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Authors: Abdullah Oğuz KIZILÇAY

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Parameter Optimization of Frequency Selective Surfaces Made of Composite Materials

Abdullah Oğuz KIZILÇAY*[1]

Abstract

Debye model is used for approximating the frequency dependent complex effective permittivity of the composite structures in filter and shielding applications at microwave frequencies. In Debye model, desired shielding effectiveness (SE) is obtained by determining the Debye parameters using trial and error method. But this may result in wasting time or not converging to an optimum solution. In this work to overcome this problem Debye parameters were optimized by using Differential Evolution (DE) algorithm. A Maxwell Garnett (MG) mixing rule was applied to these optimized parameters to obtain frequency selective surface (FSS) parameters. 12dB shielding threshold was chosen between 0.05 – 5GHz frequency range. In accordance with the obtained parameters of FSS, a structure was designed in CST simulation software and simulations had been conducted to obtain SE results. It was seen that the results obtained from analytical computations agree with those obtained from simulations.

Keywords: Frequency selective surface, Debye model, composite material, differential evolution algorithm

1. INTRODUCTION

Composite structures which include conductive inclusions such as carbon rods, spheres have become widely used materials in electromagnetic (EM) shielding problems. Filters, integrated

optical microwave guides, thin films, memory devices, new generation antennas, radar absorbing materials can be counted as application areas where composite structure are used [1-6]. Covering such a wide usage area makes researchers more involved in this subject.

Currently, many composite shield materials are designed with random parameters and numerically analyzed with software like CST, HFSS, FEKO and etc [7-8]. The obtained results are checked whether they meet expectations, before production process is initiated. However, these commercial simulation programs conducted with trial error method do not bring success and

*Corresponding author: oguzkizilcay@yyu.edu.tr
[1]Van Yuzuncu Yil University, Engineering Faculty, Electrical and Electronics Engineering Department, 65080, Van, Turkey , E-Mail: oguzkizilcay@yyu.edu.tr
ORCID: https://orcid.org/0000-0002-7607-0924

they also waste time. Fortunately, heuristic algorithms have a special place as an alternative way of overcoming similar problems.

One of the simplest optimization heuristic algorithms is Differential Evolution algorithm [9]. It was derived from genetic algorithm which can be come across widely in literature. Compared to its counterparts, DE algorithm is relatively easy to apply on problems. In this work, since there were few parameters to be optimized, DE was used.

The main principle of DE is to find local minimum or local maximum value of cost function. Thus, it would be easy to find maximum shielding with given Debye parameters. However, the main feature of FSS is to shield waves in specific frequency band. Because of that, in our case algorithm will converge to desired shielding effectiveness in 0.5 - 5GHz frequency range.

In literature, design parameters of shield materials developed by using Debye model are determined by trial error method. Also, researchers investigating different mathematical approaches did not make use of optimization method either. Seager [3] in his work produce FSS by sewing fiber on fabric. Mannaa and Aldhaheri [5] proposed FSS design aiming to shield GSM 900 and 1800 MHz frequencies. Ghosh et. al. [10] derived transmission line model for their FSS design. Kiermier and Biebl [6] also developed a transmission line model and calculated cutoff frequencies. They aimed to shield GSM and WLAN frequencies. Wang et al. [4] computed the shielding effectiveness of homogenous composite materials with cylindrical inclusions by FDTD method. They observed frequency selective attributes of composite materials. Nisanci et. al. [11] in their work analyzed the effect of physical and electrical parameters of composite structure on shielding efficiency. The common point of all these studies is that produced FSS models were developed by trial and error method. Therefore, literature lacks analytical or optimized solution in designing FSS structure. This work will be promising in optimizing the parameters needed in FSS design.

Within the scope of the study firstly the boundaries of Debye parameters and of physical parameters of material were defined. After, optimum values were selected from inside the boundaries by DE algorithm. These values were put into MG equations to get physical dimensions of FSS model. Proposed FSS was tested with numerical method FDDT widely used in solving EM problems.

