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Development of Method of Moment Based Programme to Analyze Cross Dipole Frequency Selective Surface and its Verification with Measured Results

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Abstract*: Theoretical analysis of frequency selective surface comprising of cross dipole elements has been presented in this paper. Algorithm for theoretical analysis based on method of moment has been implemented by MATLAB programming. Theoretical, simulated and experimental results are compared. Simulated result is obtained by ANSOFT designer version 2.2 software. Experimental result is obtained by standard microwave test bench. Good parity in the results is observed. The presented FSS Structure has relevance in the field of mobile and satellite communication.

***Keywords* : Cross Dipole, Frequency Selective Surface, Method Of Moment**

I. INTRODUCTION

An assemble of periodic array of patches on a dielectric substrate or that of apertures within a metallic screen is called Frequency selective surface (FSS). It exhibits frequency filtering properties like the frequency filters in traditional radio frequency (RF) circuits. The patch type and aperture type array resemble band stop and band pass filter respectively, thus realizing its application in spatial microwave and optical filters. Patch type FSS and aperture type FSS are exactly complementary to each other. Patch type FSS is also known as thin screen FSS, which is widely used due to its light weight, low volume, low cost and can be fabricated with conventional printed circuit technology. Relative permittivity of dielectric, distance between two patches, and patch dimensions are some of the primary factors on which the operating frequency of FSS structures depends on [1-2],[4],[7]. Various FSS element shapes include square patch, dipole, circular patch, cross-dipole, Jerusalem cross, ring and many more.

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Slots and slits can be incorporated on the patch to improve its efficiency [3-4], [6-9]. Thus, for more than four decades, FSS becomes the key interest of researchers and are being used as polarized filters, absorbers, electromagnetic compatibility (EC) shield, sub reflectors, radomes etc [10-14]. FSS is also used as broadband absorber and back scatter transponder [15-18]. Different types of FSS structures are theoretically analyzed by using various methods like-FDTD, FEM, MOM. The formulation of electromagnetic scattering problems for normal incidence by MOM is complicated, whereas due to its perfect accuracy in the frequency domain, it is widely used for analysis. In method of moment (MOM), the characteristic basis functions are used to considerably reduce the matrix size and to converge quickly, hence can electrically solve large problems knowing fewer unknowns [3-6]. A MOM based algorithm is theoretically established in this paper to calculate the scattered electric field of a cross dipole patch type FSS structure and then the transmission coefficient of the structure is determined by MATLAB programming from the scattered electric field. We have simulated the same cross dipole patch type FSS structure by using ANSOFT designer version 2.2 which works on MOM. The programmed and simulated results obtained have been compared with the measured data obtained by experiment. Although this paper only appraises a cross dipole patch type FSS, other type of FSSs may also be analyzed by the same method.

II. DESIGN OF FREQUENCY SELECTIVE SURFACE

The FSS structure is designed with metallic cross dipole element having length 15mm and width 1.5mm, the periodicity in both x and y direction is 29.7mm. Dimension of the FR4-epoxy substrate is 150mm X 150mm X 1.6mm as shown in Fig.1, having 4.4 relative permittivity. The FSS unit cell is given in Fig.2.

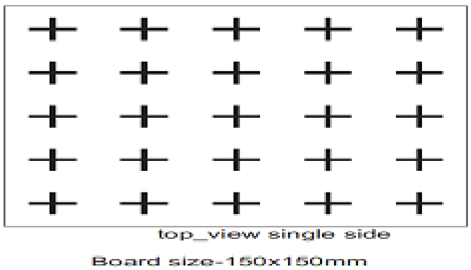

Fig.1. Part of frequency selective surface

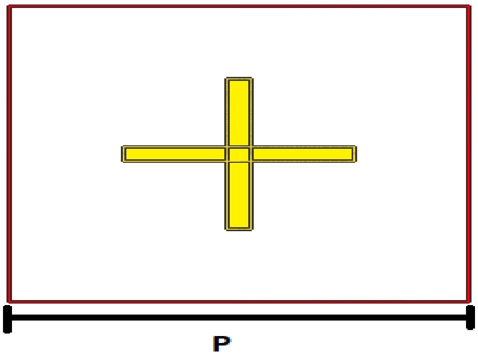

Fig.2. Unit cell of FSS structure

The calculation of resonance frequency based on MOM is described as follows:-

Starting from well known four Maxwell's equations, current density may be calculated from incident electric field like the following equations [4]:

$$\begin{pmatrix} E_x^{inc} \\ E_y^{inc} \end{pmatrix} = -\begin{pmatrix} E_x^{s} \\ E_y^{s} \end{pmatrix} = \frac{1}{j\omega\varepsilon_0}\frac{1}{(2\Pi)^2 ab}\sum_{m=-\alpha}^{+\alpha}\sum_{n=-\alpha}^{+\alpha}\begin{bmatrix} k_0^2-\alpha_m^2 & -\alpha_m\beta_n \\ -\alpha_m\beta_n & k_0^2-\beta_n^2 \end{bmatrix}$$

$$\overline{G(\alpha_m\beta_n)}\begin{pmatrix} \overline{J_x(\alpha_m\beta_n)} \\ \overline{J_y(\alpha_m\beta_n)} \end{pmatrix} e^{j\alpha_m x} e^{j\beta_n y} \tag{1}$$

Where, $\alpha_m = \dfrac{2m\Pi}{a} + k_x^{inc}$

$\beta_n = \dfrac{2n\Pi}{b} + k_y^{inc}$

$k_x^{inc} = k_0 \sin\theta\cos\phi$ and $k_y^{inc} = k_0\sin\theta\sin\phi$

$$\overline{G(\alpha_m\beta_n)} = \frac{-j}{\sqrt[2]{k_0^2-\alpha_m^2-\beta_n^2}} \xrightarrow[I]{} \quad \text{for } k_0^2 > \alpha_m^2+\beta_n^2$$

$$= \frac{1}{\sqrt[2]{\alpha_m^2+\beta_n^2-k_0^2}} \xrightarrow[I]{} \quad \text{for } k_0^2 < \alpha_m^2+\beta_n^2$$

where , θ is the incidence angle of the wave with respect to the z-axis on x-z plane and ϕ is the projection angle of incident wave on x-y plane with respect to the x-axis, k_0 is free-space wave number, the periodicity in x and y direction are given by 'a' and 'b' respectively, and the skew angle is considered as zero.

For solution, the matrix equation is represented by L(u)=g, where g is known matrix $\begin{pmatrix} E_x^{inc} \\ E_y^{inc} \end{pmatrix}$.

u is the matrix to be determined $\begin{pmatrix} \overline{J_x(\alpha_m\beta_n)} \\ \overline{J_y(\alpha_m\beta_n)} \end{pmatrix}$ and L is the total operator involved in eqn.(1).

u is the basis function which is to be chosen. In generalized form [4],

$$u = \sum_{i=1}^{n}\left(\hat{x}\, C_{xi} f_{xi} + \hat{y}\, C_{yi} f_{yi}\right) \tag{2}$$

C_{xi} and C_{yi} can be calculated, if we know the transferred basis function and λ in x and y direction.

For, cross dipole or slot type FSS, as suggested by R.Mittra, basis function may be considered as [4].

$$J_{xp} = \hat{x}\begin{Bmatrix} c_{1q}\sin\left[\dfrac{P\Pi}{L}\left(x+\dfrac{L}{2}\right)\right] + \operatorname{sgn}(x) \\ B\cos\left(\dfrac{\Pi}{L}x\right) \end{Bmatrix}$$

$$P_x(0,L)P_y(0,W)$$

$$J_{yp} = \hat{y}\begin{Bmatrix} c_{2q}\sin\left[\dfrac{P\Pi}{L}\left(y+\dfrac{L}{2}\right)\right] - \operatorname{sgn}(y) \\ B\cos\left(\dfrac{\Pi}{L}y\right) \end{Bmatrix}$$

$$P_x(0,W)P_y(0,L) \tag{3}$$

Where p=1, 2, 3, -----------

The calculated transferred basis function in y-direction is:-

$$T_{Basis}(P,\alpha_m,\beta_n) = \int_{-\alpha}^{+\alpha}\int_{-\alpha}^{+\alpha} J_y\, e^{-j\beta_n y} e^{-j\alpha_m x}\, dydx$$

