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Implementation of multilayer ferrite radar absorbing coating with genetic algorithm for radar cross-section reduction at X-band

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Genetic algorithm (GA) approach has been analyzed to optimize the thickness of various layers as well as selection of suitable ferrite material for better absorption and reduction of radar cross-section (RCS) at X-band frequency. For this purpose, the available ferrite materials with frequency-dependent permittivities $\varepsilon(f)$ and permeabilities $\mu(f)$ have been used as data base. An empirical relationship has been developed between μ and f as well as ε and f for application of GA to select the proper ferrite material at particular frequency range for minimum reflection or maximum absorption and reduction of RCS. The GA has advantage that, with fitness function, it places an upper bound on the total thickness of the coating as well as on the number of layers contained in the coating. This greatly simplifies manufacturing of absorber in the form of sheet by coating ferrite material. Four-layer coating with different thickness and different ferrite materials has been simulated by GA and the results obtained with GA have been synthesized on aluminum plate. The paint for coating over aluminum sheet has been prepared by mixing the known ferrite powders (used in data base) with glass epoxy resin with suitable amount of hardener. The absorption has been measured by absorber testing device (ATD) method and RCS has been measured by monostatic radar measurements at X-band (8-12 GHz) in anechoic chamber. The absorption and RCS were measured after each layer of coating. A considerable amount of reduction of RCS and absorption is observed as compared to the plain aluminum sheet at X-band.

Keywords: Absorber testing device, Radar cross-section, Genetic algorithm

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1 Introduction

Radar absorbing materials (RAM) have been used in industrial, commercial and military applications. One of the most important applications is the radar cross-section (RCS) reduction of military aircrafts, missiles, etc.

There are several types of materials used for radar absorbers including dielectric and magnetic materials. Magnetic absorbing material depends on magnetic losses. Magnetic loss depends on the imaginary part of the permeability. The higher the imaginary part the more is the loss. Ferrites have higher value of imaginary part of permeability; so they are used as magnetic absorbers[1]. The complex permeability spectra and their relationship with microwave absorbing phenomena are investigated in ferrite microwave absorbers. It was shown that one or two matching frequencies exist in the ferrite absorbers. This phenomenon strongly depends on the complex permeability locus of ferrite absorber on the impedance matching solution map[2]. A considerable amount of attenuation was obtained by coating ferrite layers on a metal backing[3-5]. But the attenuation was obtained only at certain frequencies. To obtain a stable attenuation at all frequencies across the band, the ferrite layers need to be optimized at all frequencies.

After studying various types of ferrites and their properties[3], multilayered radar absorbing material coating is designed. Pesque *et al*.[6] proposed a technique for designing absorbing coatings which is based on an optimal control approach. In this method, thin absorbing coatings are designed by cascading layers of different materials, which are chosen from a pre-defined set of available materials, such that the absorption properties of the coating are maximized over a specified frequency range. Its major drawback is the convergence to only a local minimum of the cost function. So the possibility of better absorption cannot be excluded. To overcome this drawback a technique based on the combinatorial optimization technique[7] of simulated annealing (SA) has also been presented. Though this technique provides better absorption, a global minimum is also not guaranteed in this technique. In this paper, multilayered coating is optimized using genetic algorithm (GA). This algorithm offers several advantages over the existing optimal control and SA techniques. The execution of the algorithm typically results in a number of high-performance designs rather than a single solution as offered by other techniques. A specific design can be selected from this set of solutions based on the criteria which were not explicitly incorporated in the objective function, such as ease of manufacturing or production cost[8].

The corresponding attenuation for different layers is observed at X-band by using an absorber testing device (ATD). The ATD consists of a standard X-band horn antenna with an extended waveguide section in which TE_{10} is the most dominating mode[3].

The RCS measurement is also done at X-band for absorber sheet with monostatic radar arrangements at various angles. The RCS method requires a double face panel, where one side is used as reflector material (reference) and the other is coated with RAM. The panel is fixed on a rotating support, which is positioned in front of the receiving and transmitting horns. The advantage of this methodology is that it allows the evaluation of the reference and RAM by rotating the device from 0 to 360°, evaluating both sides of the panel one after the other[9].