2. MATERIALS AND METHODS

Dielectric materials or composite materials with dielectric properties have low reflection loss and considerably absorption loss [12-14]. The dielectric of the material directly affects its conductivity, the impedance of the environment and thus the propagation of the EM wave. One of the models that associate this relation with the shielding effect is Debye model.

2.1. Debye Parameters in SE calculation

Dielectric varies depending on frequency [15]. The dielectric of the composite material according to the single-term Debye model is defined as

$$\varepsilon_D = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \tag{1}$$

$$\tau = \frac{1+\sqrt{2}}{2\pi F_{Low}} \tag{2}$$

where ε_s is the static relative permittivity, ε_∞ is the relative high-frequency limit permittivity, τ is the relaxation time, F_{Low} is the lowest boundary and ε_D is the complex frequency dependent relative permittivity of the equivalent homogeneous material described by the single-term Debye model [16-17]. In shielding problems ε_D determines the impedance of the material.

$$Z_m = Z_0/\sqrt{\varepsilon_D} \tag{3}$$

where Z_m is the impedance of the material. Reflection and transmission at the boundaries in depends on the impedance of the material.

$$R_1 = \frac{Z_m - Z_n}{Z_m + Z_n} \tag{4}$$

$$R_2 = \frac{Z_0 - Z_m}{Z_0 + Z_m} \tag{5}$$

$$T_1 = \frac{2Z_m}{Z_m + Z_0} \tag{6}$$

$$T_2 = \frac{2Z_0}{Z_m + Z_0} \tag{7}$$

where $R_{1,2}$ and $T_{1,2}$ are reflection and transmission coefficients respectively.

Total transmittance depends on reflection coefficients $R_{1,2}$ and transmission coefficients $T_{1,2}$. These quantities are defined as [1],[17-18].

$$T = \frac{T_1 T_2 e^{-\gamma_m W}}{1 + R_1 R_2 e^{-2\gamma_m W}} \tag{8}$$

$$\gamma_m = j\omega\sqrt{\mu_0 \varepsilon_0}\sqrt{\varepsilon_D} \tag{9}$$

where γ_m is the propagation constant. And the relation between SE with transmittance is as follows.

$$SE = -20\log(|T|) \tag{10}$$

As can be seen from Equation 2-9, ε_D in the Debye model can be used to determine the SE value. Therefore, it is possible to find the desired SE value by changing the value of ε_D.

Debye parameters and physical properties of FSS describe the flatness and the strength of SE. b_∞ is the parameter that determines the flatness of SE. This parameter is defined as

$$b_\infty = \frac{(\varepsilon_s - \varepsilon_\infty)W}{2 \cdot c_0 \cdot \tau\sqrt{\varepsilon_\infty}} \tag{11}$$

where b_∞ is dependent on ε_s , ε_∞ and W values which will be involved in optimization processes. $b \in [0.8 - 1.6]$ ensures the flatness of shielding line [16] above the threshold between the F_{Low} and F_{High} which were set to 0.5GHz and 5GHz respectively.

2.2. Differential Evolution Algorithm

The algorithm has the following steps: Initialization, Mutation, Recombination, Selection and Termination [9], [21].

2.2.1. Initialization

In this stage constant values are defined as:
Number of individuals, $NP \geq 4$
Crossover ratio, $CR \in [0\ 1]$
Mutation factor, $F \in [0\ 2]$
Generation number, G

2.2.2. Mutation

First, target individual is selected. Then 3 random distinct individuals inside population $x_{r_1,G}$, $x_{r_2,G}$ and $x_{r_3,G}$ are selected so that $r_1 \neq r_2 \neq r_3 \neq target$.