$$= \frac{LW}{2j}\begin{bmatrix} c_{2q}\begin{Bmatrix} e^{jP\frac{\Pi}{2}}\sin c\left(\dfrac{P\Pi}{L}-\beta_n\right)\dfrac{L}{2\Pi} - \\ e^{-jP\frac{\Pi}{2}}\sin c\left(\dfrac{P\Pi}{L}+\beta_n\right)\dfrac{L}{2\Pi} \end{Bmatrix} + \\ B\begin{Bmatrix} \sin c\left(\dfrac{\Pi}{L}-\beta_n\right)\dfrac{L}{4\Pi}\sin\left(\dfrac{\Pi}{L}-\beta_n\right)\dfrac{L}{4} - \\ \sin c\left(\dfrac{\Pi}{L}+\beta_n\right)\dfrac{L}{4\Pi}\sin\left(\dfrac{\Pi}{L}+\beta_n\right)\dfrac{L}{4} \end{Bmatrix} \end{bmatrix}\sin c\left(\frac{\alpha_m W}{2\Pi}\right) \tag{4}$$

The calculated transferred basis function in x-direction is:-

$$T_{Basis}^{*}(P,\alpha_m,\beta_n) = \int_{-\alpha}^{+\alpha}\int_{-\alpha}^{+\alpha} J_x\, e^{-j\beta_n y} e^{-j\alpha_m x}\, dxdy$$

$$= \frac{LW}{2j}\begin{bmatrix} c_{1q}\begin{Bmatrix} e^{jP\frac{\Pi}{2}}\sin c\left(\dfrac{P\Pi}{L}-\alpha_m\right)\dfrac{L}{2\Pi} - \\ e^{-jP\frac{\Pi}{2}}\sin c\left(\dfrac{P\Pi}{L}+\alpha_m\right)\dfrac{L}{2\Pi} \end{Bmatrix} + \\ B\begin{Bmatrix} \sin c\left(\dfrac{\Pi}{L}+\alpha_m\right)\dfrac{L}{4\Pi}\sin\left(\dfrac{\Pi}{L}+\alpha_m\right)\dfrac{L}{4} - \\ \sin c\left(\dfrac{\Pi}{L}-\alpha_m\right)\dfrac{L}{4\Pi}\sin\left(\dfrac{\Pi}{L}-\alpha_m\right)\dfrac{L}{4} \end{Bmatrix} \end{bmatrix}\sin c\left(\frac{\beta_n W}{2\Pi}\right) \tag{5}$$

λ in y direction is expressed as,

$$\lambda_i^y = \frac{LW}{2}e^{-j(\omega t+\phi)}\left[\frac{c_{2q}}{j}\begin{Bmatrix} e^{ji\frac{\Pi}{2}}\sin c2(i-1) - \\ e^{-ji\frac{\Pi}{2}}\sin c2(i+1) \end{Bmatrix} - B\right] \tag{6}$$

Where, i=1, 2, 3, ----------

λ in x direction is expressed as,

$$\lambda_i^x = \frac{LW}{2}e^{-j(\omega t+\phi)}\left[\frac{c_{1q}}{j}\begin{Bmatrix} e^{ji\frac{\Pi}{2}}\sin c2(i-1) - \\ e^{-ji\frac{\Pi}{2}}\sin c2(i+1) \end{Bmatrix} + B\right] \tag{7}$$

Where, i=1, 2, 3,-------------

$\begin{pmatrix} J_x(\alpha_m\beta_n) \\ J_y(\alpha_m\beta_n) \end{pmatrix}$ can be known using equation (4) to (7). Now, using the values of $\overrightarrow{J_x}$ and $\overline{J_y}$ into eqn.(1) the scattered electric fields $\begin{pmatrix} E_x^s \\ E_y^s \end{pmatrix}$ can be calculated.