2 Implementation of multi-layered RAM coating

Different types of ferrites with different compositions of materials were fabricated[3]. Their dielectric and magnetic properties are shown in Table 1. With the help of the dielectric and magnetic properties, multi-layered radar absorbing material coating is designed, optimized and implemented in this paper. To optimize the multilayered structure, GA tool is utilized. In the GA tool the first requirement is the database of materials, out of which the best suiting material is chosen. The available data base of the dielectric and magnetic properties of the material is presented with their frequency dependencies in Table 1.

The genetic algorithms are iterative optimization procedures that start with a randomly selected population of potential solutions, and gradually evolve towards better solutions through the application of genetic operators. Their repetitive applications to a population of potential solutions result in an optimization process that resembles natural evolution. The three genetic operators governing the iterative search are often referred to as the selection, cross-over, and mutation operators. The probabilistic nature of all the three operators greatly enhances the capabilities of the algorithm to search for a global rather than local fitness function maximum. A flow chart of GA optimization technique is shown in Fig. 1.

2.1 Multilayered RAM coating structure

Figure 2 represents the multilayered coating backed by a perfectly conducting ground plane (metal sheet). The range of thickness of particular layer has been fixed from 0.01 cm to 0.5 cm for GA optimization of layers, because of physical realization. It is difficult to coat the thickness less than 0.01 cm. On the other hand, thickness more than 0.5 cm makes the layer very thick and not good for practical application. The available databases are given in Table 1 containing a set of N_i (i = 1, . . . , N_m) for different ferrite materials with frequency dependent permittivities $\varepsilon_i(f)$ and permeabilities $\mu_i(f)$. The design goal is to determine a coating consisting of N_i layers, such that the coating exhibits a low reflection at a prescribed set of frequencies for TE and TM polarizations. The design process, therefore, encompasses the determination of the optimal choice of the material thickness of the different layers.

The reflection coefficients R^{TE} and R^{TM} for the multilayered structure are calculated using a recursive procedure[8] as

