CHAPTER – 7
DESIGN OPTIMIZATION OF SKewed OMEGA ShAPED LHM

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7.1 Objective

A novel design and optimization approach of a skewed omega shaped LHM unit cell structure has been presented in this chapter. In the absence of closed form design formulae for its resonant frequency, this chapter proposes use of Simulated Annealing (SA). The dependence of the resonant frequency on multiple geometric parameters of the unit cell is demonstrated. With these parameters a BPNN and a simulated annealing (SA) algorithm has been developed to determine the resonant frequency of the designed skewed omega LHM unit cell.

7.2 Introduction

Metamaterials, also known as left-handed materials (LHMs), are a class of composite materials designed artificially with unit cells that are much smaller than an operation wavelength and widely used to obtain the desired fascinating properties not found in nature. Metamaterials (MTM) have gained burgeoning interest from the scientific community due to their intriguing and exotic electromagnetic (EM) properties. The concept of metamaterial (MTM) started with the suggestion of the physics scientist V.Veselago in 1967 [1]. He proposed a new type of material which has simultaneously negative permittivity and permeability, and he presented general properties of electromagnetic wave propagation in such a material. He theoretically created a lossless MTM and showed the extraordinary properties of this material which is not found in nature. Then, Pendry et al. presented their studies about the negative permittivity and the negative permeability as in [2] and [3]. They stated that an array of metallic wires with suitably chosen spacing and radius can be constructed to get negative exhibition in the permittivity in 1996 [2], and a metallization of split rings can be manufactured for negative permeability in 1999 [3]. Later Smith et al. demonstrated a new type of MTM structure that shows simultaneously negative permittivity and permeability and carried out microwave experiments to test its unusual properties in 2000 [4]. The first experiment showing negative refraction index was performed using MTM consisting of a two-dimensional array of repeated unit cells of metallic wires and split ring resonators in 2001.
by Shelby et al. [5]. Several theoretical and experimental works have been studied by various researchers on MTMs and their potential applications [6-9]. The design of LHM based on shape and geometry, such as different ring-like structures such as circular, square, Ω-shaped, U-shaped, S-shaped and others are used to create new MTMs [10].

Saadoun and Engheta proposed the omega structure as an alternative to Pendry’s structure. Omega media are of special interest due to their interesting EM properties [11-12]. These types of structures are composite EM materials with a proper combination of Ω-shaped metallic inclusions in a host dielectric medium. These MTM could be regarded as bi-anisotropic or pseudo-chiral media [11]. Electric and magnetic polarizations are induced by both electric and magnetic fields in bi-anisotropic media. These types of structures are composite EM materials with a proper combination of Ω-shaped metallic inclusions in a host dielectric medium.

Here in this chapter, we have proposed a new skewed omega shaped left handed metamaterial (LHM) unit cell structure. The unit cell consist of twisted omega type metallic inclusion on the front side of substrate and a wire strip in the back side of substrate. and wire strip.

An Optimization is a technique used to maximize overall performance and minimize errors in design [15]. In this chapter we propose an optimization technique for design of MTM unit cell at a desired frequency. The parameters taken into consideration were edge length, strip width, spacing between two ring split gap, and sub thickness were varied and the variation in the resonant frequency was observed.

So this chapter proposes a novel design & optimization approach of a skewed shaped MTM unit cell structure. Due to absence of closed form design or analysis formulae for such MTM structure, this chapter proposes two stochastic methods for determination of resonant frequency of LHM unit cell: the Artificial Neural Network (ANN) and the Simulated Annealing (SA) algorithm and its implantation to obtain better transmission spectra & DNG characteristic and finally the analysis the numerical & experimental results were obtained.
7.3 MTM Unit Cell Analysis

Figure 7.1 shows schematically the skewed omega shaped MTM unit cell structure which is geometrically different from an omega shaped metamaterial unit cell structure. It consists of twisted omega type metallic inclusion on the front side of substrate and a capacitive loaded strip (CLS) in the back side of substrate. The MTM unit cell is printed on a FR-4 substrate with dielectric constant of 4.2 with loss tangent 0.017 and thickness of 0.81 mm respectively.