From these scattered electric fields E_x^s and E_y^s the transmission coefficients of the structure of mode mn due to mode kl incident is given by [4]

$$T_{TM} = \frac{j\omega\varepsilon_0 E_z^t}{\left(k_0^2+\gamma_{mn}^2\right)}\sqrt{\frac{\gamma_{mn}\left(k_0^2+\gamma_{mn}^2\right)}{\gamma_{kl}\left(k_0^2+\gamma_{kl}^2\right)}}$$

Where, $E_z^t = j\dfrac{\left(\alpha_m E_x^s + \beta_n E_y^s\right)}{\gamma_{mn}}$

$$\gamma_{mn} = -j\left(k_0^2-\alpha_m^2-\beta_n^2\right)^{1/2} \quad \text{for } k_0^2 \rangle \alpha_m^2+\beta_n^2$$

$$= -\left(\alpha_m^2+\beta_n^2-k_0^2\right)^{1/2} \quad \text{for } k_0^2 \langle \alpha_m^2+\beta_n^2$$

Thus, by calculating T_{TM} for dominant mode by MATLAB programming, we generate a graph of transmitted electric field vs frequency from where resonating frequency of the designed structure is obtained theoretically.

ANSOFT, FEKO are some efficient softwares based on MOM, by using which the transmission characteristic of a particular FSS can be produced. The cross dipole structure designed by us is simulated by ANSOFT software version 2.2, and hence, obtained the transmission coefficient vs frequency graph and thus resonant frequency of the structure. Measurement is performed in our laboratory with the fabricated cross dipole patch type FSS and its resonance frequency is determined from the transmission coefficient vs frequency curve. Further studies has been carried out with the proposed cross dipole patch type FSS structure by changing its periodicity P. Satisfactory result is accomplished focusing on the enhancement of bandwidth.

III. RESULT AND ANALYSIS

The measurement of fabricated cross dipole FSS structure shown in Fig.3 has been done in our laboratory. A variable RF oscillator is connected with the transmitting horn antenna and the receiving horn antenna is connected to a power meter with power sensor. The FSS structure is kept at far field distance from both the antennas. It has been observed that the power radiated by the RF oscillator is transmitted through the FSS at all frequencies except at 6.13 GHz.

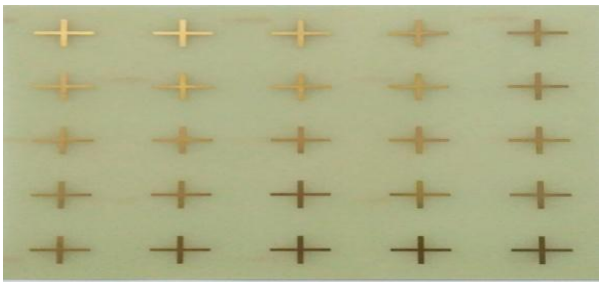

Fig.3. Fabricated frequency selective surface

The same FSS structure resonates at 6.18 GHz on simulation and acts as band stop filter. MOM is used to formulate the cross dipole patch type FSS structure and further realization is done by MATLAB programming and thus a resonance at 6.10 GHz is obtained for the periodicity of 29.7 mm in both horizontal and vertical direction with cross dipole of 15 mm length and 1.5 mm width. The transmitted coefficient vs. frequency curve of the structure shown in Fig.2 for all the three cases (theoretical, simulated and experimental) are plotted on the same graph as shown in Fig.4 and some experimental result is given in Table-1. A comparative analysis is also given in Table-2 for extensive understanding.