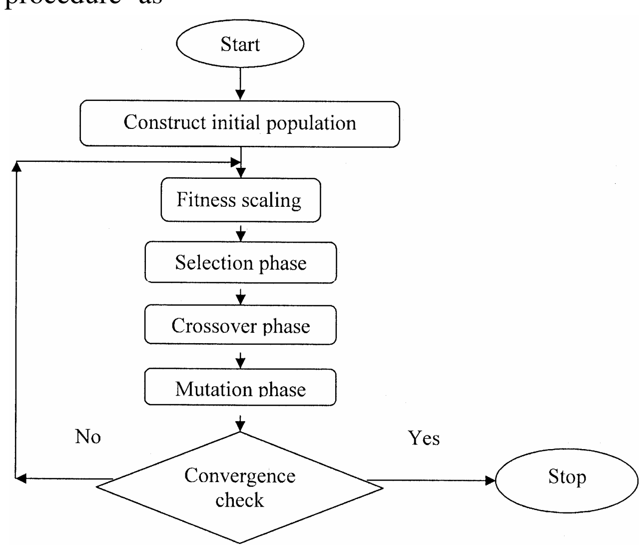

Fig. 1—Flowchart of genetic algorithm

Table 1—Database of materials for optimization

Ferrite materials	ε_r (8 GHz) α	ε_I (8 GHz) β	μ_r (8 GHz) α	μ_I (8 GHz) β
$Ba(MnTi)_{1.6}Fe_{8.8}O_{19}$	7.08 0.036194	0.36 –0.03738	1.92 0.022261	1.15 –0.02103
$Ba(MnTi)_{1.7}Fe_{8.6}O_{19}$	5.63 0.019252	2.41 0.049792	0.12 –0.08951	2.5 0.036445
$Ba(MnTi)_{1.8}Fe_{8.4}O_{19}$	2.99 –0.01396	3.24 0.045507	1.73 0.021888	0.2 –0.08288
$Ba(MnTi)_{1.9}Fe_{8.2}O_{19}$	3.99 –0.00243	1.84 0.02929	1.14 –0.01273	1.26 0.002088
$Ba(MnTi)_{2.7}Fe_{6.6}O_{19}$	8.13 0.032893	2.19 0.031065	2.03 0.032363	0.16 –0.08905
$Ba(MnTi)_{3.5}Fe_{5.0}O_{19}$	6.485 0.022805	3.816 0.056184	1.893 0.027582	0.04 –0.13677
$SrZn_{1.2}Fe_{13.2}Sn_{0.6}Mn_{0.6}O_{23.8}$	2.67 –0.02174	0.7 –0.00585	0.091 –0.08504	1.795 0.004794
$BaCo_{0.8}Mn_{0.1}Fe_{10.27}O_{19}$	6.32 0.056559	2.46 0.066381	1.205 0.020669	1.3 0.023475
$BaCo_{0.8}\,Ti_{0.8}\,Mn_{0.15}Fe_{10.2}O_{19}$	4.844 0.073397	1.053 0.027419	1.529 0.033782	1.011 0.039667
$BaCo_{0.8}\,Ti_{0.8}\,Mn_{0.1}Fe_{9.97}O_{19}$	6.48 0.030683	0.333 –0.02262	2.05 0.022722	1.81 0.029279
$BaCo_{0.8}\,Ti_{0.8}\,Mn_{0.15}Fe_{9.9}O_{19}$	3.437 0.054571	3.983 0.051031	1.493 –0.00954	0.212 –0.03343
$Ba(MnTi)_{1.6}Fe_{8.8}O_{19}$	7.08 0.036194	0.36 –0.03738	1.92 0.022261	1.15 –0.02103
$Ba(Mn_{0.15}\,Co_{0.85})_2Fe_{16}O_{27}$	8.837 0.010656	1.84 –0.00826	0.745 0.009302	2.015 0.020206
$BaTiO_3$	3.325 –0.00369	13.65 0.059571	1 0.0	0 0.0
SiC	19.68 0.0316	0.791 –0.00713	1 0.0	0 0.0
$Ba(MnTi)_{1.6}Fe_{8.8}O_{19}$	7.08 0.036194	0.36 –0.03738	1.92 0.022261	1.15 –0.02103

Note: $\mu = \mu_r - j\mu_i$, $\varepsilon = \varepsilon_r - j\varepsilon_i$ $\mu_r(f) = \dfrac{\mu_r(8\text{ GHz})}{f^{\alpha}}, \mu_i(f) = \dfrac{\mu_i(8\text{ GHz})}{f^{\beta}}, \varepsilon_r(f) = \dfrac{\varepsilon_r(8\text{ GHz})}{f^{\alpha}}, \varepsilon_i(f) = \dfrac{\varepsilon_i(8\text{ GHz})}{f^{\beta}}$

[Refs 3 and 4]

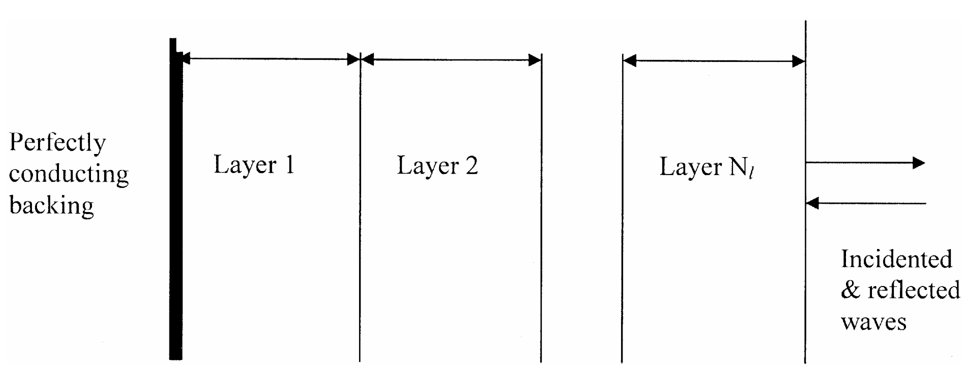

Fig. 2—Multilayered RAM coating[8]

