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Derivation of an Analytical Model of an FSS structure

Salil P[1*], K. S. Manivannan[2] , Bhuvaneswari S[3]

[1]Research Scholar, Dr. M. G. R. Educational and Research Institute, Chennai, India.

[2]Dr. M. G. R. Educational and Research Institute, Chennai, India.

[3]S. A. Engineering College, Chennai, India.

***Abstract* -** Frequency Selective Surfaces (FSS) are used in applications where frequency-selective shielding is desired. The frequency response of the FSSs is generally derived via Electromagnetic (EM) Simulation of the structure using 3D EM Simulation Software. In this paper, an attempt is made to generate an analytical model for an FSS structure using statistical methods of the Design of Experiments.

Index Terms - Frequency Selective Surfaces (FSS), Design of Experiments, Taguchi Method, Analysis of Variance (ANOVA).

INTRODUCTION

In recent times, communication systems or electronic systems, in general, are gearing towards the usage of more and more wireless technologies. With the adoption of evolving technologies like the 5G and IoT, the number of devices using electromagnetic waves for functioning is likely to witness a multifold jump. This makes every space in the surroundings crowded with electromagnetic waves. This brings in a lot of challenges, especially in the form of Electromagnetic Interference (EMI) in electronic devices.

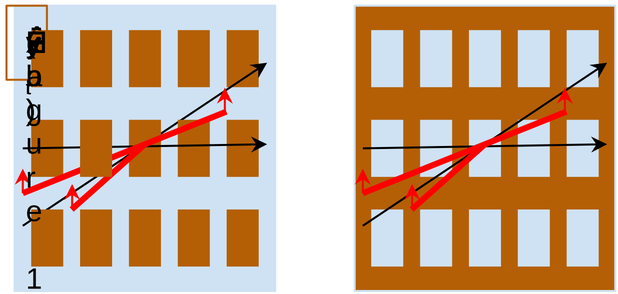
Traditionally, EM shielding with metallic enclosures with minimum discontinuities was used to reduce the EMI by suppressing the EM energy into or from a closed region. However, this approach is not suited for a device with an intentional radiator as the continuous shield blocks the required wireless channel also. Here arises the requirement for a mechanism that allows certain frequencies to pass through it while blocking other frequencies or Frequency Selective Shielding. Usage of Frequency Selective surfaces (FSS) is one way to achieve this. FSS acts as frequency-domain spatial filters for EM waves [1][2][3].

FSSs are two-dimensional periodic structures that can offer band stop or band-pass characteristics for the incident plane wave to provide selective shielding [4]. The geometry of the structure can be designed to get the desired frequency response.

The design of FSS structures is mostly based on design and optimisation using 3D Electromagnetic Simulation tools [5]. There are also works on design based on circuit theory [6][7] and other methods involving scientific techniques such as genetic algorithms [8][9][10][11]. The usage of such tools and methods requires good knowledge of EM theory. Besides, the software tools are expensive and the designing will be time-consuming. These aspects may make it out of reach for many industries. Hence it is preferred to an analytical model for FSS structure, where the structures can be easily designed by simple mathematical expressions.

FREQUENCY SELECTIVE SURFACES

FSS is a plane wave microwave spatial filter. The reflection or transmission of the FSS filter is maximum at the resonant frequency. The FSS structures are generally periodic structures with identical elements referred to as unit cells arranged in a two-dimensional array [12][13]. A simple example is given in Figure 1(a), where the structure contains an array of dipoles. This structure can be considered as an array of dipoles. A plane wave $\bar{E}_i$ incident on the structure will excite the dipoles and will induce electric currents. These generated currents in turn act as EM sources that produce secondary fields. The secondary waves from the structure, combined with the incident plane $\bar{E}_i$ wave, will create a resultant field in the surrounding FSS. The combined effect is incident plane $\bar{E}_i$ wave partly reflected in the specular direction $\bar{E}_r$ and partly transmitted in the forward direction $\bar{E}_t$. In the condition of resonance and without grating lobes, the amplitude of the reflected wave $\bar{E}_r$ may be equal to incident wave $\bar{E}_i$, while the transmitted signal $\bar{E}_t$ is equal to zero. So depending on the element design, an incoming plane wave will be either transmitted or reflected, completely or partially. In a similar way, the periodic structure array can be constructed using an array of slots as given in Figure 1 (b).



