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Investigation of the Finite Planar Frequency Selective Surface with Defect Patterns

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Abstract – In this paper, RCS characteristics on defect pattern of crossed dipole slot FSS having a finite size have been analyzed. To analyze RCS, we applied the electric field integral equation analysis which applies BiCGSTab algorithm with iterative method and uses RWG basis function. To verify the validity of this paper, RCS of PEC sphere has been compared to the theoretical results and FSSs with defect patterns are fabricated and measured. As defect patterns in FSS, missing one column, missing some elements, and discontinuity in surfaces are simulated and compared with the measurement results. Resonant frequency shifts in pass band and changes in bandwidth are observed. From the results, precisely predicting and designing frequency characteristics over defect patterns are essential when applying FSS structures such as FSS radomes.

Keywords : Frequency selective surface, Electric field integral equation, Radar cross section

1. Introduction

The Frequency Selective Surface (FSS) is the electromagnetic structure with properties of penetrating or reflecting certain frequencies as a kind of spatial filters and has been used for a long time in various fields including radomes for antenna, double reflector antenna [1]. Generally, the FSS's properties of penetrating or reflecting certain frequencies are changed depending on the size, formation, array period, and array formation of basic unit cells of the FSS [2]. In particular, many studies for the military applications have been proactively made applying the FSS in stealth technology related to reduction of Radar Cross Section (RCS) and others as a band-pass filter or a band-stop filter which could absorb or reflect radar signals.

Most of studies related to the FSS have been conducted based on infinite periodic structure as an assumption. But, along with the latest development of computer, the studies have been expanded to finite-sized FSS or curved FSS. Also, most of the studies on the FSS have been made based on the hypothesis that the FSS has an ideal and flawless structure. Effects arising due to flaws of FSS were not put into consideration in the actual manufacturing process. To design and utilize the FSS to apply it in the structures such as radomes, a conductor film composing FSS has to be manufactured and then, it have to be laminated in between dielectrics. Unlike the initial plans, various defects have been occurred including exclusion of unit cells of FSS, discontinuity on surface of FSS, and others.

Conventional finite planar FSS related studies were conducted on the assumption that all of the FSS structures did not have any defect pattern. To our knowledge, there have been no researches about the FSS with defect pattern. For this reason, this study aimed to observe changes of RCS characteristics on various defect patterns which could occur in actual events.

In relation to analysis method of FSS, unit cell was interpreted using a Floquet mode and expanded using periodic condition, in the assumption that the FSS is infinite. However, Cwik [3] and Grounds [4] calculated current distribution on the edges by considering edge effect in the assumption that the current distribution in infinite planar FSS is similar to the center area of finite planar FSS. Moreover, applying the Conjugate Gradient –Fast Fourier Transform(CG-FFT) in computational time was also proposed since Floquet's theorem could not be applied regarding finite planar FSS [5]. In 2002, Prakash [6] proposed plane wave spectral decomposition method making infinite planar FSS as the assumption, this method has advantage of saving computational time by solving problems only when a field incidents in some areas. Above these, element-by-element Method of Moments (MoM) approach was suggested because applying MoM directly requires too much computational time for interpreting FSS with multi-layer structure such as dielectrics.

This paper made an assumption regarding defects of crossed dipole slot FSS structure, which are widely applied for military purposes due to its outstanding features of stability and polarization over incidence angles, and compared RCS characteristics [1]. In case of the crossed dipole slot FSS with defects, three-dimensional MoM proposed by Rao et al. [7] was involved based on Electric Field Integral Equation (EFIE) since the FSS comprises finite sized conductors. In general, BiConjugate Gradient Stabilized (BiCGSTab) algorithm [8], one of iterative methods, is applied to enhance inefficiency of interpreting time occurring as the size of a matrix gets bigger, that is

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intended to be interpreted with MoM.