![Figure 7.1: Skewed Omega Shaped MTM Unit Cell.](image)

7.4 Stochastic Models for Resonant Frequency

The concept of simulated annealing is motivated by an analogy to annealing solids. The initial concept of simulated annealing was first published by metropolis [Metropolis 1953]. The algorithm in this chapter explained the cooling of materials in a heat bath. In the year 1983 Kirkpatrick et al. [16] took this concept and applied it to optimization domain. The idea proposed was to use simulated annealing to find feasible solutions and finally converge to an optimal solution. The optimization procedure tries to make variations in the parameter which yield new results and using this new additional information to make the idea better.

In annealing process a melt initially at high temperature initially at high temperature and disordered is slowly cooled down so that the system at any time is at thermodynamic equilibrium after reaching in low energetic crystalline structures. As
cooling proceeds the system becomes more ordered and approaches a frozen ground state. Hence the process can be thought of an adiabatic approach to lowest energy state. If the initial temperature is too slow or cooling is done insufficiently slowly then, the system may become quenched causing defects or freezing out in metastable states (here trapped in local minima).

7.4.1 Simulated Annealing (SA) Algorithm

Step1: Set \( T = T_{\text{max}} \) and \( W_{\text{opt}} = W_{\text{init}} \)
Step2: No. of Changes = No. of Iterations = 0
Step3: Present input and desired outputs. Present a continuous valued input vector \( X_0, X_1, \ldots, X_{N-1} \) and specify the desired output \( d_0, d_1, \ldots, d_{M-1} \) (Here only \( d_0 \)).
Step4: Calculate actual output \( Y_0 \) and Mean Square Error (MSE\(_{\text{old}}\)).
Step5: Produce a new set of weights \( W_{\text{new}} \) by randomization.
Step6: Calculate new output \( Y_{0\text{new}} \) and MSE\(_{\text{new}}\).
Step7: If MSE\(_{\text{new}}\) < MSE\(_{\text{old}}\) then
   i) \( W_{\text{opt}} = W_{\text{new}} \).
   ii) No. of Changes = No. of Changes + 1
      Else if \( P (\text{MSE}_{\text{new}} - \text{MSE}_{\text{old}}) > \text{random} (0, 1) \)
Step8: No. of Iterations = No. of Iterations + 1.
Step9: If current state is in equilibrium then \( T = 0.95 \times T \) and go to step1.

The major difficulty in implementing the algorithm is that there is no obvious analogy for temperature \( T \) with respect to free parameter in the combinatorial problem. Furthermore avoidance of entrapment in local minima depends on the choice of initial temperature, number of iterations at each temperature & how much temperature cool down at each step.

During the annealing process in order to attain thermal equilibrium with the gradual decrement of temperature the weight configuration changes at each stage. At each stage we randomize the weights and accept the new stage of weights to reach the global minima. The weight sets are assigned same as the back propagation algorithm in ANN.
So the artificial neural network model for assigning the weights involves three layers. One input layer one output layer and one hidden layer. The input layer consists of 5 no. of neurons for 5 variables, the output layer consists of 3 no. of neurons, and the hidden layer consists of 3 no. of neurons. The LAVENBERG-MARQUARDT (LM) was used as the training algorithm. At each stage the weight sets are calculated the sample data is divided into training and testing set of data and the neural network is trained.

Different dimensions of unit cell like edge length (L), strip width(w), spacing between two ring (c), split gap (g), and sub thickness(h) were varied and the variation in the resonant frequency was observed.

Therefore, an ANN with L, c, d, g, and h as inputs and resonant frequency as output with 3 hidden layers has been used in this work. CST MWS was used to generate 100 datasets. Out of these, 85 were used for training using back-propagation with a momentum of 0.9 to speed-up the training. To improve accuracy learning rates, in the range of 0.1 to 1.0, were used with 100 epochs per learning rate. The optimal learning rate for the present problem was found to be 0.6. With this learning rate, the MSE reduced to 0.000486 in 100 epochs while training the neural network and to 0.000367 in 82 epochs while testing (Figure 7.2)

Figure 7.2: Performance result of ANN.
Once the weight sets are assigned it is assumed that the equilibrium state at each state at a particular temperature represents 10 no. of changes in the weight set. The no. of iteration is more than 15000. The initial and final temperature is $10^0$ and $1^0$ C respectively. The temperature is lowered by a factor 0.95. Training and Test result errors are shown in the Figure 7.3.

