# EM Analysis of Metamaterial-FSS for Millimeter Wave Radome Applications

Shiv Narayan, Sangeetha B., and Divya K. M.
Centre for Electromagnetics,
CSIR-National Aerospace Laboratories
Bangalore 560017, INDIA

**e-mail**: shivnarayan@nal.res.in

***Abstract:***
***EM performance analysis of a metamaterial FSS structure has been carried out in this paper for millimeter wave radome applications. Here two MNG layers are cascaded to design the proposed metamaterial FSS structure. The EM performance of the proposed metamaterial-FSS is studied for both TE and TM polarizations using transmission line transfer matrix method. The proposed structure exhibits bandpass characteristics over a wide frequency range from 88-105 GHz with excellent transmission efficiency (> 90%). In view of airborne radome applications, the EM characteristics of proposed metamaterial-FSS structure are also studied at oblique incidence for both TE and TM polarizations.***

***Key Words: Metamaterial, frequency selective surface, radome, FSS, metamaterial-FSS, millimeter wave.***

## I. Introduction

Electromagnetic metamaterials are periodic array of non-magnetic materials exhibiting characteristics which are not readily available in nature. It is an effectively homogenous structure whose structural average cell size is much smaller than its guided wavelength. The first type of metamaterial that possesses simultaneously negative permittivity and permeability results in negative refraction index (NRI) demonstrated by Eleftheriades and Balmain [1]. Other types of metamaterials are electromagnetic bandgap structures (EBG) or photonic bandgap materials (PBG) or photonic crystals (PCs), which are artificial periodic structures. These structures are able to control the propagation of EM waves at certain frequencies [2]. Metamaterial (MTM) structures exhibit many unusual properties like negative refractive index, reversed Snell's law, and Doppler Effect, etc. These counter-intuitive effects are found to be useful for the design of millimeter and microwave components. Metamaterials are classified into four categories *vz. mu-negative* (MNG), *epsilon-negative* (ENG), and *double negative* (DNG) medium [2]. Artificial materials can also be constructed by using cascaded DPS, ENG, and MNG properties. The negative refractive index can be achieved using structures such as split rings, wire, Ω-shaped structure, S-shaped structure, etc.

The filter characteristics can be achieved either by combination of metamaterial properties such as ENG, MNG, DNG or by cascaded DPS layers and metamaterial layers [3]. Further, it is reported that with proper combination of DPS layer and metamaterial layers, different filter characteristics can be realized such as low pass, high pass, band pass, and band reject. Such types of cascaded structures are called as *metamaterial based frequency selective surfaces* (MTM-FSS).

In this paper, EM performance analysis of a novel double layered *metamaterial FSS* (MTM-FSS) structure is presented using *transmission line transfer matrix* (TLTM) method for millimeter wave radome applications. The proposed MTM-FSS exhibits bandpass characteristics over the frequency range from 88-105 GHz with very good transmission efficiency (> 90%). The details of the work are discussed in the subsequent sections.

## II. Theoretical Considerations

The schematic of proposed doubled layered MTM-FSS structure is shown in Figure 1(a), which consists of two cascaded MNG layers, designed based on *square split ring resonators* (square-SRR) at different frequencies. Figure 1(b) represents the geometry of unit cell of square-SRR, which consists of two square shaped split-rings with a gap in between them where '*a*' denotes the side length of the square, *w* denotes the width of the conductor, and *d* is the spacing between the inner and outer square loop. The EM performance analysis of proposed metamaterial FSS is performed using transmission line transfer matrix method, which is a combination of *transmission line method* (TLM) and *transfer matrix method* (TMM). This method is applicable for both TE and TM polarizations at normal as well as oblique incidence. In TLTM method, a multilayered planar structure is represented by an equivalent transmission line. Each transmission line section is described by a characteristic impedance and propagation constant, which depends on the incidence angle, frequency, and polarization of incident wave.

By using Snell's law, the relationship between the two adjacent layers $l^{th}$ and $(l+1)^{th}$ of multilayered metamaterial FSS can be expressed as

$$\gamma_l \sin\theta_l = \gamma_{(l+1)} \sin\theta_{(l+1)} \quad (1)$$

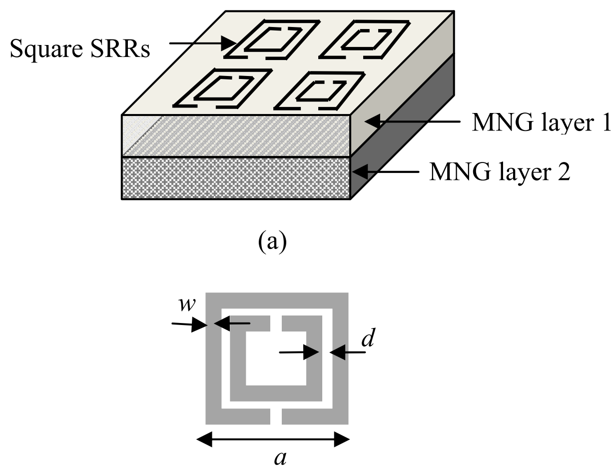


Figure 1 (a) Schematic of a two-layer metamaterial FSS structure, and (b) Geometry of unit cell of MNG layer.