$$R_i^{\text{TE/TM}} = \frac{R_{0i}^{\text{TE/TM}} + R_{i-1}^{\text{TE/TM}} e^{-2jk_{i-1}t_{i-1}}}{1 + R_{0i}^{\text{TE/TM}} R_{i-1}^{\text{TE/TM}} e^{-2jk_{i-1}t_{i-1}}} \quad \ldots (1)$$

where,

$$R_{0i}^{\text{TE}} = \frac{\mu_{i-1}k_i - \mu_i k_{i-1}}{\mu_{i-1}k_i + \mu_i k_{i-1}}, \text{ when } i > 1$$
$$= -1, \text{ when } i = 1 \quad \ldots (2)$$

and

$$R_{0i}^{\text{TM}} = \frac{\varepsilon_{i-1}k_i - \varepsilon_i k_{i-1}}{\varepsilon_{i-1}k_i + \varepsilon_i k_{i-1}}, \text{ when } i > 1$$
$$= -1, \text{ when } i = 1 \quad \ldots (3)$$

and k_i is the wave number along z-direction in i^{th} layer.

2.2 Genetic algorithm implementation

The radar absorbing material coating is designed for a 4-layer structure with conducting sheet backing. The structure is optimized for zero reflection coefficients by using *gatool* of Matlab 7.0 (Ref. 10). The parameters used to simulate the *gatool* for optimization are given in Table 2 and the obtained results are shown in Table 3. Out of the four potential solutions the first solution is implemented in this paper.

2.3 Sample preparation

The samples of ferrite powders were prepared by dry attrition and sintering process[5]. The sintering was carried out at 1150°C for 8 hours. The developed ferrite powder, 60% by weight, mixed in 40% epoxy resin and suitable amount of hardener to form a microwave absorbing paint[5]. The thickness of each coating is monitored by using micrometer measurement system.

Table 2—Parameters used in *gatool*

Fitness function	:	@objfun
Number of variables	:	8
Population type	:	Double vector
Population size	:	20
Initial range	:	[0 0 0 0 0 0 0 0 : 15 15 15 15 0.002 0.002 0.002 0.002]
Scaling function	:	Rank
Selection function	:	Roulette
Elite count	:	4
Crossover fraction	:	0.8
Generations	:	100
Time limit	:	inf
Fitness limit	:	0
Stall generations	:	50
Stall time limit	:	20

Table 3—Optimized results after application of GA to find the various solutions for different layers

Solution: 1	Thickness of the layer (in mm)
1st layer –5th material from database	1.269
2nd layer –13th material from database	0.662
3rd layer –11th material from database	1.262
4th layer– 2nd material from database	1.822
Solution: 2	
1st layer –4th material from database	0.722
2nd layer –6th material from database	0.318
3rd layer –3rd material from database	1.482
4th layer– 12th material from database	1.724
Solution: 3	
1st layer –13th material from database	0.57
2nd layer –10th material from database	0.25
3rd layer –12th material from database	1.819
4th layer– 10th material from database	0.691
Solution: 4	
1st layer –14th material from database	0.342
2nd layer –14th material from database	1.859
3rd layer –13th material from database	0.665
4th layer– 6th material from database	1.056

3 Measurement of microwave absorption

3.1 Absorption testing device (ATD) method

The microwave absorption has been measured by ATD method[3,5]. The ATD is a pyramidal horn antenna with extended waveguide section and is connected at the aperture of the horn antenna. The experimental set-up[3,5] is shown in Fig. 3 .

The reflected power is noted down without coating on aluminum plate (P_1). Then reflected power with absorber coated aluminum plate is noted (P_2). The difference in two powers gives the power absorbed by the absorber[5].

3.2 Radar cross-section (RCS) method

The RCS can technically be defined as the area of a fictitious perfect reflector of electromagnetic waves that would reflect the same amount of energy back to the transmitting/receiving radar antenna, as would do the actual target[9].

