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DESIGN AND OPTIMIZATION OF MULTILAYERED ELECTROMAGNETIC SHIELD USING A REAL-CODED GENETIC ALGORITHM

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Abstract—We report optimized design of multilayered electromagnetic shield using real coded genetic algorithm. It is observed that the shielding effectiveness in multilayer design is higher than single layered counterpart of equal thickness. An effort has been made to develop an alternative approach to achieve specific objective of identifying the design characteristics of each layer in the multilayered shielding configuration. The proposed approach incorporates interrelated factors, such as absorption and reflection in the design optimization as per specific shielding requirements. The design problem has been solved using shielding effectiveness theory based on transmission line (TL) modeling and real-coded genetic algorithm (GA) with simulated binary crossover (SBX) and parameter-based mutation. The advantage of real-coded GA lies in efficient solution for electromagnetic interference (EMI) shielding design due to its strength in solving constraint optimization problems of continuous variables with many parameters without any gradient information. Additionally, the role of material parameters, such as permittivity and permeability on reflection characteristics and shielding effectiveness, has also been investigated and optimized using the proposed models and real-coded GA. Theoretical optimization of electromagnetic parameters has been carried out for SE $\sim 40\,\text{dB}$ for many industrial/commercial applications and SE $\sim 80\,\text{dB}$ for military applications.

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1. INTRODUCTION

The Electromagnetic Interference (EMI) problems have impacted almost all electronic and electrical equipments ranging from daily use to critical applications where storage, protection and safe transmission of information are desirable. Shielding of EMI and electromagnetic pulse by using some protective materials is not only desirable but it is felt necessary to improve performance or catastrophic failure in the case of crucial devices, such as medical devices, military equipment, weapon controllers, computers, mobile phones, television sets and vents, etc. In fact, shielding is a technique to reduce or prevent the transmittance of disruptive electromagnetic energy from one device to another via conduction and/or radiated paths. This enables the device to operate compatibly with its electromagnetic environment. The shielding or its efficiency against electromagnetic (EM) waves is measured in terms of shielding effectiveness (SE) and it is defined as *the ratio of the signal received (from transmitter) without the shield to the received signal inside the shield* [1].

To meet the shielding criteria laid down by various regulations [2] as per specific needs, the quest for materials R & D began covering a broad range including the metals, magnetic materials, plastics coated with conductive layers, i.e., conductive composites, etc. Literature reveals that intrinsically conducting polymers (ICPs), such as Polyaniline-Polyurethane (PANI/PU) based conducting composites, exhibit excellent materials properties, such as high conductivity and permittivity, lighter weight, good environmental stability and ease in synthesis which is considered desirable for shielding applications [3]. However, while working with polymer composites to achieve desired electromagnetic properties, it was observed that their mechanical properties deteriorate with increase in the mass fraction of conductive materials into the insulating matrix. Further, there are technological limitations in striking a perfect balance among film thickness, conductivity and mechanical properties of the ICPs in order to achieve the desired electromagnetic shielding properties. This has, in fact, been noted in terms of observed improvement in EMI Shielding properties of PANI/PU film produced by spray coating method which limits the thickness of the composite at an acceptable range of values [4]. An alternative way to prepare thicker material is to use multilayer approach favoring higher SE for the same thickness as of a single layer composite material [5]. However, among the methods or materials available to design and develop, such a shield, an offset should be reached in terms of shielding performance, thickness, weight and manufacturing cost.

To achieve minimum reflection coefficient of the multilayered compound from the predefined database of various materials, the selection of materials is obtained by employing genetic algorithm (GA) [6]. Similar approach has been adopted to optimize the selection of material by formulating different objective functions, such as SE, reflection or absorption from the given set of materials to achieve minimum thickness by several other groups [7–10]. In place of selecting materials from the predefined database, researchers in [3] optimize the material parameters from the given range (upper and lower bounds) to achieve the desired shielding efficiency of the multilayered compound for a given application using the binary-coded GA. However, the results reported are not unique and lack reproducibility for a given SE requirement.

Most of the applications of the GA to constraint optimization problems are addressed by the penalty function approach. The penalty function involves a lot of penalty parameters which has to be set appropriately to guide the search towards the feasible solutions. Besides, literature [11] reveals that solving the optimization problem of continuous search space using binary-coded GA has a number of difficulties, such as (a) Transition to neighboring solution requires alteration of many bits (called as hamming cliffs), (b) The string length must be chosen priori to achieve certain precision. However, high precision requires larger string length, which increases the computational complexity, and (c) Single-point crossover may not always be able to create the feasible children solution from the two feasible parent solutions.

In this paper, we propose three types of possible objective formulations subjected to various constraints with an aim to optimize the multilayered shielding structure. Proposed formulations are applied to optimize three-layered structure of PANI/PU composite. Two of our formulations consider interrelated factors, such as absorption and reflection in the design optimization as per specific shielding requirements. To eliminate the difficulties associated with binary GAs, we employ real-coded GA with simulated binary crossover operator (SBX) and a parameter based mutation [11–13]. As reported in the literature that in the case of continuous variables the use of real-coded GA with constraint handling functions, SBX and parameter-based mutation operator provides an efficient, reliable and accepted solution with more robustness (i.e., more number of successful GA runs finding solutions close to the best-known solution) than the binary-coded GA. For the penalty function we used the fitness function proposed by [13]. The optimization has been carried out in view of the requirement of SE $\sim$ 40 dB for many industrial/commercial applications and SE $\sim$ 80 dB for military applications (Federal Communications Commission (FCC) Class B, Part 15), at 50 MHz and 8 GHz of frequency respectively. Further, SE variation is investigated with respect to permeability and permittivity, with an aim to optimize by introducing the permeability into the outer layer and permittivity of the supporting layer.

2. THEORETICAL AND CONCEPTUAL BACKGROUND

2.1. Electromagnetic Shielding Effectiveness Calculation

Electromagnetic shielding effectiveness can be specified in the terms of reduction in magnetic (and electric) field or plane wave strength. It is generally expressed in decibels (dB) as a function of the logarithmic ratio of incident and transmitted electric (E) (or magnetic (H)) fields or wave power (P) (1):

$$\mathrm{SE}\,(\mathrm{dB}) = 20\log_{10}\left|\frac{E_i}{E_t}\right|, \quad \text{or} \quad 20\log_{10}\left|\frac{H_i}{H_t}\right|, \quad \text{or} \quad 10\log_{10}\left|\frac{P_i}{P_t}\right| \tag{1}$$

where subscripts i and t represent incident and transmitted field or power, respectively.

The effectiveness of the shield and the resulting attenuation of EMI depends on a variety of factors including the material parameters (i.e., permittivity, permeability and thickness), source to shield distance, frequency, angle of incidence, polarization of the wave and shielding geometry. However, in many practical applications, most of the variables are already fixed by the nature of the problem itself. For instance, the SE for planar structure at normal incidence in far-field region requires the optimum choice of the remaining parameters, such as thickness and electromagnetic properties of the shielding material.

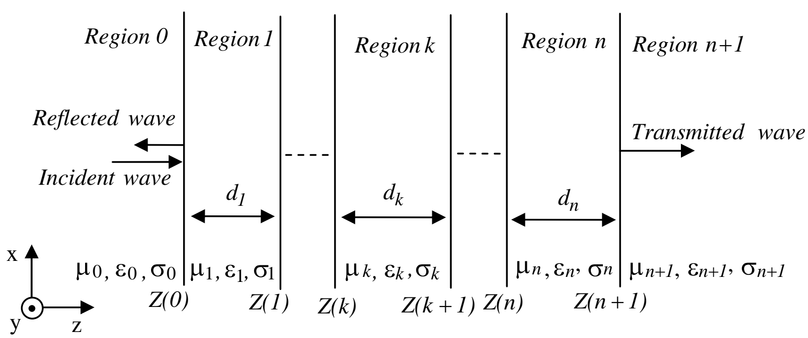

Figure 1. Normal incidence of plane wave on a planar multilayer shield.