Here the incident plane wave excitation causes magnetic currents that create the secondary fields. In both cases, the secondary fields generated depend on the amplitude of the produced currents which in turn depends on the structure and frequency. Hence the required currents and field characteristics can be obtained by properly designing elements to obtain the filter response. The dipole FSSs or patch structures are designed to act as stopband filters while the slot FSSs or slot structures, demonstrate passband characteristics [14][15].

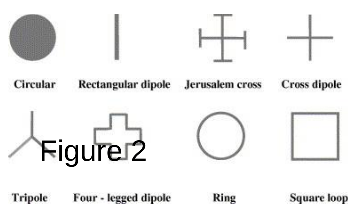
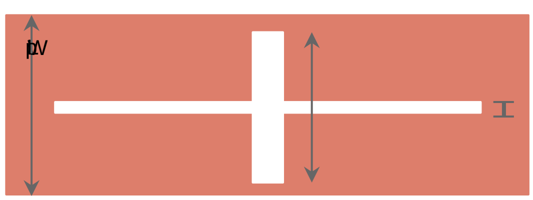


Figure 2

FSS elements can be of various shapes. Some of the common structures are given in Figure 2. The element size, shape, and periodicity of an FSS structure decide the resonant frequency. The structure can be also designed in such a way to obtain multiple pass or stop bands [16]. The FSS structures can be arranged in multiple layers to obtain the desired response [17].



In this study, an FSS of a simple cross structure of slot type as given in figure 3 is analysed. It consists of two perpendicular slots on a metallic sheet of square shape. The physical dimensions of the structure, i.e. length L, width W, and periodicity p define the frequency response of the FSS structure. The FSS structure will offer a passband shielding effectiveness for the plane wave.

STATISTICAL ANALYSIS

In this study, the analysis of the data obtained by the validated simulation method was carried out via statistical methods. The first decision that was to be made was to define the input combinations for which the output was to be obtained. The simple cross-defined above involves three dimensions that can be varied in defined steps. Taking all combinations of these variations will generate a large set of data that will be time-consuming as well as makes it difficult to analyse.

DESIGN, MODELLING AND SIMULATION OF THE FSS

An FSS structure is to be designed to get a passband with the centre frequency at 1.8GHz. The frequency response of the above-mentioned FSS structure is determined by EM Simulation. The 3D EM analysis software package, CST Studio Suite was used for the design, modelling and simulation of the specified FSS structure. The following are the parameters considered for a unit cell of the simple cross FSS structure.

1. Cell height
2. Cell width
3. Slot length
4. Slot width

The Cell height and Cell width were made to be equal for the rectangular structure. To begin with, a square Aluminium sheet of 100mm x 100mm and 1mm thickness with slots of length 50mm x 5mm was considered. The model was defined with unit cell boundary conditions. The model in the CST studio is shown in Figure 4.

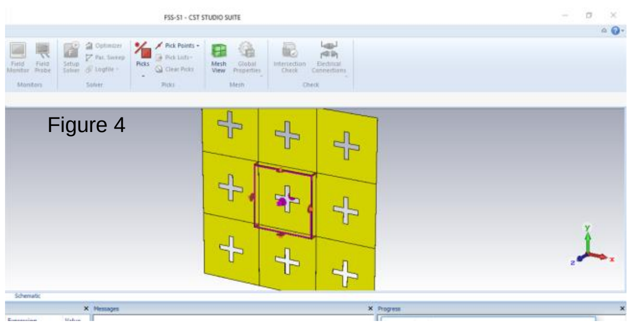


Figure 4

The Floquet ports were defined on the incident and exit faces of this unit cell. The model was then simulated over the frequency range of 1.5GHz to 2GHz. The structure was optimised for the passband at 1.8GHz by variations. The frequency response of the optimised structure is given in Figure 5