2. Electric Field Integral Equation Analysis

To analyze frequency characteristics of finite-sized crossed dipole slot FSS structure, this paper used EFIE-based three-dimensional MoM using the Rao Wilton Glisson (RWG) function as a basis function proposed by Rao et al [7]. When the entire field is set as $\vec{E}$, (1) is established between $\vec{E}^i$, incident plane ware in FSS and $\vec{E}^s$, scattered electric field. Since FSS consists of perfect electric conductor (PEC), (2) satisfying $\vec{E}_{\tan} = 0$ is established.

$$\vec{E} = \vec{E}^i + \vec{E}^s \tag{1}$$

$$\Phi(\vec{r}) = \frac{j}{4\pi\omega\varepsilon} \int_S \nabla'_s \cdot \vec{J}(\vec{r}\,')G(\vec{r},\vec{r}\,')dS \tag{2}$$

Here, $\Phi(\vec{r})$ is a scalar potential. s stands for FSS surface while $\vec{J}$ stands for current distribution on the surface. $G(\cdot)$ means a medium of Green's function. The RWG function proposed by Rao [7] divides surface of an object that is intended to be interpreted as shown in (3) by triangular patch as shown in Fig. 1, and finds the current induced by each triangular factor. Each variable given in (3) is shown in Fig. 1. Here, $a_n^{\pm}$ represents the area of each triangle.

$$f_n^{\pm}(\vec{r}) = \begin{cases} \dfrac{l_n}{2a_n^{\pm}} \vec{\rho}_n^{\pm} & \vec{r} \in T_n^{\pm} \\ 0 & \vec{r} \notin T_n^{\pm} \end{cases} \tag{3}$$

Using the RWG function given in (3), the current distribution, $\vec{J}$, can be obtained as shown in (4).

$$\vec{J}(\vec{r}) = \sum_{n=1}^{N} J_n \vec{f}_n(\vec{r}) \tag{4}$$

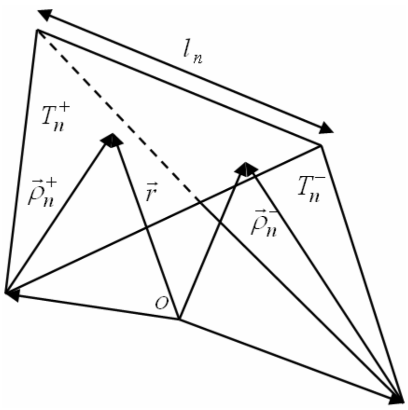


Fig. 1. Triangular Patch for RWG

To find the coefficient of current distribution, given in (4), Galerkin method needs to be applied in (2). In this process, the following determinant has to be solved. $[Z_{mn}]$ is the impedance matrix determined by interpretation structure, and $[V_m]$ is the source allowed by interpretation structure.

$$[Z_{mn}][J_n] = [V_m] \tag{5}$$

In general, the coefficient of current distribution could be found out using widely known Gaussian elimination or LU decomposition methods. However, there is a shortcoming of increase in computational speed in case where the size of a matrix gets bigger. To overcome such shortcoming, finding coefficient using iterative method has been proposed.

The Conjugate Gradient Method (CGM), Biconjugate Gradient Method (BiCGM), Conjugate Gradient Squared (CGS), BiCGSTab and other iterative methods have been proposed depending on various conditions like when the matrix is a symmetric matrix or not and etc [9]. In the paper, BiCGSTab algorithm [8] was used since its convergence speed is relatively faster and its convergence properties are more stable than CGS.