The RCS of a flat plate as a function of the angle (θ) incident to the surface can be approximately described[12] as

$$\sigma(\theta)=\frac{4\pi A^2}{\lambda^2}\left[\frac{\sin(kb\sin\theta)}{kb\sin\theta}\right]^2\cos^2\theta \qquad \ldots (4)$$

where,

σ = Radar cross-section (m^2)

λ = Wavelength (m)

A = Area of the square plate

θ = Angle from normal to the plate

k = 2π/λ

b = Dimension of plate sides.

The theoretical RCS value of a perfect flat rectangular reflector as a function of incident radiation frequency can be expressed as[9]

$$\sigma_{AL}=\frac{4\pi A^2}{\lambda^2} \qquad \ldots (5)$$

The RCS of the sheet with absorber coating is expressed as[12]

$$\sigma_{ABS}(\theta)=\frac{P_{rABS}}{P_{rAL}}\sigma_{AL} \qquad \ldots (6)$$

where σ_{ABS} is the RCS of absorbing sheet in m^2, σ_{AL} the RCS of aluminum sheet in m^2, P_{rABS} the power received from the absorbing sheet, and P_{rAL} the power received from the aluminum sheet.

3.3 Experimental set-up

The method for RCS measurement requires a double face panel, where one side is used as reflector material (reference) and the other side is coated with RAM. The panel is fixed on an azimuth elevation positioner, which is positioned in front of the receiving and transmitting horn. The advantage of this methodology is that it allows the evaluation of the reference and RAM by rotating the device from 0 to 360°, evaluating both sides of the panel one after the other. Figure 4 shows a simplified scheme of the devices used in the RCS measurement. It is not necessary to make two separate measurements, because the RCS diagram of RAM is made by rotating the device from 0 to 180° and the reference (metal plate-reflector) is made from 180 to 360°. Thus, it is a self-calibrating measurement[9]. The experimentation was carried out inside the anechoic chamber and the set-up for RCS measurement is shown in Fig. 4.

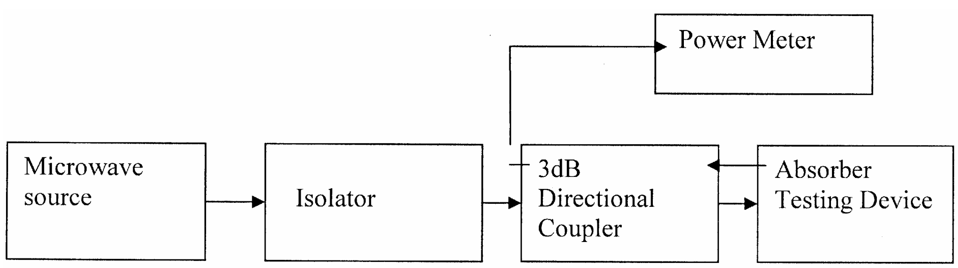

Fig. 3—Schematic diagram for the experimental set-up

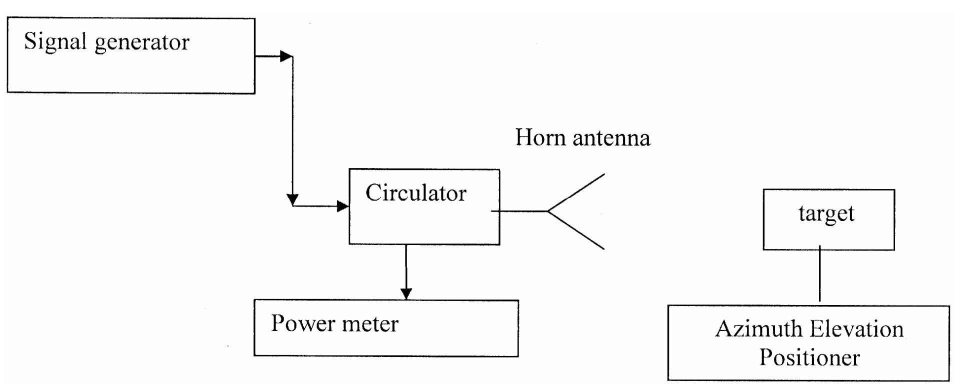

Fig. 4—Experimental set-up for RCS measurement

4 Result and discussion

4.1 ATD measurement

The first solution, out of four optimized solutions, is chosen for implementation. The average attenuation for all the frequencies after the first coat is around 0.6 dB with the maximum attenuation of 1.1 dB at 9.5 GHz as shown in Fig. 5(a).