Table-1: Experimental Result

Freq. (GHz)	S21 (dB)	Freq. (GHz)	S21 (dB)	Freq. (GHz)	S21 (dB)
4	-0.464	4.38	-1.12	4.76	-0.969
4.02	-0.720	4.4	-1.36	4.78	-1.65
4.04	-1.00	4.42	-0.920	4.8	-1.55
4.06	-0.779	4.44	-0.571	4.82	-1.77
4.08	-0.795	4.46	-0.165	4.84	-1.40
4.1	-0.900	4.48	-0.031	4.86	-1.48
4.12	-0.683	4.5	-0.254	4.88	-1.90
4.14	-1.05	4.52	-0.037	4.9	-1.88
4.16	-0.956	4.54	-0.326	4.92	-2.55
4.18	-0.881	4.56	-0.104	4.94	-2.75
4.2	-0.708	4.58	-0.252	4.96	-2.58
4.22	-0.399	4.6	-0.225	4.98	-2.66
4.24	-0.746	4.62	-0.119	5	-2.31
4.26	-1.00	4.64	-0.261	5.02	-2.13
4.28	-1.44	4.68	-0.583	5.04	-2.44
4.3	-1.87	4.68	-0.896	5.06	-1.84
4.32	-1.68	4.7	-0.904	5.08	-1.33
4.34	-1.40	4.72	-0.853	5.1	-0.775
4.36	-1.29	4.74	-0.506	5.12	-0.197
Freq. (GHz)	**S21 (dB)**	**Freq. (GHz)**	**S21 (dB)**	**Freq. (GHz)**	**S21 (dB)**
5.14	-0.405	6.1	-19.0	7.04	-1.37
5.16	-0.111	6.12	-20.8	7.06	-1.37
5.18	-0.143	6.13	-20.92	7.08	-1.30
5.2	-0.142	6.14	-19.9	7.12	-0.631
5.22	-0.060	6.16	-15.0	7.14	-0.798
5.24	-0.428	6.18	-11.9	7.16	-0.844
5.26	-0.652	6.2	-10.1	7.18	-0.371
5.28	-0.747	6.22	-8.28	7.2	-0.093
5.3	-1.43	6.24	-7.47	7.22	-0.164
5.32	-1.52	6.26	-5.89	7.24	-0.385
5.34	-1.49	6.28	-4.30	7.26	-0.440
5.36	-1.67	6.3	-3.29	7.28	-0.705
5.38	-1.27	6.32	-2.35	7.3	-1.14
5.4	-0.936	6.34	-2.69	7.32	-1.72
5.42	-1.07	6.36	-2.44	7.34	-1.78
5.44	-0.724	6.38	-2.09	7.36	-0.921
5.46	-0.627	6.4	-1.59	7.38	-0.868
5.48	-1.07	6.42	-1.06	7.4	-0.171
5.5	-0.852	6.44	-0.964	7.42	-0.201
5.52	-1.16	6.46	-1.51	7.44	-2.21
5.54	-1.52	6.48	-1.50	7.46	-5.69
5.56	-1.52	6.5	-1.42	7.48	-1.12
5.58	-2.07	6.52	-1.55	7.5	-0.265
5.6	-3.46	6.54	-1.49	7.52	-0.226
5.62	-4.74	6.56	-1.56	7.54	-0.939
5.64	-6.38	6.58	-1.71	7.56	-1.30
5.66	-6.21	6.6	-1.59	7.58	-1.74
5.68	-5.46	6.62	-1.46	7.6	-2.16
5.7	-4.91	6.64	-1.18	7.62	-1.75
5.72	-4.56	6.66	-0.986	7.64	-1.39
5.74	-3.44	6.68	-0.880	7.66	-1.41

5.76	-2.97	6.7	-0.730	7.68	-1.99
5.78	-2.67	6.72	-0.691	7.7	-1.96
5.8	-2.45	6.74	-0.201	7.72	-1.60
5.82	-3.12	6.76	-0.070	7.74	-1.22
5.84	-3.15	6.78	-0.125	7.76	-0.792
5.86	-3.22	6.8	-0.194	7.78	-0.438
5.88	-2.65	6.82	-0.278	7.8	-0.127
5.9	-3.98	6.84	-0.312	7.82	-0.089
5.92	-5.62	6.86	-0.122	7.84	-0.033
5.94	-5.85	6.88	-0.399	7.86	-0.031
5.96	-6.48	6.9	-0.463	7.88	-0.034
5.98	-6.25	6.92	-0.535	7.9	-0.054
6	-6.24	6.94	-0.641	7.92	-0.082
6.02	-7.43	6.96	-0.703	7.94	-0.099
6.04	-8.47	6.98	-0.934	7.96	-0.129
6.06	-10.7	7	-0.925	7.98	-0.143
6.08	-14.7	7.02	-0.953	8	-0.161