Consider a plane wave normally incidenting onto the planar multilayer composite of thickness $d_1, \ldots, d_n$ with layers' boundaries at $Z(0), Z(1), \ldots, Z(n)$, respectively as shown in Fig. 1. Each medium is assumed to be homogeneous and isotropic with the parameters of the constitutive kth layers are denoted as permittivity (ε_k), permeability (μ_k), conductivity (σ_k), and thickness (d_k). The 0th and $(n+1)$th regions are semi-infinite which may carry different characteristics.

The electromagnetic shield transmitting the plane EM waves have been found to be analogous to the two wire power transmission line. Modeling the SE theory for any number of layers or laminations of a single sheet against normal incidence using the transmission line theory is easier than field method [14, 15]. The input impedance seen at the left boundary of the kth layer towards the right side is given by (2):

$$Z_{in}(d_k) = \eta_k \frac{Z(d_k)\cos h(\gamma_k d_k)+\eta_k \sin h(\gamma_k d_k)}{Z(d_k)\sinh(\gamma_k d_k)+\eta_k \cos h(\gamma_k d_k)}, \quad k = 1, 2, \ldots, n \quad (2)$$

where γ_k, η_k, and $Z(d_k)$ respectively represent the propagation constant, characteristic impedance and load impedance; $\gamma_k = \sqrt{j\omega\mu_k(\sigma_k + j\omega\varepsilon_k)} = \alpha_k + j\beta_k$, $\eta_k=\sqrt{\frac{j\omega\mu_k}{(\sigma_k+j\omega\varepsilon_k)}}$, $\omega = 2\pi f$, where f is the frequency of the EM waves.

Real part of the propagation constant α_k is attenuation constant and it is measured in nepers per meter (Np/m), whereas β_k is the phase constant and is measured in radians per meter (rad/m).

The transmission coefficients, which are the ratios of transmitted to the incident fields is given by the following expression (3):

$$T_m = P_m \prod_{k=1}^{n} \frac{\exp\left[-d_k(\gamma_k - \gamma_0)\right]}{\left[1 - q_k \exp(-2\gamma_k d_k)\right]} \quad (3)$$

where m represents either electric field (E) or magnetic field (H) and

$$P_E = \frac{2^{n+1}\eta_1\eta_2 \ldots \eta_n Z_L}{(\eta_0 + \eta_1)(\eta_1 + \eta_2) \ldots (\eta_k + Z_L)},$$
$$P_H = \frac{2^{n+1}\eta_0\eta_1 \ldots \eta_n}{(\eta_0 + \eta_1)(\eta_1 + \eta_2) \ldots (\eta_n + Z_L)}$$
$$q_k = \frac{(\eta_k - \eta_{k-1})(\eta_k - Z(d_k))}{(\eta_k + \eta_{k-1})(\eta_k + Z(d_k))}, \quad k = 1, 2, \ldots, n$$

The total shielding effectiveness can be determined by using (3) as (4):

$$\mathrm{SE_{dB}} = -20\log_{10}|T_m| \quad (4)$$

When the shield is inserted in the homogeneous media, i.e., $Z_L = \eta_{k+1} = \eta_0$, the shielding effectiveness of incident plane wave against electric and magnetic fields will be the same. In this work, we assume that the impedance of the media around the shield are the same; in such a case, P_E will be equal to P_H. Corresponding absorption loss (A) in dB inside the shield, the total reflection loss (R) in dB from both surfaces of the shield and the correction term (B) in dB due to successive re-reflections in the homogeneous media are (5):

$$\begin{aligned} \mathrm{SE_{dB}} &= 20\log_{10}\left|\exp\sum_{k=1}^{n}\gamma_k d_k\right| - 20\log_{10}|p| \\ &\quad +20\log_{10}\left|\prod_{k=1}^{n}\left(1-q_k\exp(-2\gamma_k d_k)\right)\right| = A+R+B \end{aligned} \tag{5}$$

2.2. Shielding Material

Many types of materials are available for shielding from EMI including metals, ferrites, conductive polymers made by adding carbon black, carbon fiber, metal powders, or metallic fillers [16]. However, compared to the metals or composite polymer (CPs), ICPs, such as PANI/PU, have some better properties as mentioned above in Section 1. The freestanding films of PANI/PU were experimentally prepared and linear fitting of the DC conductivity at different concentrations of PANI are provided in [3, 17]. The DC conductivity of the composite PANI/PU freestanding films with different concentrations of PANI is reproduced in Table 1.

Conductivity at different concentrations of the PANI/PU films is a percolation phenomenon and follows the scaling law of the electrical percolation (6):

$$\sigma(p) = \sigma_0 (p - p_c)^t \tag{6}$$

where σ_0, p_c, p, t are respectively reference conductivity, percolation threshold, concentration of PANI in the blends, and critical exponent. The experimental results are fitted by plotting $\log(\sigma(p))$ vs $\log(p - p_c)$and incrementally varying p_c until the best linear fit is obtained. The best fitted linear model yields the values of critical exponent, percolation threshold and reference conductivity 2.361, 0.188% and 3.2608 S/m, respectively.

Table 1. DC conductivity of the composite PANI/PU.

Material	PANI 0.2/PU	PANI 0.5/PU	PANI 1/PU	PANI 4.7/PU	PANI 8.8/PU	PANI 16/PU	PANI 44/PU
Conductivity σ (S/m)	10^{-4}	0.1	2.44	235	792	2456	11500

3. PROBLEM FORMULATION AND SOLUTION METHODOLOGY

3.1. Problem Formulation

Multilayer materials provide a higher potential to get a material with better properties, such as higher SE, lower weight, and lower cost. At the same time, construction of such materials presents the challenges to obtain the design characteristics of each layers, i.e., thickness and conductivity, under some specified objective. This problem can be formulated as an optimization problem with objective function, such as SE, absorption or reflection within given constraints of the design characteristics of each layer.

Before going into the details of the solution methodology, we present the proposed problem formulations for multilayered composite material.

3.1.1. Model I

In this model, we consider the case when the total thickness of the composite material is fixed. The objective function depends on the level of desired $\mathrm{SE_{fix}}$, i.e., 40 and 80 dB shielding. The problem can be stated as (7)–(9):

$$f\left(\epsilon_1,\mu_1,\sigma_1,d_1,\ \ldots\ ,\epsilon_k,\mu_k,\sigma_k,d_k\right)$$
$$= \text{Minimize}\left\{20\log\left(\left|10^{-\frac{\mathrm{SE_{fix}}}{20}}-\left|T(\epsilon_k,\mu_k,\sigma_k,d_k)\right|\right|\right)\right\}; \quad (7)$$

$$\text{Subject to}\quad d_1+,\ \ldots\ ,+d_k = D \quad (8)$$

$$\left.\begin{array}{l}\sigma_{1L},\ \ldots\ ,\sigma_{kL} \le \sigma_1,\ \ldots\ ,\sigma_k \le \sigma_{1U},\ \ldots\ ,\sigma_{kU}\\ d_{1L},\ \ldots\ ,d_{kL} \le d_1,\ \ldots\ ,d_k \le d_{1U},\ \ldots\ ,d_{kU}\\ \varepsilon_{1L},\ \ldots\ ,\varepsilon_{kL} \le \varepsilon_1,\ \ldots\ ,\varepsilon_k \le \varepsilon_{1U},\ \ldots\ ,\varepsilon_{kU}\\ \mu_{1L},\ \ldots\ ,\mu_{kL} \le \mu_1,\ \ldots\ ,\mu_k \le \mu_{1U},\ \ldots\ ,\mu_{kU}\end{array}\right\} \quad (9)$$

where D is the total thickness of the material, T $(\varepsilon_k,\ \mu_k,\ \sigma_k,\ d_k)$ the transmission coefficient as defined in (3), $\mathrm{SE_{fix}}$ the desired shielding effectiveness, ε_k, μ_k, σ_k the electrical properties of the material chosen, and d_k the thickness for kth layer. In operations research, the equality constraints are generally handled by converting them into the inequality constraints, such as $D \le d_1+,\ \ldots\ ,+d_k \le D+\psi$, where ψ is a small positive value. Besides, it is advised to normalize constraints to avoid any influence from any particular constraints. Now (8) can be rewritten as:

$$\left(\left(d_1+\ \ldots\ +d_k\right)/D\right)-1 \ge 0, \quad \text{and} \quad 1-\left(\left(d_1+\ \ldots\ +d_k\right)/\left(D+\psi\right)\right) \ge 0$$