After applying the second layer above the first one, there is a significant improvement in the attenuation level. The average attenuation level improved to 3 dB and interestingly there are two peaks of attenuation level at frequencies of 9.5 GHz (12.6 dB) and 11.5 GHz (16.8 dB) as shown in Fig. 5(b). This is due to the resonance effect in ferrites at these frequencies. Because, one of the main reasons of attenuation is the resonance phenomena occurred in ferrite material with incident frequency[2,3].

The plot for third layer as shown in Fig.5(c) is better than the first two layers. The attenuation is almost uniform throughout the frequency range. The maximum attenuation is 14.3 dB at 8 GHz, being the minimum of 6.4 dB at 8.5 GHz as shown in Fig.5(c).

The fourth layer gave a more stable result. The average attenuation is around 10 dB, being the maximum of 12 dB at 10 GHz and minimum of 6.8 dB at 11 GHz as shown in Fig. 5(d). This is similar to the result at third layer since the attenuation saturates at 4^{th} layer. One more reason behind the saturation is that, as thickness increases further there will be a decrease in attenuation[2].

4.2 RCS Measurement

The RCS is calculated at X-band for aluminum (Al) sheet of 0.0929 m^2 surface area. The powers received from the Al sheet and absorber coated sheet are measured by experimental method in the anechoic chamber. The variation of RCS with azimuth angle at the steps of 10^o was noted.

The results obtained show a significant reduction in RCS due to the application of ferrite material coating. The RCS of the Al sheet increases as the frequency increases. This is because RCS is inversely proportional to the wavelength of the incident frequency. The RCS of Al sheet at 8 GHz is 82.52 m^2 and 185.68 m^2 at 12 GHz. The reduction in RCS can be observed from Tables 4, 5 and 6 after two, three and four layers of coating, respectively. The RCS for the absorber coated sheet after first two coatings is of 71.22 m^2 at 8 GHz showing a reduction of 13.7%. As the frequency is raised the RCS also increases, being 156.955 at 12 GHz with a reduction of 15.47%. There is a reduction of 42.96 m^2 at 10 GHz which shows a RCS reduction of 33.32%.

After three layers of coating (Table 5), it is observed that maximum RCS reduction is 26.96% at 8 GHz, while at other frequencies of X-band spectra a good amount of reduction is observed.

The minimum RCS is obtained after 4 layers of coating at 8 GHz. The RCS of the absorber at this frequency is 55.66 m^2, giving a reduction of 26.86 m^2 from 82.52 m^2. The percentage reduction is 32.55%. It

