.9729 | |

| | | | |
|---|---|---|---|
| **Total thickness in mm** | 5.1920 | 4.5071 | 4.2168 |

Table 10. Comparative statistical analysis after 20 trials for model4

| **Algorithm** | Best | Worst | Mean | Standard deviation |
|---|---|---|---|---|
| **PSO** | -15.8569 | -13.2509 | -14.7254 | 0.7198 |
| **FA** | -15.3363 | -12.8856 | -14.0259 | 0.7724 |
| **ABC** | -14.9729 | -12.9493 | -13.8431 | 0.5397 |

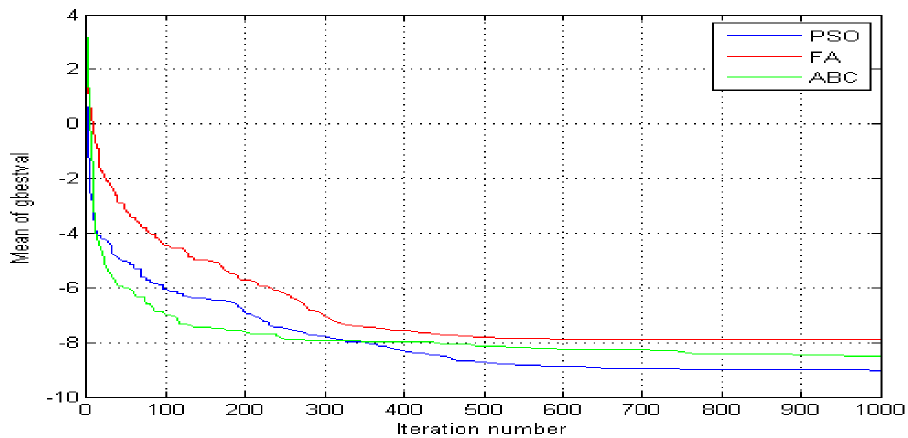


Figure 9.Mean of best fitness value versus iteration (Model 1)

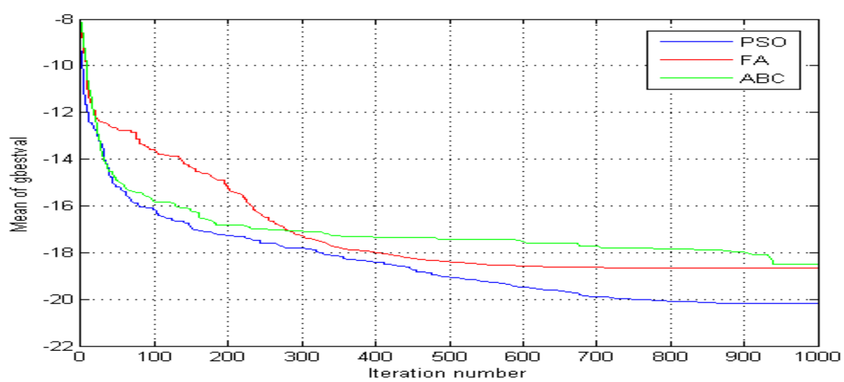


Figure 10. Mean of best fitness value versus iteration (Model 2)

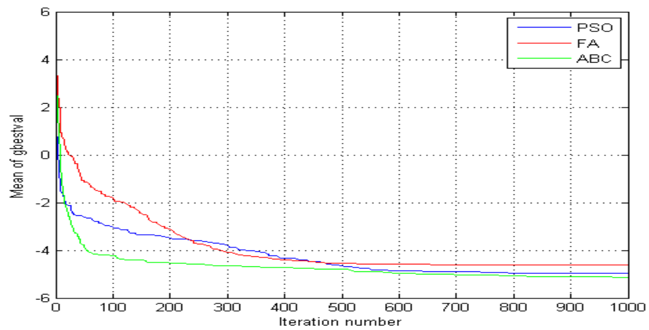


Figure 11. Mean of best fitness value versus iteration (Model 3)

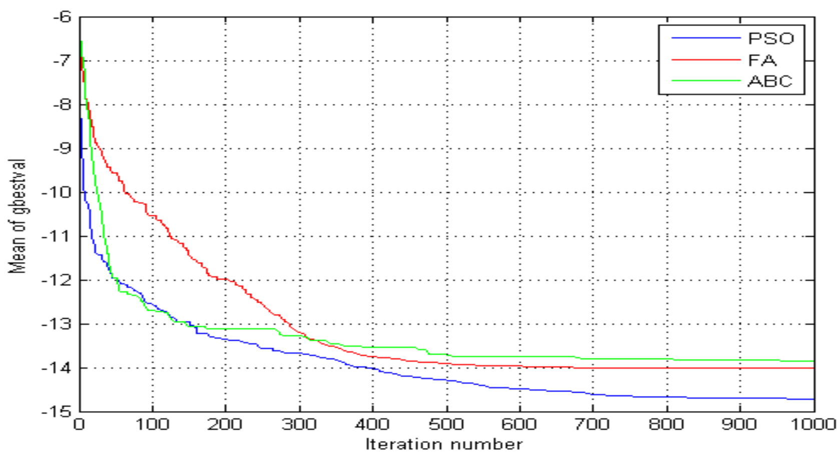


Figure 12. Mean of best fitness value versus iteration (Model 4)

## 6. CONCLUSIONS

A comparative study of three very popular evolutionary algorithm such as particle swarm optimization (PSO), firefly algorithm (FA) and artificial bee colony optimization (ABC) has been presented in this paper for the optimum design of thin broadband multilayer microwave absorber for oblique incidence ($30^0$) considering arbitrary polarization of the electromagnetic wave. The comparison of simulation results for different parameters and their statistical analysis between different algorithm have been demonstrate for every model which make our study more convenient for the design of the same. Moreover, it has also been emphasized that for normal incidence of electromagnetic wave both TE and TM yield the same magnitude of the reflection coefficient and set the reflection coefficient between the last layer of the multilayer structure and the PEC ($R_{N,N+1}$) to +1 for TM polarization where as it set to -1 for TE polarization of the electromagnetic wave, which seems to be neglected in many papers handling the same problem.

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