The variables in (9) for the kth layer, viz., conductivity, thickness, permittivity and permeability vary in the range $(\sigma_{kL}, \sigma_{kU})$, (d_{kL}, d_{kU}), $(\varepsilon_{kL}, \varepsilon_{kU})$, and (μ_{kL}, μ_{kU}).

Depending on applications, a device needs an appropriate shielding that can either absorb or reflect the incident electromagnetic energy on it. So, rather than optimizing every component of total SE, it would be better to maximize one component of total SE (5) while keeping other components within bounds and as specified in constraints. The following proposed models will demonstrate the generation of suitable material as described above that provides high absorption or high reflection.

3.1.2. Model II

The objective is to maximize the absorption for the level of desired $\mathrm{SE_{fix}}$, i.e., 40 dB commercial/industrial, or 80 dB military application. The problem can be stated as (10):

$$\begin{aligned}
& f\left(\epsilon_1, \mu_1, \sigma_1, d_1, \ldots, \epsilon_k, \mu_k, \sigma_k, d_k\right) \\
& = \text{Maximize}\left\{20 \log\left(A(\epsilon_k, \mu_k, \sigma_k, d_k)\right)\right\}; \qquad (10) \\
\text{Subject to} \quad & \left(\mathrm{SE}\left(\epsilon_1, \mu_1, \sigma_1, d_1, \ldots, \epsilon_k, \mu_k, \sigma_k, d_k\right)/\mathrm{SE_{fix}}\right) - 1 \geq 0 \\
& 1 - \left(\mathrm{SE}\left(\epsilon_1, \mu_1, \sigma_1, d_1, \ldots, \epsilon_k, \mu_k, \sigma_k, d_k\right)/(\mathrm{SE_{fix}} + \psi)\right) \geq 0 \\
& \left.\begin{array}{l}
\sigma_{1L}, \ldots, \sigma_{kL} \leq \sigma_1, \ldots, \sigma_k \leq \sigma_{1U}, \ldots, \sigma_{kU} \\
d_{1L}, \ldots, d_{kL} \leq d_1, \ldots, d_k \leq d_{1U}, \ldots, d_{kU} \\
\varepsilon_{1L}, \ldots, \varepsilon_{kL} \leq \varepsilon_1, \ldots, \varepsilon_k \leq \varepsilon_{1U}, \ldots, \varepsilon_{kU} \\
\mu_{1L}, \ldots, \mu_{kL} \leq \mu_1, \ldots, \mu_k \leq \mu_{1U}, \ldots, \mu_{kU}
\end{array}\right\}
\end{aligned}$$

3.1.3. Model III

In this model, the objective is to maximize the reflection for the level of desired $\mathrm{SE_{fix}}$, i.e., 40 dB and 80 dB shielding effectiveness. The objective function and constraints are defined as (11):

$$\begin{aligned}
& f\left(\epsilon_1, \mu_1, \sigma_1, \ldots, \epsilon_k, \mu_k, \sigma_k\right) \\
& = \text{Maxmize}\left\{-20 \log\left(R(\epsilon_k, \mu_k, \sigma_k)\right)\right\}; \qquad (11) \\
\text{Subject to} \quad & \left(\mathrm{SE}\left(\epsilon_1, \mu_1, \sigma_1, d_1, \ldots, \epsilon_k, \mu_k, \sigma_k, d_k\right)/\mathrm{SE_{fix}}\right) - 1 \geq 0 \\
& 1 - \left(\mathrm{SE}\left(\epsilon_1, \mu_1, \sigma_1, d_1, \ldots, \epsilon_k, \mu_k, \sigma_k, d_k\right)/(\mathrm{SE_{fix}} + \psi)\right) \geq 0 \\
& \left.\begin{array}{l}
\sigma_{1L}, \ldots, \sigma_{kL} \leq \sigma_1, \ldots, \sigma_k \leq \sigma_{1U}, \ldots, \sigma_{kU} \\
d_{1L}, \ldots, d_{kL} \leq d_1, \ldots, d_k \leq d_{1U}, \ldots, d_{kU} \\
\varepsilon_{1L}, \ldots, \varepsilon_{kL} \leq \varepsilon_1, \ldots, \varepsilon_k \leq \varepsilon_{1U}, \ldots, \varepsilon_{kU} \\
\mu_{1L}, \ldots, \mu_{kL} \leq \mu_1, \ldots, \mu_k \leq \mu_{1U}, \ldots, \mu_{kU}
\end{array}\right\}
\end{aligned}$$

3.2. Proposed Methodology Using Real Coded GA

GA optimizers generally require the user to select among a number of options before beginning the optimization, such as population size (N), probability of crossover (P_c), probability of mutation (P_m), selection type, details of fitness function, crossover and mutation type. Previous population sizing considerations based on schema processing suggested that it should increase with the problem size [18]. Although the correct N should also depend on the underlying signal-to-noise in a problem with this argument [13] followed a simple procedure to calculate the population size as: $N = 10n$, where n is the number of variables in a problem. Besides, larger populations provide more genetic diversity, which in turn result into faster convergence. Crossover probability (P_c) around 0.7 has been found to be optimal for a wide variety of problems however, high P_c ensures rapid searching and it is a primary way for a GA to search for new and better solutions [19]. In the real-coded GA the mutation operator is the only one that creates new variable values, so we must take much larger P_m than binary-coded GA (P_m typically $0.01 - 0.1$) [20].

The evaluation procedure and reproduction operator remain the same in real-coded GA as that of binary-coded GA; however the crossover and mutation operations are different. Without going into the details, we provide here the procedure to perform p_m and p_c on the population in Steps 5 and 6 of the implemented real coded GA.

Listed below are the steps of the implemented GA with various operators to solve our proposed formulation.

Step 1: Choose N, P_c, P_m, maximum number of generation ($G_{\max}$) and tournament size (T_n).

Step 2: Generate initial population (solutions) using uniform distribution within the specified range of individual electromagnetic parameters and thickness of each layer.

Step 3: Compute objective function and check constraints on these points of population for any violation. If solution is infeasible (i.e., at least one constraint is violated) use fitness function (12),

$$F(\vec{x}) = f(x) = \begin{cases} f(\vec{x}), & \text{if } g_j(\vec{x}) \geq 0 \ \forall\, j = 1, 2, \ldots, m, \\ f_{\max} + \sum_{j=1}^{m} \langle g_j(\vec{x}) \rangle, & \text{otherwise.} \end{cases} \tag{12}$$

where $F(\vec{x})$ is the fitness function, $g_j(\vec{x})$ the number of constraints $j = 1, 2, \ldots, m$, $\langle g_j(\vec{x}) \rangle$ (bracket penalty operator) $= g_j(\vec{x})$, when $g_j(\vec{x})$ is negative and zero, otherwise, $f_{\max}$ is objective function value of the worst feasible solution in the total population. For minimization problem, the fitness function can be transformed and often used as follows (13):

$$\mathcal{F}\left(\vec{x}\right) = \frac{1}{1 + F\left(\vec{x}\right)} \tag{13}$$

Step 4: Select the good strings in the population to form the mating pool using the tournament selection operator with replacement.