where $\gamma_l$ is the propagation constant and is given by

$$\gamma_{lz} = j\omega\sqrt{\mu_l \varepsilon_l}\cos\theta_l \tag{2}$$

where $\varepsilon_l$ and $\mu_l$ are permittivity and permeability of the $l^{th}$ layer, respectively. $\omega = 2\pi f$ is the angular frequency and $\theta_l$ denotes the incidence angle at the $l^{th}$ layer. The characteristic impedances for both TE and TM waves can be given by

$$Z_{0l}^{TE} = \eta_l \sec\theta_l \tag{3}$$

$$Z_{0l}^{TM} = \eta_l \cos\theta_l \tag{4}$$

The transfer matrix of the entire metamaterial FSS structure can be determined by

$$[T]_{(l+1)l} = [L]_{(l+1)}[I]_{(l+1)l}, \quad l = 0, 1, \ldots\ (N-1) \tag{5}$$

where $N$ is the number of layers. Here, the wave amplitude transmission matrix $[L]_{(l+1)}$ and discontinuity transmission matrix $[I]_{(l+1)}$ can be calculated using the expressions given in [3].

The transmission coefficient ($t$) and reflection coefficient ($r$) of the entire metamaterial FSS structure can be expressed as

$$\begin{bmatrix} t \\ 0 \end{bmatrix} = [T]_{(N+1)0}\begin{bmatrix} 1 \\ r \end{bmatrix} \tag{6}$$

where

$$[T]_{(N+1)0} = [T]_{(N+1)N}[T]_{N(N-1)} \ldots [T]_{(l+1)l} \ldots [T]_{10} \tag{7}$$

Finally, the power reflection $R$, and power transmission $T$, of the proposed MTM-FSS structure can be determined by

$$R = rr^* \tag{8}$$

$$T = tt^* \tag{9}$$

In this work, the complex relative permeability of the MNG structures (square SRR structure) at millimeter wave frequencies is determined by Lorentz and Resonance models [4], [5] as

$$\mu_{eff} = 1 - \frac{\left(f_{mp}^2 - f_{m0}^2\right)}{f^2 - f_{m0} - j\Gamma_m f} \tag{10}$$

where $f_{mo}$ and $f_{mp}$ are the magnetic resonant frequency and magnetic plasma frequency of the SRR, respectively. $\Gamma_m$ represents the magnetic damping factor. The magnetic plasma frequency can be given as

$$f_{mp} = \frac{\omega_0}{2\pi\sqrt{1-F}} \tag{11}$$

where $F = 4(a/p)^2$ is the fractional volume occupied by the unit cell. $p$ represents the periodicity of square SRR unit cell.

In order to determine the resonant frequency of square-SRR, equivalent circuit method is used since square-SRR can be represented by lumped $LC$ resonant circuit as shown in Figure 2. The resonant frequency of $LC$ resonant circuit is calculated by

$$f_0 = \frac{1}{2\pi\sqrt{LC_s}} \tag{12}$$

where, $C_s$ represents the equivalent capacitance and $L$ is the effective inductance due to induced current in the rings.

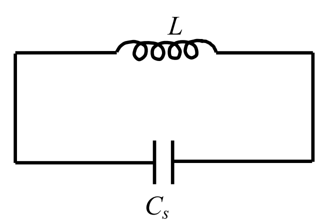


Figure 2 Lumped equivalent circuit of square SRR.

The expressions for effective inductance of $LC$ resonant circuit is given by

$$L = \frac{4.86\mu_0}{2}(a-w-d)\left[\ln\left(\frac{0.98}{\rho}\right) + 1.84\rho\right] \tag{13}$$

where $\rho$ is the filling factor of inductance, $w$ and $d$ are width and spacing between the inner and outer square loop. The effective capacitance of $LC$ resonant circuit is given by

$$C_s = \left[a - \frac{3}{2}(w+d)\right]C_{pul} \tag{14}$$

where $C_{pul}$ represents the per unit length capacitance between the square rings [6].