To verify the validity of this paper, RCS characteristics on NASA metallic almond structure and PEC sphere were investigated. For the comparison with experimental results

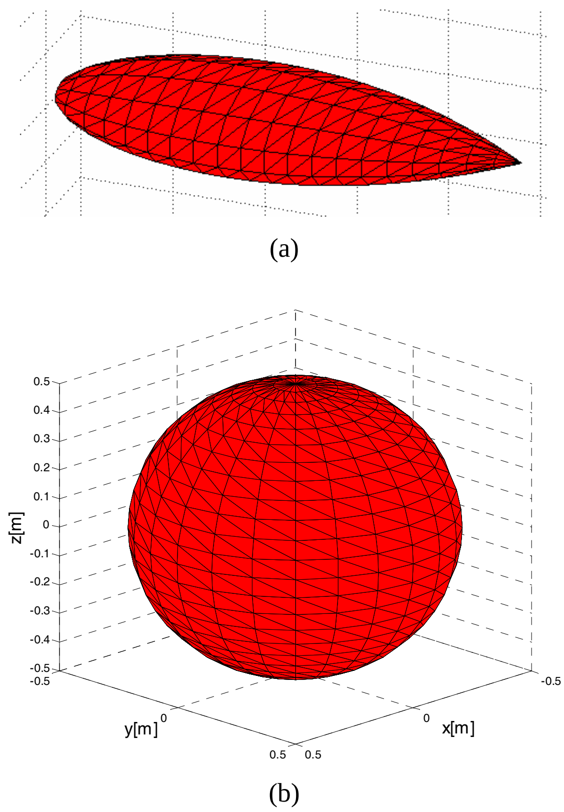
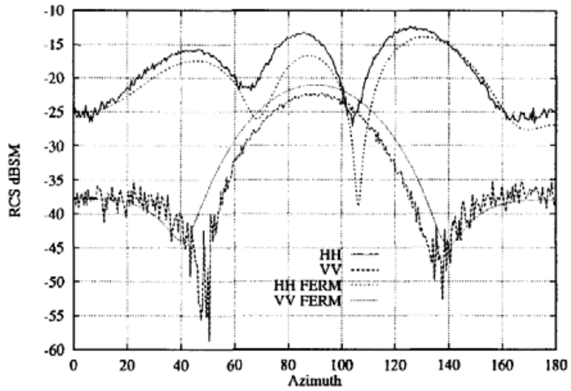
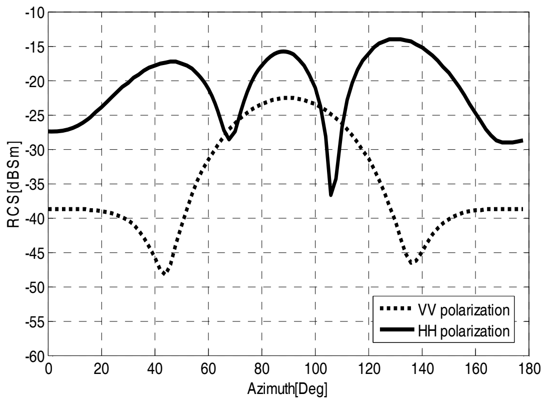


Fig. 2. RCS validation model: (a) NASA almond (b) PEC sphere

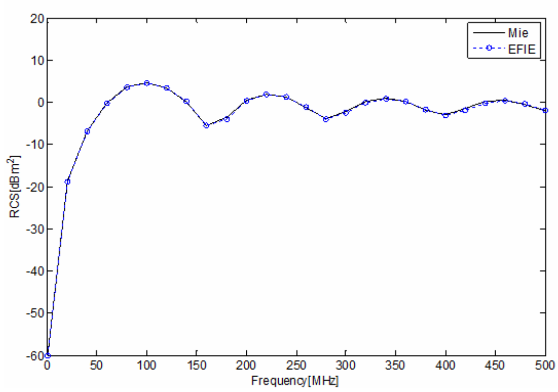
of Ref. [10], we used same design parameters for almond structure, i.e. total length of the almond is 9.936 inch. Fig. 3(a) shows the experimental results presented in Fig. 3 of Ref. [8]. In Fig. 3(b), we presented our RCS simulation results and obtained the good agreements. Fig. 2(b) is the PEC sphere with a diameter 1 m. The characteristics of RCS were compared with Mie's theoretical interpretation results, presented in Fig. 3(c), and the comparison was verified to coincide well.