The program is developed using C++ coding techniques using DEV CPP compiler. The obtained results are plotted using MATLAB.

![Performance of Simulated Annealing](image.png)

**Figure 7.3: Performance Result of Simulated Annealing**

### 7.5 Experiment, Results & Discussions

#### 7.5.1 Performance of the Models

Table 7.1 shows the performance of the models vis-à-vis that of the EM-simulation using CST MSW. It is observed that they follow each other very closely with acceptable error tolerance.

It was observed that Simulated Annealing performs better due to the randomization approach in SA to find solution in search space which leads us to global minima.
Table 7.1 shows the results obtained from simulation and results obtained from optimization. The error is calculated using the following relation.

$$
    \textit{error} = |f_0^d - f_0^c|
$$

(7.1)

where, $f_0^d$ represents the desired frequency and $f_0^c$ represents the calculated frequency. It can be seen, from Table 7.1 that the errors obtained are in the order of $10^{-3}$ which shows the accuracy of the algorithm. Finally the error was plotted with respect to frequency as shown in Figure 7.4.

### Table 7.1: Testing result using SA.

<table>
<thead>
<tr>
<th>Frequency obtained from simulation</th>
<th>Frequency obtained from optimization</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.259</td>
<td>13.237864</td>
<td>0.021136</td>
</tr>
<tr>
<td>13.78</td>
<td>13.729061</td>
<td>0.050939</td>
</tr>
<tr>
<td>11.5</td>
<td>11.536875</td>
<td>0.036875</td>
</tr>
<tr>
<td>11.887</td>
<td>11.831630</td>
<td>0.05537</td>
</tr>
<tr>
<td>13.279</td>
<td>13.212869</td>
<td>0.066131</td>
</tr>
<tr>
<td>11.982</td>
<td>11.940696</td>
<td>0.041304</td>
</tr>
<tr>
<td>12.807</td>
<td>12.829849</td>
<td>0.022849</td>
</tr>
<tr>
<td>12.84</td>
<td>12.802551</td>
<td>0.037449</td>
</tr>
<tr>
<td>12.614</td>
<td>12.610826</td>
<td>0.003174</td>
</tr>
<tr>
<td>11.884</td>
<td>11.877900</td>
<td>0.0061</td>
</tr>
<tr>
<td>12.08</td>
<td>12.095297</td>
<td>0.015291</td>
</tr>
<tr>
<td>11.754</td>
<td>11.686257</td>
<td>0.067743</td>
</tr>
<tr>
<td>13.268</td>
<td>13.314468</td>
<td>0.046468</td>
</tr>
</tbody>
</table>
7.5.2 Optimized MTM Unit Cell Design

We proceed to design the MTM unit cell with optimized dimensions for an operating frequency of 14.2GHz. The optimized dimensions are shown in Table 7.2.

The MTM unit cell is printed on a FR-4 substrate with dielectric constant of 4.2 with loss tangent 0.017 and thickness of 0.81 mm respectively.

CST Microwave Studio (CST MWS) based on finite integration technique and ANSOFT HFSS based on finite element method were used to evaluate the S-parameters of the unit cell.

Table 7.2: The optimized dimensions obtained for 14.2 GHz.

<table>
<thead>
<tr>
<th>Parameter (in mm)</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>4.2</td>
</tr>
<tr>
<td>c</td>
<td>0.6</td>
</tr>
<tr>
<td>w</td>
<td>0.45</td>
</tr>
<tr>
<td>g</td>
<td>0.5</td>
</tr>
<tr>
<td>d</td>
<td>0.6</td>
</tr>
</tbody>
</table>
In the simulation setup, the unit cell was surrounded with the air medium and excited with a time varying EM signal on z-axis, in which the E-field was aligned with the CLS metallic wire. Perfect electric conductor (PEC) boundary condition was applied along the boundaries perpendicular to x-axis, whereas perfect magnetic conductor (PMC) is applied to the boundaries perpendicular to y-axis. The structure was excited by the fundamental mode of one of the waveguide ports located at z_{min} & z_{max} limits of the unit cell, which was equivalent to a transverse electromagnetic (TEM) wave with \(E_x\) and \(H_y\) field components propagating along the z-axis. The simulation was performed over the frequency range of 10–20 GHz.