In order to use the tournament selection procedure, we first create the random set of competitors and then form the pair of competitors equal to T_n. The winner among the formed pair of competitor is the string corresponding to the competitor with the best fitness $\mathcal{F}\left(\vec{x}\right)$. Repeat this process T_n times to get the population equal to N.

Step 5: Perform crossover on random pairs of population using simulated binary crossover operator (SBX).

SBX operator can control the children solution around the parent solution using the distribution index. For this, first select the parents that will undergo for crossover operation by generating number of random numbers in the range $(0, 1)$ equal to N (corresponding to each string) and check if the random number is $\leq P_c$, then select that string for crossover otherwise the strings are directly placed in an intermediate population.

The procedures of calculating the two children solution c_1 and c_2 from the two parents p_1 and p_2 are as follows:

i) First, generate a random number u between 0 and 1, then find the ordinate $\bar{\beta}$ from the polynomial probability distribution function as follows:

$$\bar{\beta} = \begin{cases} (2u)^{1/(\eta_c+1)}, & \text{if } u \leq 0.5 \\ \left(\frac{1}{2(1-u)}\right)^{1/(\eta_c+1)}, & \text{otherwise,} \end{cases}$$

where η_c is the distribution index and can take any nonnegative value. A small value of η_c allows the children solution to be created far away from the parent solutions and vice versa. For solving all the problems we have used $\eta_c = 1$.

ii) The children solution are calculated as:

$$\begin{aligned} c_1 &= 0.5\left[(p_1 + p_2) - \bar{\beta}\left|p_2 - p_1\right|\right] \\ c_2 &= 0.5\left[(p_1 + p_2) + \bar{\beta}\left|p_2 - p_1\right|\right] \end{aligned}$$

For calculating the c_1 and c_2 within the given constraints of p^L and p^U, $\bar{\beta}$ needs to be changed as:

$$\bar{\beta} = \begin{cases} (\alpha u)^{1/(\eta_c+1)}, & \text{if } u \leq \frac{1}{\alpha} \\ \left(\frac{1}{2-\alpha u}\right)^{1/(\eta_c+1)}, & \text{otherwise,} \end{cases}$$

where $\alpha = 2 - \beta^{-(\eta_c+1)}$ and $\beta = 1 + \frac{2}{c_2 - c_1} \min\left[\left(p_1 - p^L\right), \left(p^U - p_2\right)\right]$.

Here it is assumed that $p_1 < p_2$. Moreover, the above equation can be modified for $p_1 > p_2$.

Step 6: Perform mutation operation with mutation probability of P_m.

To calculate the mutation for the constraint variables, a perturbance factor $\bar{\delta}$ is defined as follows:

$$\bar{\delta} = \begin{cases} \left[2u+(1-2u)\left(1-\delta\right)^{\eta_m+1}\right]^{1/(\eta_m+1)} - 1 & \text{if } u \leq 0.5; \\ 1-\left[2(1-u)+2\left(u-0.5\right)\left(1-\delta\right)^{\eta_m+1}\right]^{1/(\eta_m+1)} & \text{otherwise,} \end{cases}$$

where u is the random number between 0 and 1. η_m is the distribution index and can take any nonnegative value, $\delta = \min\left[\left(p - p^L\right), \left(p^U - p\right)\right] / \left(p^U - p^L\right)$ and the maximum permissible perturbance in the parent value p is $\Delta_{\max} = p^U - p^L$. Thereafter, the mutated child solution is calculates as follows:

$$c = p + \bar{\delta}\Delta_{\max}$$

Step 7: Replace the old population with the newly formed population.

Step 8*:* Check for the termination criteria, i.e., $G_{\max}$ *or (fitness or time of calculation)*, *if* satisfied stop *Else* repeat from Step 3.

Each step of the proposed algorithm is illustrated to solve the following problem:

Illustration: Consider Model I for $\mathrm{SE_{fix}} = 80\,\mathrm{dB}$ at 8 GHz, with the following constraints:

$$\begin{aligned} &500 \leq d_1{+}125{+}d_3 \leq 500.01 \\ &30 \leq \sigma_1, \sigma_3 \leq 10,000 \\ &\varepsilon_1{,}\varepsilon_3{=}\ 0,\ \ \varepsilon_2{=}\ 3.1 \ \text{ and } \ \sigma_2{\approx}\ 0 \\ &10 \leq d_1,\ \ d_3 \leq 300 \end{aligned}$$

The shielding structure considered in this paper is very thin (i.e., thickness < 1 mm in all cases), so we have represented the thickness range of each layer and total thickness range of the three-layered structure in µm.

Step 1: Let us assume $N = 4$, $P_c = 0.9$, $P_m = 0.01$, $T_n = 2$.

Step 2: The initial random populations generated for the above problem are as follows:

N	σ_1	d_1	σ_3	d_3
1	482.3971	114.8680	8133.4304	206.9318
2	4373.0423	235.2334	8697.0530	164.2786
3	5197.0610	109.9155	1610.3226	275.0075
4	8449.9190	69.35973	3511.7743	124.7470

Step 3: Now, calculating the corresponding objective function, constraints, fitness function and fitness function using transformation rule at each string of population is as follows:

N	$f(\vec{x})$	$g_j(\vec{x})$	$F(\vec{x})$	$\mathcal{F}(\vec{x})$
1	−63.059746	−0.141866 0.1418897	−57.193811	−0.017795
2	−89.633059	0.0653656 −0.065337	−57.270340	−0.017771
3	−61.672711	0.0264615 −0.026434	−57.309243	−0.017759
4	−57.335677	−0.482381 0.4823956	−56.853296	−0.017904

Clearly, for the current solution, one of the constraints is violated. $f_{\max} = -57.335677$, $F(\vec{x})$ and $\mathcal{F}(\vec{x})$ can be computed.

Step 4: Tournament selection:

	Competitors	Pairs	Winner with best $\mathcal{F}(\vec{x})$
$T_n = 1$	2, 1, 4, 3	2, 1 4, 3	2 3
$T_n = 2$	3, 4, 1, 2	3, 4 1, 2	3 2

Now, new population consists of the following strings:

New N	Winners	σ_1	d_1	σ_3	d_3
1	2	4373.0423	235.2334	8697.0530	164.2786
2	3	5197.0610	109.9155	1610.3226	275.0075
3	3	5197.0610	109.9155	1610.3226	275.0075
4	2	4373.0423	235.2334	8697.0530	164.2786

Step 5: Executing this step, let the generated random numbers are 0.9794, 0.1759, 0.9436, 0.2460 and our chosen P_c was 0.9($>$ 0.1759 and 0.2460), thus the string 2 and 4 will undergo for crossover operation.