(a)



(b)



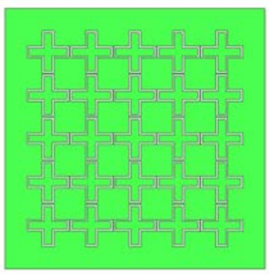
(c)

Fig. 3. RCS Comparison results (a) Experimental RCS (Ref. [10]) and (b) Simulation of the NASA almond; (c) Comparisons with MIE theory for PEC sphere

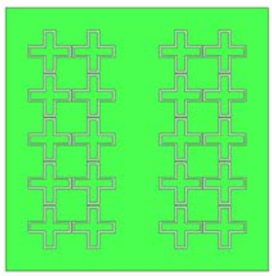
3. Simulation and Measurement Results

The normal crossed dipole slot free-standing FSS structure for reference is shown in Fig. 4(a). The structure was designed as a finite 5×5 array structure, and the total size is 38.4×38.4 mm for Ku-band operation. Each unit cell has the size of 6.4×6.4 mm and each slot has the width of 0.2 mm. We used the adaptive triangular mesh and the mesh size depends on the structure, for example, the simulation structure in Fig. 4(a) has the 1708 triangular mesh. RCS simulation results were assessed by using previously stated three-dimensional MoM and shown in Fig. 4(a). In this paper, the prepared FSS structure with defects was designed with possible defect structure that could be occurred in case of manufacturing the actual FSS. Fig. 4(b), Figs. 4(c) and Fig. 4(d) were presumed to be missing one column, missing elements, and discontinuity in junction surface, respectively. Simulation of RCS characteristics on each assumption are shown in Fig. 5.

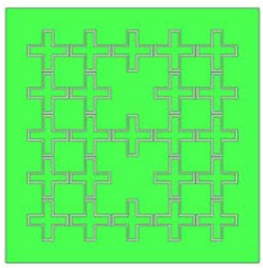
In case of having defect patterns, movement in pass band of frequencies and bandwidth were observed in common in all of cases. In case of the defect pattern in Fig. 4(b), 500MHz of downward movement was observed from 14.2GHz to 13.7GHz, taking the frequency having the lowest RCS value as the standard among the pass band. In case of the defect pattern in Fig. 4(c), upward movement from 14.2GHz to 15.5GHz was observed and, in particular, distortion in characteristics of frequency patterns outside the pass band was observed. On the other hand, in case of discontinuity in surface as shown in Fig. 4(d), slight shrink only in bandwidth was observed although the lowest RCS value was same as the original frequency values. To sum up, the defect in surface of FSS in Fig. 4(d) were assumed



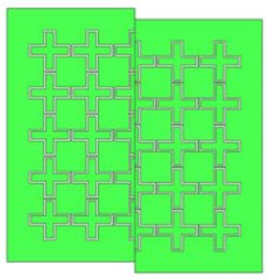
(a) Normal



(b) Missing one column



(c) Missing elements



(d) Miss-aligned pattern

Fig. 4. Finite planar FSS with defect patterns

to maintain fundamental characteristics relatively well. The study was able to conclude that among the anticipated defects in case of manufacturing the actual size FSS, defect patterns like Figs. 4(b) and 4(c) without FSS factors were verified to affect higher frequencies and those factors need to be taken into consideration.

To verify the simulation results, we fabricated the finite planar FSSs with defect patterns and presented in Fig. 6. In order from the left in Fig. 6, no defect FSS, missing one column, missing elements and miss-aligned pattern are presented, respectively. The FSSs are fabricated on 0.04 mm polyimide film with a dielectric permittivity of 4.4 and a loss tangent of 0.02. Instead the RCS measurement, we performed the measurement of the reflection characteristics because our main interests are the resonant frequency shift and changed bandwidth due to defect patterns in FSSs. To measure the reflection characteristics of fabricated FSSs, the experiments were performed using a calibrated vector network analyzer and waveguide measurement setup [11] using WR-75, which has the operation frequency range from 9.84 GHz to 15.0 GHz.