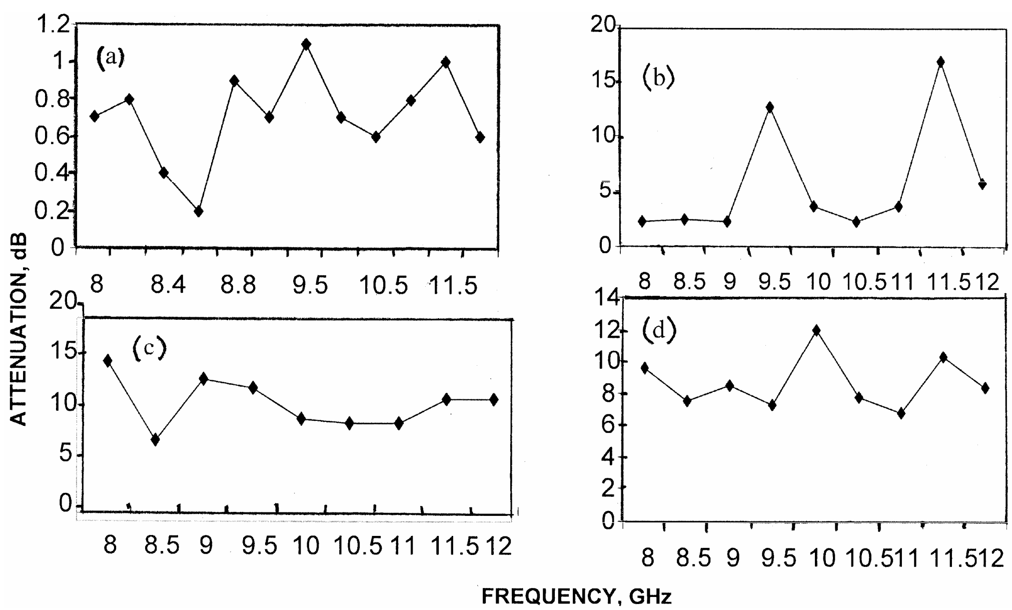

Fig. 5—Attenuation vs frequency plot of (a) Layer 1 [$Ba(MnTi)_{3.5}Fe_{5.0}O_{19}$], (b) Layer 2 [$BaTiO_3$], (c) Layer 3 [$Ba(MnTi)_{1.6}Fe_{8.8}O_{19}$] and (d) Layer 4 [$Ba(MnTi)_{1.7}Fe_{8.6}O_{19}$]

Table 4—RCS reduction chart after 2-layer coating

Frequency GHz	RCS (Al) m^2	RCS(Abs) m^2	Reduction in RCS m^2	% reduction in RCS
8	82.5266	71.2187	11.3	13.7
9	104.4478	87.6797	16.77	16
10	128.9479	85.9833	42.96	33.32
11	156.0269	125.66	30.367	19.43
12	185.6849	156.955	28.73	15.47

Table 5—RCS reduction chart after 3-layer coating

Frequency GHz	RCS (Al) m^2	RCS(Abs) m^2	Reduction in RCS m^2	% reduction in RCS
8	82.5266	60.27	22.25	26.96
9	104.4478	83.12	21.32	20.41
10	128.9479	101.80	27.14	21.05
11	156.0269	141.70	14.32	9.18
12	185.6849	166.43	19.25	10.37

Table 6—RCS reduction chart after 4-layer coating

Frequency GHz	RCS (Al) m^2	RCS(Abs) m^2	Reduction in RCS m^2	% reduction in RCS
8	82.5266	55.66	26.86	32.55
9	104.4478	84.5	19.95	19.08
10	128.9479	106.7614	22.188	17.21
11	156.0269	131.58	24.45	15.67
12	185.6849	172.1	13.68	7.36

is apparent from the Tables 4 and 5 that the RCS increases with the increase in frequency which is true for both the cases. If we compare the results from Tables 4, 5 and 6, it is very clear that the maximum reduction of RCS at 8 GHz is after the 4-layer coating, while at 10 GHz two-layer coating also gives good results.

5 Summary and conclusions

A four-layered radar absorbing coating is designed and optimized by using genetic algorithm. The optimized layer material and its corresponding thickness are obtained. Then the paint is prepared by using the ferrite materials and resin and coated on an Al sheet. Implementation of multilayered radar absorbing coating by using GA gives very encouraging results. The optimized layer materials and their thicknesses are implemented and tested by an ATD (X-band). It has been observed that the attenuation increases as the number of layers are raised and stable results are obtained at 4-layer coating. Then the same layers are coated on an Al plate of size (304.8×304.8 mm^2) and RCS (m^2) is measured for both Al sheet and the ferrite coated sheet at X-band by the method discussed in above sections. The results showed a RCS reduction of 10-35% when the ferrites coating are applied on the Al sheet. Better results are obtained at 10 GHz for 2-layer coating and at 8 GHz for 4-layer coating. From the above observations it can be concluded that we have to optimize the RAM layer thicknesses on a particular frequency so that it will be easy to make the system as per the requirement.

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