## III. EM DESIGN CONSIDERATIONS

In this work, the proposed metamaterial-FSS structure consists of two MNG ($\mu$-negative) layers as shown in Figure 1 (a), where each MNG layer is composed of square split ring resonators designed in different dielectric medium. For MNG layer 1, polyurethane foam ($\varepsilon_r$= 1.23 and $\tan\delta_e = 0.0024$) is used as dielectric medium and Teflon ($\varepsilon_r$ = 2.08 and $\tan\delta_e$ = 0.0002) is considered for the MNG layer 2. The relative permeability of each MNG layer is computed by the relation (10). Here, the MNG Layer 1 and 2 are designed for magnetic resonance frequency 75 GHz and 117 GHz respectively. The design dimensions of the MNG layer 1 are optimized to be; periodicity, $p$ = 0.8 mm, length of the side of the square, $a$ = 0.45 mm, width of the square loop conductor, $w$ = 0.042 mm, and spacing between the inner and outer square, $d$ = 0.08 mm. The optimized dimensions of the second MNG layer 2 are; $p$ = 0.75 mm, length of the side of the square, $a$ = 0.42 mm, width of the square loop conductor, $w$ = 0.056 mm, and spacing between the inner and outer square, $d$ = 0.09 mm. The thickness of the MNG layer 1and 2 is optimized to be 0.3 mm and 0.5 mm, respectively.

## IV. EM PERFORMANCE ANALYSIS

The EM performance of two-layer metamaterial-FSS has been investigated in this paper for TE and TM polarizations. The transmission and reflection characteristics of the proposed metamaterial-FSS are studied at normal as well as oblique incident angles such as 30°, and 45° for TE polarization as shown in Figs. 3 and 4, respectively. It is observed that the proposed metamaterial-FSS exhibits more than 90% transmission efficiency over a wide frequency range from 88-105 GHz and outside this frequency band shows sharp roll-off characteristics. Further, the transmission and reflection characteristics of the proposed metamaterial-FSS are studied for TM polarization at normal and oblique angle of incident (30° and 45°) as shown in Figs. 5 and 6, respectively.

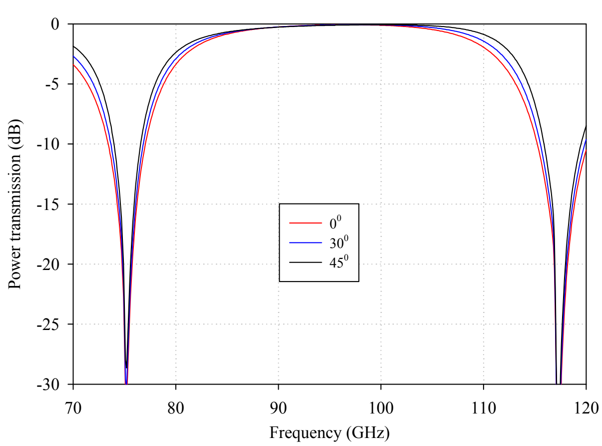


Figure 3 Power transmission characteristics of two-layer metamaterial-FSS for TE polarization at different angle of incidence (0°, 30°, 45°).

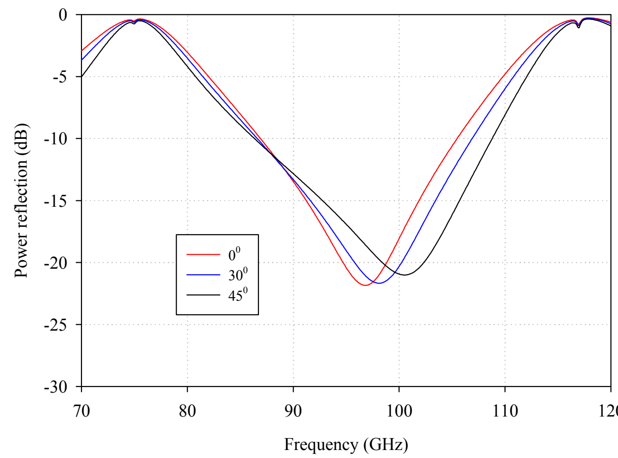


Figure 4 Power reflection characteristics of two-layer metamaterial-FSS for TE polarization at different angle of incidence (0°, 30°, 45°).

