Design of miniaturized FSS structure using Optimization Technique based on Machine Learning

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Abstract. This work presents the design of a miniaturized FSS structure characterized by three resonant frequencies for S and C-band applications. When an incident normalized plane wave is illuminated, the miniaturized FSS shows three rejecting bands at 2.42 GHz, 7.2 GHz, and 9 GHz simultaneously with the wide bandwidth of 2.3 GHz from 5.8 GHz to 8.1 GHz. The Frequency Selective Surface is designed by creating some rectangular slots within the square patch. The resultant slotted square patch can achieve a size reduction of 93.2%, 47.8%, and 18.98%. The measured results show great acceptance for the simulated ones. The theoretical investigation has been done by the Ansoft HFSS EM simulation tool. An experimental investigation has been performed and analytical results are achieved. A machine learning technique is implemented which also validates the experimental resonant frequency values.

Keywords: frequency selective surface, size reduction, multiple resonant frequencies, wide bandwidth, machine learning

1. Introduction

Now a day, a lot of researchers are involved in making use of the Electromagnetic Band Gap (EBG) present in periodic elements as Frequency Selective Surfaces (FSSs), subreflectors [1]. FSS is 2 dimensional array of patch or aperture elements designed with periodicity and etched in metal sheets. In radar cross section reduction, frequency selective surfaces are used in radomes, and also used as subreflectors in frequency reuse mechanism [2,3]. Frequency Selective Surfaces has gained attention for their spatial filtering characteristics. FSS practically used is finite one but treated as infinite array. The characteristics of infinite FSS are obtained by usage of proper elements. To obtain lesser operating frequency, size of the structure will be increased in proportion. With increase in size, space occupancy will be point of concern. To achieve low frequency of operation without increase in size of structure, size reduction is needed [4-7]. The proposed FSS in the paper is designed by cutting one rectangular ring type slot and one polygon shaped slot in it. The simulated and the experimental results are considered for analysis. It is observed that the FSS with slots in it has lower resonance frequency and enhanced performances than patch FSS without slots. FSS has multiple resonant frequencies within S, C and X Band. In this work machine learning is used as efficient computational technique to design optimizer.

1.1 Machine Learning Technique

When the analytical model of a system is not available, while input and output data can be measured or simulated, machine learning can be an alternative tool to explain the system via mathematical equations. The mathematical model includes numerous parameters that can be optimized to approximate the system transfer function. The training process is used to determine the parameter. Among machine learning algorithms, the neural network is one of the most famous mathematical structures to have become a foundation of the data-driven model [8].
1.2 Artificial Neural Network

Similar to our human learning technique, Neural Network acts accordingly. ANN comprises of nonlinear computation technique which includes the relationship between present input and output [9]. In neural networks, multiple neurons that are units of processing are connected in many layers. Neurons are grouped and interconnected by weights. It has input, hidden, and output layers. Each input is multiplied by a weight and the sum of bias and weighted inputs are applied to the activation function and the output is obtained. In this work, a back propagation algorithm is implemented to reduce error at output neurons. It is learning or training algorithm.

Initially training data set is created for formation of training matrix. Activation function is shown in (1). Output is produced as shown in (2)

\[
\Phi(x) = \frac{1}{1 + e^{-x}} \tag{1}
\]

\[
Y = \Phi(\sum_{i=1}^{n} x_iW_i) + b_i \tag{2}
\]

In this back propagation training algorithm the simulated input/output dataset is used to train the network. Here synaptic weight \( w \) is updated many times and can be expressed as (3)

\[
\Delta w = -\eta \frac{\delta E}{\delta w(n)} \tag{3}
\]

2. Design

The periodic unit (Shown in Figure 1) whose dimensions are presented in Figure 1 is selected for proposed FSS. Periodicity in x and y direction is taken as 26 mm (shown in Figure 2). The copper coating is only on one side of the FR4 substrate. The measurement of a patch with slots inside it has been showed in Figure 1. The dimension of the FR4 substrate is 200 mm X 200 mm X 1.6 mm.

Figure 1. A square patch with slot (shaded part indicate copper)
The length and breadth of Patch are input to the network. Each of these inputs is multiplied by connection weights. Here bias value is taken as unity. Products are summed and fed to the activation function to generate results. In this way, 3 layer neural networks will result gives desired resonant frequency and bandwidth as output. For layered network, the cost function is computed and used to adjust the threshold and weights for the next input. The cost function is to be minimized. The lower the cost function, the closer the actual value to the predicted value. Finally, the network learns how to analyze the data that leads to the error becoming marginally lesser in each pass. The data is given in feedback from output to input. We can only update the weighted synapses connecting input variables to the neuron.