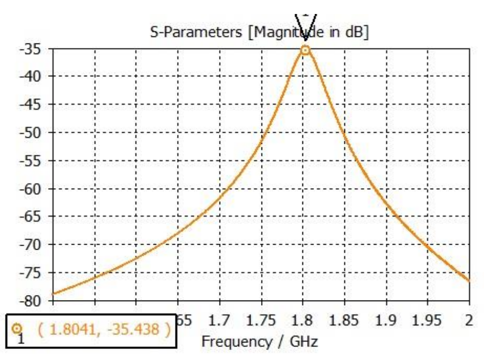


Figure 5

EXPERIMENTAL VALIDATION OF THE OPTIMISED FSS

The optimised structure is then validated with experimental measurements. The measurements were carried out inside a shielded semi-anechoic chamber used for EMC measurements. For the validation, a 3x3 array of the optimised dimensions was fabricated with an aluminium sheet. This structure was positioned vertically on a wooden table.

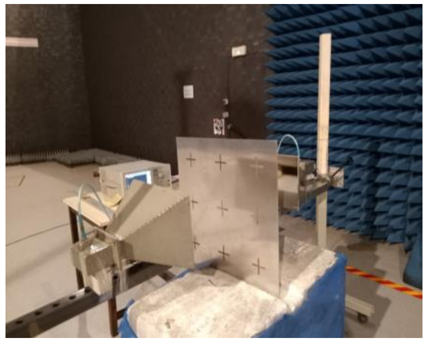


Figure 6

Narrowband Standard Gain Horn Antennas were used as the transmitter and the receiver. The transmitting and receiving antennae ports were connected to Port 1 and Port 2 of a Network Analyser respectively. The photograph of the setup is shown in Figure 6. The frequency response of the structure was measured as S21 in the Network Analyser. The results were found to be in concurrence with the simulated results with pass-band at 1.8GHz, thereby validating the simulation procedure. The obtained frequency response is given in Figure 7.

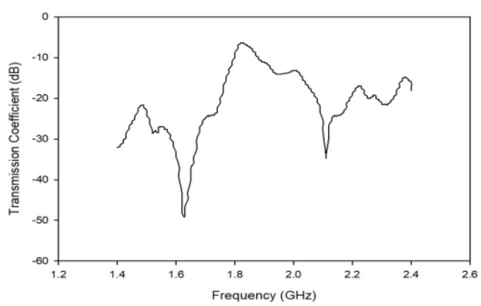


Figure 7

STATISTICAL ANALYSIS

The above described simple cross-slotted FSS structure was then analysed statistically for the relation between the input geometrical parameters i.e. length L, width W, and periodicity p and the output frequency response i.e. centre frequency and 3dB bandwidth. This requires a finite set of known data that relates the input parameters to the output values that are obtained by simulation. Based on these data the variance of the output values with respect to the input parameters is to be determined. It is preferred to have a small set of data that at the same time effectively covers all variance in the expected output.

The data set was derived via the Taguchi Method based on the Design of Experiments (DOE) [18]. The Design of Experiments is a statistical technique for determining the correlation between input elements influencing a process and its output or result. DOE approaches are employed to examine and prepare experiments for the optimisation of processes or designs containing natural factors that influence output variation [19]. It is a statistical method by which mathematical models are developed through experimental trials in order to predict the likely output, given the input data or parameters [20]. In this case, a set of models with defined input parameters i.e. are subjected to experiments via simulation to obtain the response.