Create a trial individual by adding weighted difference of 2 randomly selected individuals to third one.

$$V = x_{r_1} + F \cdot \left(x_{r_2} - x_{r_3}\right) \tag{12}$$

2.2.3. Recombination

The values of parameters inside trial individual are replaced with the value of corresponding parameter inside target individual with probability CR.

$$u_{j,i,G+1} = \begin{cases} u_{j,i,G+1} & if\ rand_{j,i} \leq CR \quad or \quad j = I_{rand} \\ x_{j,i,G} & if\ rand_{j,i} > CR \quad and \quad j \neq I_{rand} \end{cases} \tag{13}$$

where $i = 1,2, \dots, NP; j = 1,2, \dots, D$; $rand_{j,i} \sim U[0\ 1]$ and I_{rand} is a random integer from in $[1,2, \dots, D]$. D is the solution's dimension.

2.2.4. Selection

The calculated cost value of target individual is compared with the one of trial vector V. A vector with better cost value is admitted to the next generation.

2.2.5. Termination

The algorithm terminates when the defined generation number is reached or stopping criteria is met.

2.3. Optimizing Parameters

The main purpose of the optimization is to obtain the physical properties of the shielding material. Additionally, final output must be available in the market or can be produced by use of composites. Therefore, computations must be carried out regarding these cases. For this, boundaries of Debye parameters were chosen specifically.

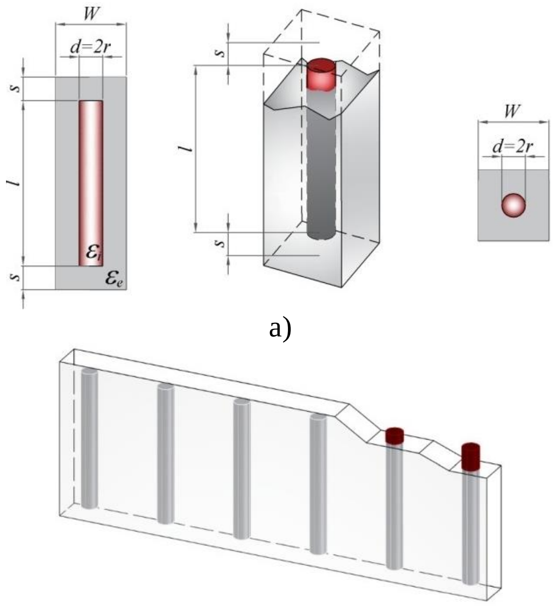
In order to start the algorithm several configurations must be done. Accordingly, width $W \in [1\ \ 4]mm$, dielectric constant $\varepsilon_\infty \in [1\ 100]$ and Debye parameter $\varepsilon_s \in [1000\ \ 4000]$ was set [16] and DE algorithm parameters were initialized. The pseudocode of the algorithm is given in the Appendix.

As it is seen from the pseudocode the algorithm converges to the solution in iteration T. A variable T was assigned as 20, which was adequate to find the solution. A case of failure may be faced with if only desired shielding is unattainable because of narrow boundaries of Debye parameters. In this case, desired shielding should be lowered or Debye parameters boundaries should be widened. After, algorithm may be initiated from the beginning.

Population size was determined as 20 and they filled with random numbers not exceeding boundaries. Inside iteration, a random target individual was chosen among individuals in population. Once a target individual was chosen it was exposed to mutation and recombination which resulted in new individual called trial vector. Afterwards the fitness of trial vector was evaluated at frequency F_{Low}. The fitness results included SE and b values. If newly found SE was greater than desired SE, then trial vector is reevaluated and SE was checked whether it was greater than desired SE for whole frequency range from F_{Low} to F_{High}. In case of failure, code would run from the beginning of current loop and another target would be chosen for further operations. However, in case of success and if variable b fitted in its defined boundaries then the code will print results and terminate.