Assumed learning rate within 0 to 1 and randomly considered weights. In this work weights are initialized between 0.1 to 0.6.

**Step1.** Feed forward computation:
- I: Determination of outputs of the input layer
- II: Calculation of inputs of hidden layer
- III: Determination of the outputs of hidden neurons
- IV: Calculation of the inputs of the output layer
V: Estimation of the outputs of Output layer
VI: Determination of the error in prediction

Step 2. Back propagation
  Calculated backward phase- The error is back propagated from final output to initial state.
  Weight updating is done. Updating of weights is decided by learning rate
  I: Weights between output layer neuron and the neuron of the hidden layer have been updated
  II: Weights between input layer neuron and the neuron of the hidden layer have been updated

Step 3. Repeat 1 and 2 and update weights after each observation
Step 4. Stopped when the value of the error is sufficiently small.

Dielectric material: 4.4 is the value of relative permittivity, Thickness-1.6mm, Length of patch (L)-20mm, Breadth of patch (B) - 20mm, Periodicity- 26mm, Training data set samples (N) – 600 samples
The network is defined with 2 input nodes and 10 hidden nodes, 2 output nodes. The sigmoid function is taken as activation function. Bias input is taken as 1 in both layers.

3. Measurement

Transmission characteristics have been observed with experimental set up for the Frequency Selective Surface (shown in Figure 5) within a 2GHz to 10GHz frequency band. To accept the proposed design, the prototype using exact dimensions of designed single layer FSS with FR4 as a dielectric substrate was built (shown in Figure 4). The thickness of the FR4 dielectric substrate used was 1.6mm. Transmission responses of the FSS were computed. Results after the experiment with the surface have been taken as shown in figure 6.
4. Result and Discussion

In this article, both theoretical and experimental studies have been performed on Frequency Selective Surface (FSS) for size reduction and multiple resonant frequencies. The theoretical investigations are carried out by the Ansoft HFSS EM simulation tool. The experiment is also performed. The result is also given in table 1. The FSS is designed by cutting rectangular slots as enclosed path and a polygon inclined at 45° within a square patch keeping the uniform periodicity of 26mm. The designed FSS can provide a size reduction of 93.2%, 47.8%, and 18.98% corresponding to resonant frequencies 2.42GHz, 7.2GHz, and 9GHz with a bandwidth of 0.3 GHz, 2.3GHz, and 0.6GHz respectively (shown in Figure 6) in comparison to conventional patch Frequency Selective Surface. It is observed that the design shows a significant size reduction. It can be observed that two resonance frequencies are in S, C, and X Band. These two properties in a single FSS makes it a good design for multipurpose applications.

![Normalized Transmitted Electric Field Vs Frequency](image)

**Figure 6. Transmission characteristics versus Frequency**

| S.No | Resonant Freq (GHz) | Gain in dB | Bandwidth (GHz) |
|------|---------------------|------------|-----------------|
| 1    | 2.42                | 35         | 0.3             |
| 2    | 7.2                 | 39         | 2.3             |
| 3    | 9                   | 20         | 0.6             |

Table 1: Results in Tabular Form

In ANN initial weights are taken at random basis. The amount of error or deviation will be back traced and new weights are calculated. Table 2 shows output of neural network with respect to some desired frequency values (2.42GHz, 7.2GHz and 9GHz).

![Normalized Transmitted Electric Field Vs Frequency](image)

**TABLE 2** Resonant Frequency As A Function Of L And B Of Patch.

| L (mm) | B (mm) | $R_f$ (GHz) | BW  |
|--------|--------|-------------|-----|
| 20.1   | 19.8   | 2.7         | 0.32|
| 19.8   | 18.7   | 2.82        | 0.398|
| 19.9   | 19.957 | 2.6         | 0.27|
5. Conclusion

In our work, reduction of size of the frequency-selective surface has been presented. The performance of the designed FSS has been investigated both theoretically and practically. A prototype of the FSS has been fabricated for validating the design. The square patch FSS without slot resonating at 10GHz has the length 20mm. However, the proposed FSS resonating at 2.42 GHz should have the length 76.92mm but its actual length is 20mm. So the size reduction achieved is 93.2%. The simulation and measurement both indicate that the FSS structure has a remarkable reduction in area and exhibits two resonating frequencies within the S and C band. Experimental results agree well with the simulated results. The designed FSS can be used in Satellite Communication for the reduction of the number of reflectors. As one of the resonant frequencies is 2.4GHz so it can also be used in IoT applications. The ANN results given in Table 2 showed this technique as flexible and accurate. It is also used as an optimizer. The ANN model was trained with data obtained by simulation of FSS design.

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