The children solutions obtained after crossover operation are:

	u	$\bar{\beta}$	c_1	c_2
σ_1	0.2645	0.7266	5084.4377	4485.6656
d_1	0.5361	0.9683	111.90057	233.24840
σ_3	0.2804	0.6593	2817.4762	7489.8994
d_3	0.1321	0.4763	246.01600	193.27021

After crossover the population consists of the following strings:

N	σ_1	d_1	σ_3	d_3
1	4373.0423	235.2334	8697.0530	164.2786
2	5084.4377	111.9005	2817.4762	246.0160
3	5197.0610	109.9155	1610.3226	275.0075
4	4485.6656	233.2484	7489.8994	193.2702

Step 6: Because there are total $4 \times 4 = 16$ genes in the whole population, we generate a sequence of random number (1, 2 ... 16) from the range (0, 1) as follows: 0.2160, 0.4859, 0.3609, 0.1941, 0.5397, 0.3785, 0.0098, 0.7955, 0.4948, 0.1167, 0.4013, 0.4203, 0.0816, 0.4860, 0.0059, and 0.3741. The corresponding genes to be mutated are as follows:

Random number	Chromosome number	Bit position	Variable	Variable value
0.0098	2	3	σ_3	2817.4762
0.0059	4	3	σ_3	7489.8994

In all our simulations, we set $\eta_m = 100 + t$, where t is the current generation number. Thus, in the initial generation we mutate the genes (variables) with expected 1% perturbance and as the generations proceed, we mutate with lesser perturbance. After mutation, we get the child solution as follows:

Random number	$\bar{\delta}$	C
0.8380	0.010990	2927.0479
0.9833	0.032790	7816.8218

Step 7: The new population is:

N	σ_1	d_1	σ_3	d_3
1	4373.0423	235.2334	8697.0530	164.2786
2	5084.4377	111.9005	2927.0479	246.0160
3	5197.0610	109.9155	1610.3226	275.0075
4	4485.6656	233.2484	7816.8218	193.2702

Step 8: This completes one iteration of the GA. Now checking the termination criteria, i.e., $G_{\max}$, not reached, therefore, proceed to Step 3 for the next generation simulation.

4. RESULTS AND DISCUSSION

The formulations of the proposed models for the data provided for the material parameters' range of three-layered compounds of PANI/PU and Kapton in Table 2 are place at Appendix A. The middle layer is made of Kapton (a polymer), which has high mechanical strength, toughness, chemical resistance and a good interaction with PANI/PU composite in chemical production process.

The models formulated are solved by running the proposed approach for several independent trials. Now considering Model I, for 40 dB (80 dB) optimization at 50 MHz (8 GHz) frequency with total thickness of 250 µm (500) µm, and running the algorithm with $N = 100$, $P_c = 0.9$, $P_m = 0.01$, $T_n = 4$ and $G_{\max} = 150$, the best obtained solutions are provided in column two of Tables 3–4, respectively. From the resulted conductivity the appropriate concentration of PANI in the blends (mass percentage) is calculated using (6) and shown in column three, whereas rest of columns show absorption, reflection, re-reflection correction factor and SE, respectively.

Table 2. Parameters range for the three-layered composite.

No. of layer	Material	Permittivity ε	Conductivity σ (S/m)	Thickness d (µm)
1	PANI/PU	0.0	$30 - 10^4$	$10^* - 300$
2	Kapton	3.1	≈ 0	125
3	PANI/PU	0.0	$30 - 10^4$	$10^* - 300$

*Here we take the modification of the lower bound in thickness as presented in [3, 17], $d_{\min} = 10$ µm.

Table 3. Design parameters for 40 dB at 50 MHz.

S. No.	Material parameters	Total mass percentage	Absorption (dB)	Reflection (dB)	Re-reflection (dB)	SE
1	$\sigma_1 = 8678.568087$, $d1 = 37.209358$ $\sigma_3 = 2306.626703$ $d3 = 87.845328$,	44.71071	0.937871	95.160668	−56.098539	40.00000
2	$\sigma_1 = 8096.157969$, $d1 = 53.903777$ $\sigma_3 = 1252.528192$, $d3 = 71.174903$	40.22202	0.899283	92.214066	−53.113350	39.999999

Table 4. Design parameters for 80 dB at 8 GHz.

S. No.	Material parameters	Total mass percentage	Absorption (dB)	Reflection (dB)	Re-reflection (dB)	SE
1	$\sigma_1 = 4656.756870$, $d1 = 126.693902$ $\sigma_3 = 6684.915150$, $d3 = 248.336607$	47.337793	44.687639	53.271679	−17.959314	80.00000
2	$\sigma_1 = 7591.989534$, $d1 = 159.377334$ $\sigma_3 = 4749.657811$, $d3 = 215.648863$	48.919511	44.377262	53.899908	−18.277164	80.00000

Table 5. Design parameters for 40 dB at 50 MHz.

S. No.	Material parameters	Total mass percentage	Reflection (dB)	Re-reflection (dB)	SE
1	$\sigma_1 = 885.171617$ $d1 = 300$ $\sigma_3 = 886.863957$, $d3 = 300$ Objective function = 2.179474 dB	21.8540	81.1271257	−43.206710	40.09988
2	$\sigma_1 = 885.353151$, $d1 = 300$ $\sigma_3 = 884.590673$, $d3 = 300$ Objective function = 2.178187 dB	21.8433	81.1169053	−43.2053652	40.08972

In Table 3, reflection value is very high, more than double the required SE. Obviously, these material parameters can provide a very high SE if by some means we control the re-reflections. At low frequency, the absorption loss is generally insignificant and reflection loss becomes the dominant factor to obtain the required SE. In Table 4, one can observe that the reflection is higher than absorption which is more than half the required SE and re-reflection correction factor less than 18 dB.

Considering Model II and performing the GA simulation for $N = 400$, $P_c = 0.9$, $P_m = 0.4$, $T_n = 8$ and $G_{\max} = 400$, the material parameters for 40 dB and 80 dB shielding effectiveness are given in Tables 5 and 6, respectively.

Results depicted in Table 5 represent that even though objective function is to achieve high absorption, its optimal value comes around 2.17 dB, only which is less than reflection. On the other hand, the total thickness is increased to 725 µm to achieve the maximum absorption loss. This design has a very low total mass fraction but could not be a choice by the decision maker due to increased thickness which will results in increased weight of the total composite. On comparing the results of Table 4 and Table 6 indicates that the maximization of absorption provides solution of 51.65 dB as absorption, which is the maximum possible in the given range and SE required and higher than absorption value provided in Table 4 by 7 dB (considering absolute value). Also on the positive side total mass fraction and reflection losses are lesser than the total mass fraction and reflection shown in Table 4. The total thickness obtained after optimization is 725 µm which could be reasonable for achieving 80 dB shielding in which 51.56 dB SE is due to absorption loss.

Solving Model III for 40 dB and 80 dB shielding with an algorithm settings, $N = 400$, $P_c = 0.9$, $P_m = 0.4$, $T_n = 8$ and $G_{\max} = 400$, the resulting solutions are shown in Tables 7–8, respectively.

Tables 7–8 depicts the maximum possible reflection loss within the given constraints. At lower frequency for 40 dB shielding it is highest and more than the double of required SE. While for higher frequency applications reflection loss is 58.26 dB. For both type of applications, this design may be little costly due to increased mass fraction but

Table 6. Design parameters for 80 dB at 8 GHz.

S. No.	Material parameters	Total mass percentage	Reflection (dB)	Re-reflection (dB)	SE
1	$\sigma_1 = 151.001095$, $d1 = 300$ $\sigma_3 = 9853.180268$, $d3 = 300$ Objective function $= 51.657763$ dB	35.2404	40.7938998	−12.353384	80.09827
1	$\sigma_1 = 9846.668389$, $d1 = 300$ $\sigma_3 = 151.879104$, $d3 = 300$ Objective function $= 51.659091$ dB	35.2445	40.8135972	−12.372690	80.09999

Table 7. Design parameters for 40 dB at 50 MHz.