In Fig. 7, we presented the measured reflection characteristics of the defected FSSs. Because of polyimide film, the resonant frequency of fabricated FSSs is supposed to have lower values compared to FSSs in free space. In the past research [12], as the dielectric thickness increases, all FSS configurations have an initial rapid decline of the resonant frequency from the free space value. The resonant frequency of FSSs with dielectric predicted by design

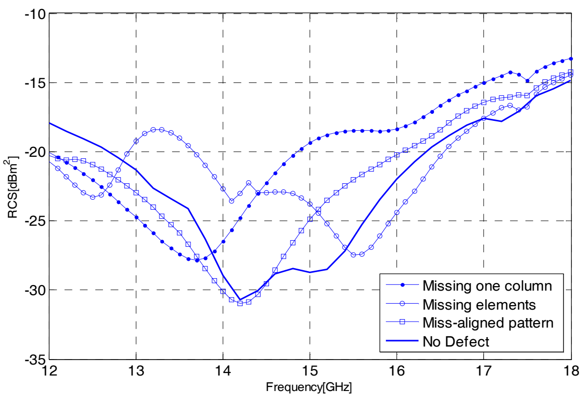


Fig. 5. Simulated RCS of finite planar FSSs with defect patterns

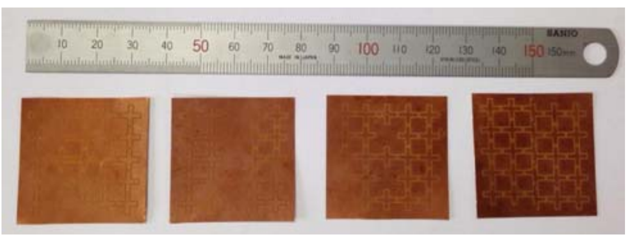


Fig. 6. Fabricated finite planar FSSs with defect patterns

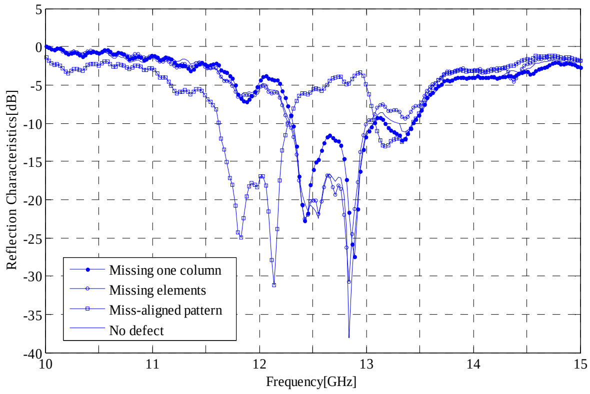


Fig. 7. Measured reflection characteristics of finite planar FSSs with defect patterns

equation proposed in [13] is agreed well with the measured resonant frequency. The measurement results cannot be compared with simulation results because the simulation results are presented as monostatic RCS. But, from the measurement results, we can know that the defect patterns in FSSs can cause the variation of the resonant frequency. One of the reasons of differences between measurement and simulation is because the internal dimension of WR75, 19.050×9.525 mm, does not fit fabricated FSS.

4. Conclusion

In this paper, changes in RCS characteristics on defect pattern of crossed dipole slot FSS having a finite size have been analyzed for the first time by applying three-dimensional MoM which applies BiCGSTab algorithm with iterative method and uses RWG function as basis function. To verify effectiveness of methods used in this paper, RCS of PEC sphere has been compared to the theoretical results. We also fabricated and performed the measurement of FSSs with defect patterns to verify the simulation results. In three theorized cases of defect patterns, including missing one column, missing some elements, and discontinuity in surfaces, the study confirmed that defect patterns were the causes in movement frequencies in pass band and changes in bandwidth, in case of manufacturing the actual size FSS by examining changes in RCS characteristics. Therefore, precisely predicting and designing frequency characteristics over defect patterns are essential when applying FSS structures such as FSS radomes.

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