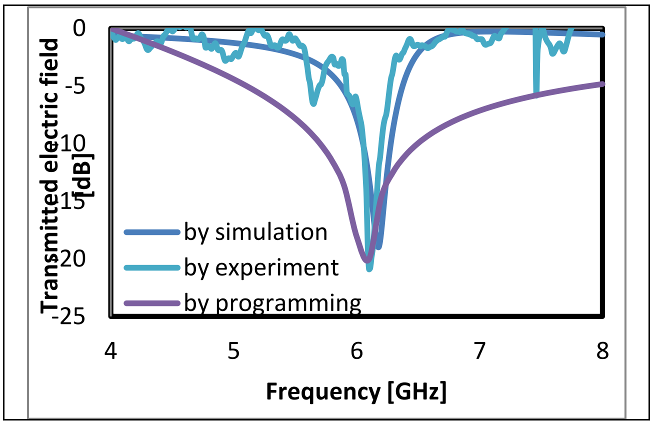

Fig.4. Transmission coefficient vs frequency graph

Table-2: Comparative Study of Results

FSS Structure	Resonant Frequency (GHz)	Transmission Coefficient (dB)
Theoretical	6.10	-20.02
Simulated	6.18	-18.99
Experimental	6.13	-20.92

The performed experiment thus successfully validates the theory as shown in Fig.4 and Table-2. In order to enhance the bandwidth of the FSS structure (proposed), a parametric study by changing the periodicity of the FSS structure has been conducted as given in Table-3.

Table-3: Parametric Study of the FSS by changing the Periodicity

Periodicity P(mm)	Resonant Frequency (GHz)	Transmission Coefficient (dB)	Bandwidth (MHz)
37.5	5.90	-14.50	100
30	6.12	-18.60	223
29.7	6.18	-19.00	230
29	6.22	-19.29	250
28	6.25	-20.00	270
27	6.27	-20.61	290
26	6.32	-21.26	320
25	6.34	-22.00	360
24	6.37	-22.81	400
23	6.39	-23.52	440
22	6.41	-24.37	480
21	6.44	-25.20	540
20	6.44	-26.28	620
19	6.44	-27.22	700
18	6.40	820	-28.31

It is observed from the study that varying the periodicity of the cross dipole patch type FSS structure from 37.5 mm to 18 mm the bandwidth changes from 100 MHz to 820 MHz respectively. Thus, the bandwidth increases with decreasing the periodicity, a maximum of 820 MHz is obtained for the periodicity of 18 mm and at the same time a good band separation is observed with the transmission coefficient of -28.31 dB at resonance frequency of 6.40 GHz. The transmission characteristics vs frequency for periodicity of 18 mm is illustrated in Fig.5.

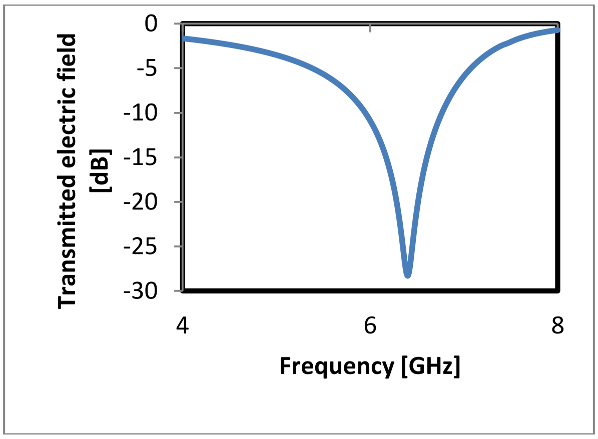

Fig.5. Transmission coefficient vs frequency graph for periodicity 18mm.

IV. CONCLUSION

FSS structures are simulated using ANSOFT and HFSS softwares based on MOM numerical technology. It has been observed that the result changes with the choice of messing or number of steps in the range of frequencies while analyzing the structure with the softwares.

Thus, the formulation of two dimensional cross dipole structures are instigated by MATLAB programming to calculate the transmission coefficient, the same structure is simulated by ANSOFT designer version 2.2 software and an experiment has been done with the fabricated cross dipole structure with the help of standard microwave test bench. Comparing the three results given in Table-2, it is observed that the resonant frequency and transmission coefficient obtained theoretically by us are in proximate with the experimental result than the simulated one and is independent of choice of messing or number of steps in the range of frequencies. Thus, it can be concluded that the theory and the MATLAB code established in this paper is more effective to analyze an FSS structure. Also from the parametric study of variation of periodicity, optimum bandwidth is obtained with minor variation of operating frequency. The endeavor in this paper has further scope of similar formulation on other typical FSS structures.

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