S. No.	Material parameters	Total thickness	Absorption (dB)	Re-reflection (dB)	SE
1	σ_1=10000, d1=10 σ_3=10000, d3=42.556365 Objective function=102.136081	177.556365	0.64136387	-62.7774387	40.00000
2	σ_1 =10000 , d1 = 42.556375 σ_3 =10000 , d3 = 10 Objective function =102.136081	177.556375	0.64136400	-62.7774371	40.00000

Table 8. Design parameters for 80 dB at 8 GHz.

S. No.	Material parameters	Total thickness	Absorption (dB)	Re-reflections (dB)	SE
1	σ_1 =10000, d1=74.603934 σ_3 =10000, d3=188.544826 Objective function=58.26201dB	388.14876	40.620054	-18.882028	80.00004
2	σ_1=10000, d1=190.46295 σ_3 =10000, d3=72.68154 Objective function =58.26201dB	388.14449	40.619395	-18.881375	80.00003

on the other hand this is lighter in weight due to very thin thickness and could have a potential applications for the aerospace industries, satellites and space vehicles.

Further, in this work the variation of SE, absorption, reflection and re-reflection parameters with the variation in permittivity and permeability is investigated. The SE of the high conductive materials is independent of their permittivity or in other words any conducting medium will behave as a good conductor when $\sigma/_{\omega\varepsilon} \geq 10$ [21]; in this case, the value of permittivity is so small in comparison with conductivity that it can be neglected in SE computation. In all our results, it is observed that the first and third layers are conductive layers, to which increasing the permittivity will have no significant effect on SE. Therefore, the effects of middle layer permittivity on the reflection, re-reflection and in turn SE are observed and depicted in Fig. 2 and Fig. 3.

In Fig. 2, variation of re-reflection and reflection with respect to permittivity of middle-layer at different frequencies is shown, where conductivity and thickness of outer layers are fixed and used from results represented in the first row of Table 4. It can be observed that with increasing dielectric constant reflection decreases and re-reflection increases, since both terms are used for the SE calculation, the overall effects of these two terms are compensated and have no significant influence over the SE, as shown in Fig. 3 and provided in Table 9.

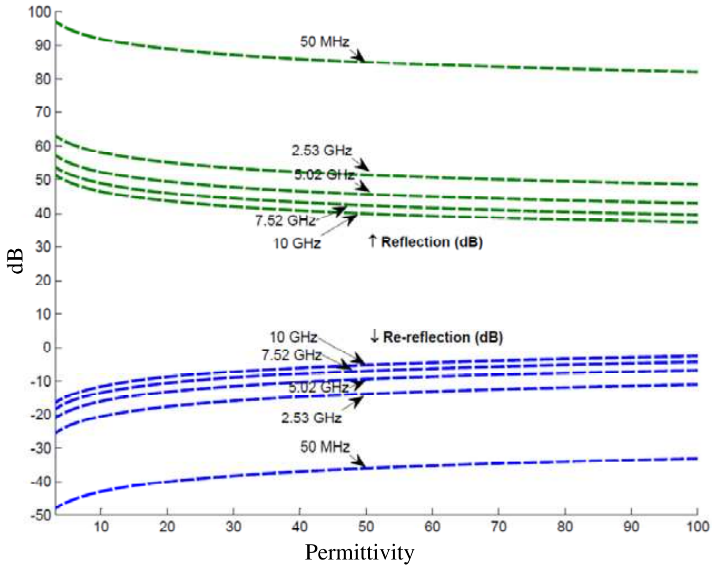

Figure 2. Variation of the reflection and re-reflection as a function of middle-layer permittivity at different frequency.

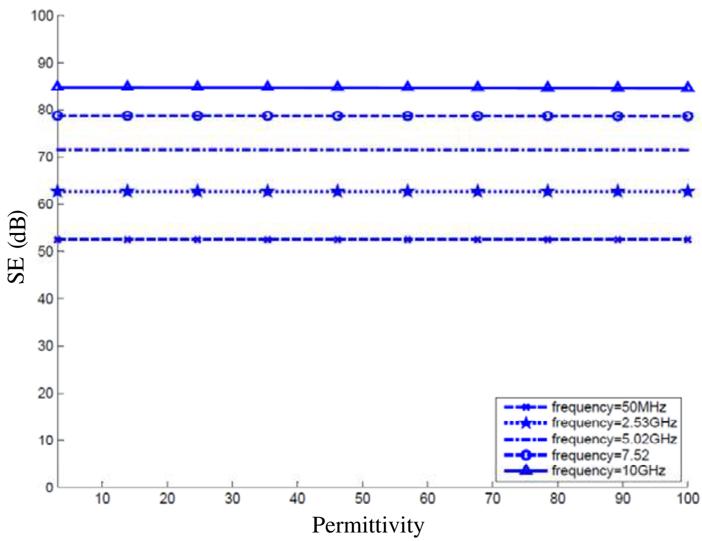

Figure 3. Variation of SE as a function of middle-layer permittivity at different frequency.

Table 9. Shielding effectiveness at different frequency and permittivity of the middle layer.

Frequency	Permittivity		
	3.1	**50**	**100**
50MHz	52.58	52.58	52.58
2.53GHz	62.75	62.74	62.74
5.02GHz	71.64	71.61	71.59
7.52GHz	78.74	78.69	78.63
10GHz	84.83	84.73	84.64

Table 10. Re-reflection (RR) and Reflection (R) values at different frequency and permittivity (of the middle layer).

Frequency	Permittivity		
	3.1	**50**	**100**
50MHz	RR=-48.03dB, R=97.07dB	RR=-36.00dB, R=85.04dB	RR=-33.02dB, R=82.06dB
2.53GHz	RR=-25.53dB, R=63.11dB	RR=-13.79dB, R=51.36dB	RR=-10.97dB, R=48.54dB
5.02GHz	RR=-21.02dB, R=57.25dB	RR=-9.436dB, R=45.63dB	RR=-6.71dB, R=42.88dB
7.52GHz	RR=-18.37dB, R=53.81dB	RR=-6.915dB, R=42.3dB	RR=-4.27dB, R=39.6dB
10GHz	RR=-16.50dB, R=51.37db	RR=-5.172dB, R=39.95dB	RR=-2.62dB, R=37.29dB

Table 11. Range of parameters for the three layered composite.

No. of layer	Relative Permittivity ε_r	Relative Permeability μ_r	Conductivity σ (S/m)	Thickness d (μm)
1	0.0	2	$30-10^4$	$10-300$
2	50	0	≈ 0	125
3	0.0	2	$30-10^4$	$10-300$

Table 10 shows the re-reflection (RR) and reflection (R) in dB, at three permittivity values and five frequency values. At low frequency, lower RR and higher R values are observed. As the frequency increases, RR increases, and R decreases. The permittivity value of 50 increases RR by 12.03 dB at 50 MHz, and 11.328 at 10 GHz and decreases R around same values. Further increasing the permittivity value has less influence on RR and R values, e.g., RR increases to only 2.78 dB at 50 MHz on increasing permittivity value from 50 to 100. Since achieving higher permittivity may increase the cost of material without much reduction in reflection loss, based on above observation we fixed the permittivity at 50. Now, new ranges of parameters for three layered material are provided in Table 11.

Optimization formulations are shown in Appendix A, within the range of the variables as provided in Table 11, and the optimal choice of conductivity and thickness for outer layers is determined

Table 12. Design parameters for 40 dB at 50 MHz.

S. No	Material parameters	Total mass percentage	Absorption (dB)	Reflection (dB)	Re-reflection (dB)	SE
1	σ_1=1253.101628, d1=36.495277 σ_3=5421.155791, d3=88.510565	35.941949	1.347655	72.496950	-33.844600	40.000006
2	σ_1 =232.167431, d1=56.169092 σ_3 =7445.532678, d3=68.836730	32.921430	1.172795	66.683905	-27.856698	40.000002

Table 13. Design parameters for 80 dB at 8 GHz.