Figure 7.5 shows the magnitude and phase of simulated S-parameters results from CST MWS compared with HFSS. As it can be seen there is a good agreement between both the simulation results. The simulated transmission and reflection coefficient of the designed MTM unit cell are phase reversal to each other. The dip in phase of \(S_{11}\) at 14.2 GHz and the phase reversal onwards it indicates the presence of negative regions.

To verify the double Negative (DNG) characteristics of proposed MTM structure, the Scattering parameters obtained from the simulation were then imported into a file which was used by the MATLAB for modified NRW method [13] [14] to calculate the effective permittivity and permeability of the unit cell.
As shown in Figure 7.6, the real part of the effective permeability ($\mu_r$) is negative from 13.8 GHz to 14.7 GHz, which is above the magnetic resonance frequency. The real part of the effective permittivity ($\varepsilon_r$) is negative from 14.1 GHz to 18.2 GHz.

![Figure 7.6: Effective retrieval characteristics.](image)

As shown in Figure 7.7, the negative refractive index is found from 13.8 GHz to 18.2 GHz. Thus double negative (DNG) phenomenon results in negative refractive index and thus backward wave propagation occurs within this transmission band in the purposed magnetic medium.

![Figure 7.7: Refractive Index.](image)
7.5.3 Experimental Result

To validate the DNG characteristic and reflection spectra with the simulation result of skewed omega structure, the transmission & reflection experiment of a unit cell sample has been carried out. The parallel plate waveguide (PPW) system is utilized to measure the transmission and reflection properties of the MTM pair of probes inside the PPW is acting as the transmitter and receiver and the absorbing foams are placed to the both sides of the probes so as to fix the sample under test (SUT) and absorb electromagnetic waves. The SUT fills the section between the two probes. We inserted the sample into the PPW system and recorded its S-parameters by an Agilent 8719ES network analyzer.

In Figure 7.8 the measurement result shows that there is a good agreement between simulation & measurement for skewed omega MTM structure. The discrepancy between the retrieval and measured result mainly caused due to use of the lossy FR4 substrates as well as the fabrication error.

![Figure 7.8: Measurement result of prototype](image)

7.5.4 Current Distribution & Radiation Pattern

We have also carried out the simulations in order to monitor the magnitude of the electric and magnetic field at the unit cell structure by using CST MWS. The simulations were performed at 14.2 GHz which correspond to the reflection dip in the simulated
transmission spectra of MTM unit cell. In the simulation, we have used the field monitor facility in CST MWS to find out magnitude of electric field intensity within the skewed omega shaped unit cell.

The confinement of the E-field and the current distribution on the ring & the strip at the resonant frequency is shown in Figure 7.9. It is observed that the skewed omega is circulating the current around it as required by a split ring-resonator for producing magnetic resonance, where as the strip is supporting current for electrical resonance thereby confining the E-field.

![Figure 7.9: E-field distribution & Surface current](image)

### 7.6 Chapter Summary

A skewed omega shaped LHM unit cell is designed using BPNN and simulated annealing. In this chapter we have studied numerically & experimentally reflection spectra & the LHM characteristics behaviour of a new concentric edge coupled MTM structure whose unit cell is composed of concentric skewed omega inclusion and capacitive strip wire. Different parameters such as permittivity, substrate thickness, conductor strip width, spacing between rings, arm length, gap between the arms were also investigated and different data sets were obtained through parameter variation. With these parameters a BPNN and a simulated annealing algorithm were developed to determine the resonant frequency of the proposed LHM unit cell. The predicted results were in close agreement with measurement results on prototype skewed omega LHM unit cell.
A modified NRW method was used to attain the effective medium parameters, refractive index and also the dispersion characteristic from simulated S-parameters result. It was shown that the new LHM structure exhibits DNG behaviour in the frequency region of 13.8 GHz to 18.2 GHz. The parameter retrieval results, negative refractive index and transmission measurement, all validate the proposed structures exhibit a wideband LHM passband. We also performed simulations in order to observe how the surface currents flow at magnetic and electrical resonances.

REFERENCES