3. RESULTS AND DISCUSSION

As a result of code run, Debye parameters were found as $\varepsilon_\infty = 11.056$, $\varepsilon_s = 3826$, $W = 3.97mm$. The host permittivity was chosen as $\varepsilon_e = 11.5$ that is close to permittivity of inclusion. It was determined with accordance of availability of this material. Other physical parameters of shield material was found by evaluating Debye parameters in Maxwell Garnet equations [22-23]. As a result of computation, physical parameters of material were found as $s = W/4$, conductivity $\sigma = 103.93\,S/m$, length $l = 177.7mm$ and radius $r = 0.46mm$. Figure 1a shows physical dimensions of every single inclusion.



a)

b)

Figure 1. a) Cylindrical inclusion and its extent, b) 3D shielding material

Obtained physical parameters indicated low conductive dielectric material. 3D FSS (Figure 1b) was designed in CST simulation software [24], where electric field polarized plane wave excitation was used. Electric field probe was placed behind the shielding material. After setting other physical parameters, simulation was started (Figure 2).

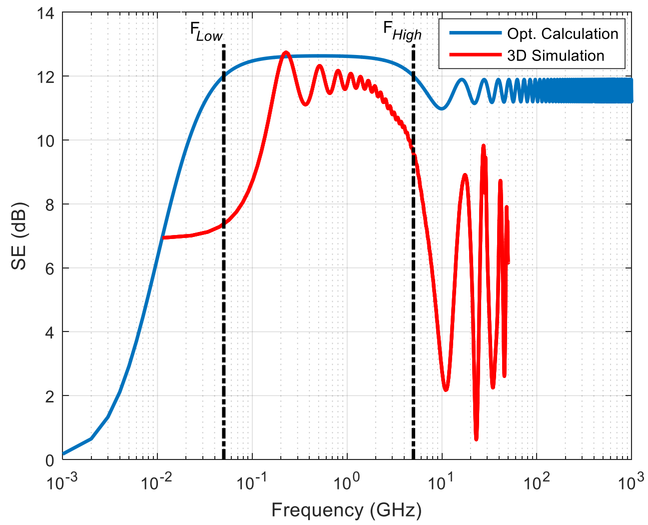


Figure 2. Comparison of Debye model with CST simulation

Debye parameters were evaluated in Eq. 1-10 and obtained SE values were simulated as in Figure 2. It is obvious that SE above threshold is quite flat. This is also guaranteed by value b which was found as 0.98.

In the Figure a red line indicates the simulation result whereas blue line indicates the optimized calculation. As it is seen from Figure, between F_{Low} and F_{High}, CST simulation results are similar to those obtained by analytical computation.

4. CONCLUSION

In this work, despite traditional trial and error method, Debye parameters were optimized with the help of Differential Evolution algorithm and obtained in a much faster and precise way. Afterwards, in order to obtain physical parameters of FSS, these parameters were evaluated in Maxwell Garnett solutions. Then, a shield was modeled and simulated in CST Studio software which analysis EM interference problems with FDTD method. The SE results from proposed work and simulation was compared. It was seen that they nearly overlapped between F_{Low} and F_{High}. It can be concluded that, the performance of thought shield model can be predicted before production. This will save time and ease the computation process.

Appendix

A pseudocode given below is referred in section 2.3. It describes an implementation of DE algorithm on Debye parameters.

```
initialize algorithm, define Debye parameters and
set their boundaries
for (iteration from 1 to T)
    for (target from 1 to population)
        determine target
        follow mutation and recombination steps
        evaluate trial vector fitness at F_Low
        if (SE ≥ desiredSE)
            target = trial
            for (frequencies from F_Low to F_High)
                evaluate trial vector fitness at F
                if(SE < desiredSE)
                    set flag
                    break loop
                end
            end
            if(not set flag && b ∈ [0.8 – 1.6])
                set foundFlag
                break loop
            end
        end
    end
    if(foundFlag)
        break loop
    end
end
print target
```

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The Declaration of Conflict of Interest/Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The authors contributed equally to the study

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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