S. No.	Material parameters	Total mass percentage	Absorption (dB)	Reflection (dB)	Re-reflection (dB)	SE
1	σ_1 =3338.958087, d1=178.825390 σ_3 =4591.410896, d3=196.205734	40.769708	51.580165	33.289688	-4.869844	80.000008
2	σ_1 =5679.280620, d1=259.687677 σ_3 =1622.202411, d3=115.321149	37.839234	52.861538	31.355716	-4.217257	79.999998

by optimization technique based on real-coded GA as described in Subsection 3.2.

Using Model I for 40 dB (80 dB) optimization at 50 MHz (8 GHz) frequency with total thickness of 250 μm (500) μm and running the algorithm with $N = 100$, $P_c = 0.9$, $P_m = 0.01$, $T_n = 4$ and $G_{\max} = 150$, resulting solutions are provided in Tables 12 and 13, respectively. Assuming that with fixed material parameters (relative permittivity and permeability) specified for outer layers as provided in columns 2 & 3 of Table 11, the parameter conductivity still follows the scaling law of electrical percolation (6). This assumption is merely for calculating the mass fraction required to obtain the optimized conductivity. While using Model II, total mass fraction was minimized using the penalty function approach. It provides the decision maker to obtain a suitable and problem specific solution, instead of total mass fraction, total conductivity or total thickness can be used to model the optimization formulation to constrain the total of them to be lowest possible.

The variation in SE, RR, and R with respect to relative permittivity of middle layers at different frequency can be seen in Fig. 2 and Fig. 3. SE is negligibly changed, while decreasing trend can be seen for reflection loss with respect to increasing the permittivity value. Low reflection type of material could have potential applications for military uses. Further reduction in reflection or increments in absorption loss were achieved through adding permeability to outer layers. The result, presented in Tables 12 and 13, show that there is more than 20 dB decrement in the reflection loss in both the cases for 40 dB and 80 dB shielding when comparing to the reflection loss value provided in Table 3 and Table 4. Whereas due to permeability the value of absorption increased by more than 0.4 dB and 6 dB for 40 dB and 80 dB shielding respectively.

Next, considering Model II to maximize the absorption for the level of desired SE_{fix}, i.e., 40 dB (80 dB) at 50 MHz (8 GHz) frequency with total thickness of 250 μm (500) μm and running the algorithm with $N = 400$, $P_c = 0.9$, $P_m = 0.4$ (for 40 dB), $P_m = 0.2$ (for 80 dB), $T_n = 8$ and $G_{\max} = 300$, results are provided in the Tables 14–15 respectively. In comparison to the above solved models here evaluation function is penalized for achieving the minimum mass fraction or minimum conductivity possible.

Results of Tables 14–15 show that the solutions with penalty

Table 14. Design parameters for 40 dB at 50 MHz.

S. No.	Material parameters (Using penalty function)	Total mass percentage	Reflection (dB)	Re-reflection (dB)	SE
1	σ_1=30, d1=10.001043 σ_3=4563.583098, d3=115.098951 Objective function=1.351349	24.437590	56.113899	-17.465233	40.000014
2	σ_1=4563.581699, d1=115.099186 σ_3=30, d3=10.000542 Objective function =1.351351	24.437587	56.113897	-17.465220	40.000029
	(Without penalty function)				
1	σ_1=3667.479003, d1=48.830881 σ_3=4614.923074, d3= 76.253622 Objective function =1.404354	41.580194	76.422310	-37.737925	40.088739
2	σ_1=4281.948027, d1= 73.003699 σ_3=4118.172900, d3= 52.082155 Objective function =1.401255	41.891925	76.599088	-37.975097	40.025246

Table 15. Design parameters for 80 dB at 8 GHz.

S. No.	Material parameters (Using penalty function)	Total mass percentage	Reflection (dB)	Re-reflection (dB)	SE
1	σ_1=6614.858766, d1= 300 σ_3=30, d3=75.099839 Objective function=54.162190	28.098479	20.777414	5.060443	80.000047
2	σ_1=30, d1=75.033705 σ_3=6615.276985, d3=299.999988 Objective function =54.163081	28.099153	20.777670	5.061154	80.001906
	(Without penalty function)				
1	σ_1=6676.827273, d1= 289.760078 σ_3=375.024059, d3=85.243207 Objective function=55.290236	33.099590	26.852788	-2.046177	80.096847
2	σ_1=6326.199965, d1=300 σ_3=389.246740, d3=75.099727 Objective function=55.323587	32.647519	26.754060	-2.012838	80.064809

Table 16. Design parameters for 40 dB at 50 MHz.

S. No.	Material parameters	Total thickness	Absorption (dB)	Re-reflection (dB)	SE
1	σ_1=10000, d1=33.111923 σ_3=10000, d3=19.443349 Objective function=84. 095459	177.555272	0.907007	-45.002462	40.000004
2	σ_1=10000, d1=27.909513 σ_3=10000, d3=24.645533 Objective function =84.095459	177.555047	0.907003	-45.002459	40.000002

Table 17. Design parameters for 80 dB at 8 GHz.

S. No.	Material parameters	Total thickness	Absorption (dB)	Re-reflection (dB)	SE
1	σ_1=10000, d1=155.917944 σ_3=10000, d3=52.308958 Objective function=40.873339 dB	333.226902	45.455978	-6.329291	80.000026
2	σ_1=10000, d1=50.882197 σ_3=10000, d3=157.359131 Objective function =40.873339dB	333.241328	45.459127	-6.332022	80.000444

function provide lesser reflection and lesser total mass fraction or conductivity than without penalty function. This could be one of the best approaches for designing the shielding with desired thickness and minimum mass fraction or conductivity to achieve lighter and thin shield with maximum possible absorption loss.

Finally using Model III for maximizing the reflection as an objective or cost function and running the algorithm with $N = 400$, $P_c = 0.9$, $P_m = 0.4$, $T_n = 8$ and $G_{\max} = 300$, solution obtained are provided in the Tables 16–17, respectively.

Total reduction in thickness could be possible by solving the SE parameters for maximizing reflection as an objective function. Results depicted that the reflection loss is decreased by 18.04 dB and 17.38 dB on comparing reflection loss of Tables 16–17 with Tables 7–8. Looking at these four tables closely, one can observe that the total thickness at low frequency 50 MHz for 40 dB application does not show any change, while at high frequency 8 GHz it reduces by 54.90 μm. Material parameters Table 17 presents thin and moderately reflective shield and could have a potential application for aerospace.

5. SUMMARY AND CONCLUSION

In this paper, three models for the design of multilayered EMI shield at normal incidence of plane waves are proposed. The plane wave shielding theory based on the transmission line modeling is adopted for SE calculation. The proposed design problem formulations are solved for three-layered composite using real-coded GAs, and the resulting solutions are compared and discussed stepwise. Further, the reflection and SE characteristics with respect to the effect of permittivity were investigated. Based on the present analysis, a suitable relative permittivity for the middle layer was selected, and an additional design parameter (i.e., magnetic permeability) was also considered for outer conducting layers. Optimization was carried out using proposed models with additional material parameters. A comparison between the two types, i.e., a material layer of appropriate relative permittivity with and without permeability, shows that optimization results are acceptable and far improved in all aspects including materials parameters, design parameters and overall shielding effectiveness for a design based on both permittivity and permeability considerations. This is evident from the results reported in various tables of this paper. Reference [10] suggests a new direction for further research towards experimental realization and measurement of such multilayer composites. However, the differences lie in the achievable "thickness" of the composite material (where it varies from 1 mm single layer to 1 cm multilayer) and our predicted results for three-layered composite (varies from $\sim$ 177 μm to $\sim$ 725 μm for 40 dB and $\sim$ 333.2 μm to $\sim$ 725 μm for 80 dB) considering all cases. Therefore, the experimental realization and validity of the predicted results yet remains challenging.