Though mathematically very complex, the Taguchi method is a commonly used method of DOE, where the optimisation can be done at a subsequently low cost. For many DOE techniques, the number of experiments required grows exponentially with the number of input parameters. It is important to limit the number of parameters as much as possible to reduce the size of the problem and the effort required to solve it. The purpose of the experimental procedure is to produce an effect or desired result. This is measured as a function of standard deviation. For a process with various input factors, it is necessary to analyse the outputs that result from varying these inputs. This results in a large number of possible input variable combinations. It will be hard and time-consuming to analyse all of these variables. The Taguchi method significantly reduces the number of experimental combinations while adequately representing the variations. The selected combinations are defined as orthogonal arrays based on the number of parameters and variation range for each parameter.

With the Taguchi method, an orthogonal array of L25 table with 3 input factors was generated. Hence only 25 runs were sufficient to analyse the structure. The FSS structures with these values were simulated to obtain the output parameters - the resonant frequency and the 3 dB bandwidth. The generated data is given in Table 1.

TABLE IDATA SET - INPUT PARAMETERS VS OUTPUT VALUES

Sl	Input			Output	
	L (mm)	W(mm)	p(mm)	Freq(GHz)	BW(GHz)
1	40.00	05	100	3.2630	0.0954
2	40.00	10	125	3.0515	0.0720
3	40.00	15	150	2.9075	0.0512
4	40.00	20	175	2.7905	0.0403
5	40.00	25	200	2.6780	0.0361
6	53.75	05	125	2.5250	0.1056
7	53.75	10	150	2.4440	0.0958
8	53.75	15	175	2.4125	0.0788
9	53.75	20	200	2.2385	0.0685
10	53.75	25	100	2.8265	0.5066
11	67.50	05	150	2.0615	0.0972
12	67.50	10	175	2.0255	0.0974
13	67.50	15	200	1.9985	0.0880
14	67.50	20	100	2.3360	0.5944
15	67.50	25	125	2.2370	0.3961

16	81.25	05	175	1.7330	0.0889
17	81.25	10	200	1.6970	0.0908
18	81.25	15	100	1.9130	0.6087
19	81.25	20	125	1.8095	0.4221
20	81.25	25	150	1.8455	0.3178
21	95.00	05	200	1.4945	0.0791
22	95.00	10	100	1.5395	0.5759
23	95.00	15	125	1.6070	0.4135
24	95.00	20	150	1.5980	0.3266
25	95.00	25	175	1.580	0.2665

The set of data representing the possible variance in the expected output was subjected to regressive analysis using the Analysis of Variance (ANOVA) technique. ANOVA is used to predict a continuous outcome on the basis of one or more categorical variables. As the levels obtained with the Taguchi technique is a categorical set, With the analysis, the relationship between the input i.e. length L, width W, & periodicity p and the output i.e. centre frequency Freq and bandwidth BW is obtained as

Freq = 4.3685+0.0008*W − 0.0034*p − 0.025*L

BW = 0.317+0.0105*W − 0.0039*p + 0.005*L

To validate the generated model, an arbitrary slotted simple cross FSS structure with the following dimensions were considered.

Slot Length L = 80mm

Slot Width W = 10mm

periodicity p = 100mm

The above structure was modelled and simulated using CST Studio to obtain the centre frequency and bandwidth BW. The results were compared with that obtained from the analytical expression and are given in Table 2

TABLE 2

COMPARISON OF RESULTS

	Results obtained via	
	Simulation	Analytical Expression
Centre Frequency (GHz)	2.7557	2.7825
Bandwidth (MHz)	0.1890	0.2295

From the above table, it is evident that the analytical expression derived shows a good concurrence with the validated simulation results.

CONCLUSION

The work demonstrates the usage of statistical techniques to obtain an analytical expression for an FSS structure. The frequency response obtained by the expression closely matches the actual performance of the structure. This expression can be used for designing the FSS for the desired shielding without using simulation tools that require great expertise and involve cost and time.

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