To sum up, the proposed approach with real-coded GA optimization technique can provide vital insight for design and fabrication of an EMI shield. Secondly, scope exists for the incorporation of additional materials/design parameters for further improvement of the shielding quality.

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APPENDIX A. FORMULATIONS OF THE PROPOSED MODELS

A.1. Model I

For $SE_{\text{fix}} = 40\,\text{dB}$ (80 dB) optimization at 50 MHz (8 GHz) frequency with total thickness of 250 µm (500) µm, objective function and constraints are as follows:

$$\begin{aligned}
&f\left(\epsilon_1, \mu_1, \sigma_1, d_1, \ldots, \epsilon_k, \mu_k, \sigma_k, d_k\right)\\
&= \text{Minimize}\left\{20\log\left(\left|10^{-\frac{SE_{\text{fix}}}{20}} - |T(\epsilon_k, \mu_k, \sigma_k, d_k)|\right|\right)\right\};\\
&500 \le d_1 + 125 + d_3 \le 500.01\\
&30 \le \sigma_1, \sigma_3 \le 10,000\\
&\varepsilon_1, \varepsilon_3 = 0,\ \ \varepsilon_2 = 3.1 \ \text{ and } \ \sigma_2 \approx 0\\
&10 \le d_1, d_3 \le 300
\end{aligned}$$

A.2. Model II

To maximize the absorption for the level of desired SE_{fix}, i.e., 40 dB (80 dB) at 50 MHz (8 GHz) frequency, the objective function and constraints are as follows:

$$\begin{aligned}
&f\left(\epsilon_1, \mu_1, \sigma_1, d_1, \ldots, \epsilon_k, \mu_k, \sigma_k, d_k\right)\\
&= \text{Maximize}\left\{20\log\left(A(\epsilon_k, \mu_k, \sigma_k, d_k)\right)\right\};\\
&40(80) \le SE_{\text{fix}} \le 40.1(80.1)\\
&30 \le \sigma_1, \sigma_3 \le 10,000\\
&\varepsilon_1, \varepsilon_3 = 0,\ \ \varepsilon_2 = 3.1 \ \text{ and } \ \sigma_2 \approx 0\\
&10 \le d_1, d_3 \le 300
\end{aligned}$$

A.3. Model III

To maximize the reflection for the level of desired SE_{fix}, i.e., 40 dB (80 dB) at 50 MHz (8 GHz) frequency, the objective function and constraints are as follows:

$$\begin{aligned}
&f\left(\epsilon_1, \mu_1, \sigma_1, \ldots, \epsilon_k, \mu_k, \sigma_k\right)\\
&= \text{Maxmize}\left\{-20\log\left(R(\epsilon_k, \mu_k, \sigma_k)\right)\right\};\\
&40(80) \le SE_{\text{fix}} \le 40.1(80.1)\\
&30 \le \sigma_1, \sigma_3 \le 10,000\\
&\varepsilon_1, \varepsilon_3 = 0,\ \ \varepsilon_2 = 3.1 \ \text{ and } \ \sigma_2 \approx 0\\
&10 \le d_1, d_3 \le 300
\end{aligned}$$

REFERENCES

1. *IEEE Standard: Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures*, IEEE Standard 299, 1997, (revision of IEEE Standard 299, 1991).
2. Morgan, D., "A handbook for EMC testing and measurement," *The Institution of Engineering and Technology*, London, 2007.
3. Hoang, N. H., J.-L. Wojkiewicz, J.-L. Miane, and R. S. Biscarro, "Lightweight electromagnetic shields using optimised polyaniline composites in the microwave band," *Polymers for Advanced Technologies*, Vol. 18, 257–262, 2007.
4. Jourdan, L., O. Schütze, T. Legrand, E.-G. Talbi, and J. L. Wojkiewicz, "An analysis of the effect of multiple layers in the multi-objective design of conducting polymer composites," *Materials and Manufacturing*, Vol. 24, 350–357, 2009.
5. Naishadham, K., "Shielding effectiveness of conductive polymers," *IEEE Transactions on Electromagnetic Compatability*, Vol. 34, No. 1, 47–50, 1992.
6. Michielssen, E., J.-M. Sajer, S. Ranjithan, and R. Mitra, "Design of lightweight, broad-band absorbers using genetic algorithms," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 41, 1024–1031, Jan. 1993.
7. Öktem, M. H. and B. Saka, "Design of multilayered cylindrical shields using a genetic algorithm," *IEEE Transactions on Electromagnetic Compatability*, Vol. 43, No. 2, 170–176, 2001.
8. Jiang, L. Y., X. Y. Li, and J. Zhang, "Design of high performance multilayer microwave absorbers using fast pareto genetic algorithm," *Sci. China Ser. E.-Tech. Sci.*, Vol. 52, No. 9, 2749–2757, 2009.
9. Dib, N., M. Asi, and A. Sabbah, "On the optimal design of multilayer microwave absorbers," *Progress In Electromagnetics Research C*, Vol. 13, 171–185, 2010.
10. Micheli, D., et al., "Broadband electromagnetic absorbers using carbon nanostructure-based composites," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 59, No. 10, 2633–2646, 2011.
11. Deb, K. and R. B. Agrawal, "Simulated binary crossover for continuous search space," *Complex Systems*, Vol. 9, 115–148, 1995.
12. Deb, K. and M. Goyal, "A combined genetic adaptive search (Gene AS) for engineering design," *Computer Science and Informatics*, Vol. 26, No. 4, 30–45, 1996.

13. Deb, K., "An efficient constraint handling method for the genetic algorithm," *Computer Methods in Applied Mechanics and Engineering*, Vol. 186, 311–338, 2000.
14. Schulz, R. B., V. C. Plantz, and D. R. Brush, "Shielding theory in practice," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 30, No. 3, 187–201, 1988.
15. Han, F. and L. C. Zhang, "Degeneration of shielding effectiveness of planar shields due to oblique incident plane waves," *IEEE 1996 International Symposium on Electromagnetic Compatibility, Symposium Record*, 82–86, Aug. 19–23, 1996.
16. Yavuz, Ö., M. K. Ram, M. Aldissi, P. Poddar, and H. Srikanth, "Polypyrrole composites for shielding applications," *Synthetic Materials*, Vol. 151, 211–217, 2005.
17. Hoang, N. N., "Réalisation et caractérisation de structure composite polyaniline-polyuréthane dans le domaine de micro-ondes. Modélisation et optimization de blindage électromagnétique multicouche en utilisant un algorithme génétique," Ph.D. thesis, Ecole Doctorale Des Sciences Physiques et de l'Ingenieur, Université de Bordeaux 1, France, 2005.
18. Goldberd, D. E., K. Deb, and J. H. Clark, "Genetic algorithms, noise, and the sizing of populations," *Complex Systems*, Vol. 6, 333–362, 1992.
19. Johnson, J. M. and Y. Rahmat-Samii, "Genetic algorithms in engineering electromagnetic," *IEEE Antennas and Propagation Magazine*, Vol. 39, No. 4, 7–21, 1997.
20. Vukoć, S. and L. Sopta, "Binary-coded and real-coded genetic algorithm in pipeline flow optimization," *Mathematical Communications*, Vol. 4, 35–42, 1999.
21. Guru, B. and H. Hiziğru, *Electromagnetic Field Theory Fundamentals*, 2nd edition, 362–374, Cambridge University Press, 2009.