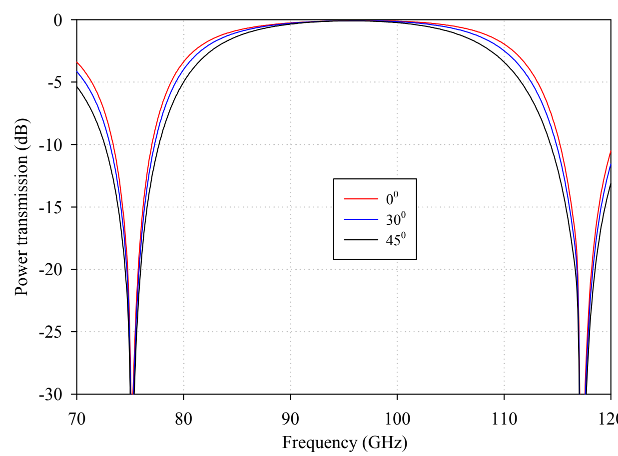


Figure 5 Power transmission characteristics of two-layer metamaterial-FSS for TM polarization at different angle of incidence (0°, 30°, 45°).

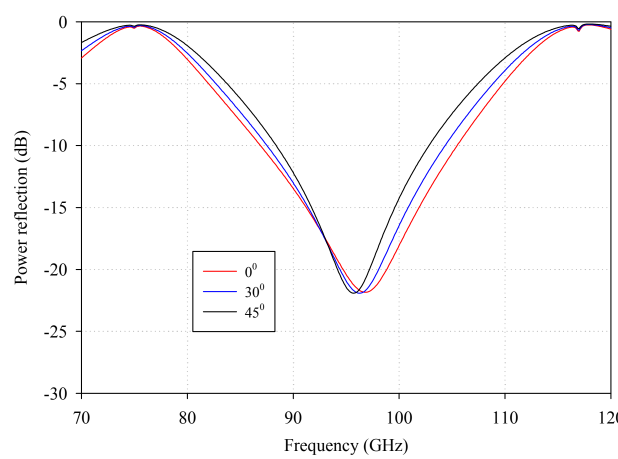


Figure 6 Power reflection characteristics of two-layer metamaterial-FSS for TM polarization at different angle of incidence (0°, 30°, 45°).

It is observed that the proposed metamaterial FSS structure exhibits similar performance as that of TE polarization. Moreover, the proposed structure exhibits more than 95% transmission over the frequency range 90.8-102.2 GHz with centre frequency 96.9 GHz at oblique incidence for both polarizations. Thus the metamaterial FSS structure shows polarization independent bandpass characteristics, which is desirable for radome applications.

## V. CONCLUSIONS

The EM performance analysis of a double layered metamaterial FSS structure has been carried out in this paper based on TLTM method for both TE and TM polarizations. The proposed structure exhibited excellent bandpass characteristics over a wide frequency band from 88 GHz to 105 GHz with very good transmission efficiency (> 90%). The proposed structure also showed the stability of EM characteristics *w.r.t.* different incidence angles and polarizations. This confirms the suitability of proposed metamaterial-FSS structure for airborne radome applications.

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## BIO DATA OF AUTHOR(S)

**Dr Shiv Narayan** obtained the Ph.D. degree in Electronics Engineering from Indian Institute of Technology (IIT-BHU), Banaras Hindu University, Varanasi, India in August 2006. He received his M.Sc. degree in Physics (with specialization in Electronics) from Banaras Hindu University, Varanasi, India in 2001. He is currently with the Centre for Electromagnetics (CEM) of CSIR-National Aerospace Laboratories (CSIR-NAL), Bangalore, India as Scientist, since May 2008. Earlier, between March 2007-May 2008, he held the position of Scientist B in SAMEER (Society for Applied Microwave Electronics Engineering and Research), Kolkata, India. His research interests are broadly in the field of Electromagnetics applications and the topics include: frequency selective surfaces (FSS), RAS, Radome, metamaterials, numerical methods in electromagnetics, EM material characterization, microstrip patch antenna, pattern synthesis of antenna array. Particularly, he is working on the design and analysis of FSS structures based on advanced numerical techniques (MM-GSM, FDTD) for aerospace applications for last four years. Dr Shiv is the author/ co-author of 35 technical documents including peer reviewed journal and conference papers.

**Ms Sangeetha B.** obtained her BE (ECE) degree from Visvesvaraya Technological University, Karnataka, India. She is currently a Project Engineer with the Centre for Electromagnetics of CSIR-National Aerospace Laboratories (CSIR-NAL), Bangalore, India, where she works in the areas of FSS, metamaterials, and microstrip antennas.

**Ms. Divya K. M.** received her B. Tech. degree in Electronics and Communication Engineering from Calicut University, Kerala in 2010 and completed her M. Tech. degree in Microwave and Radar Electronics from Cochin University Science and Technology (CUSAT), Kerala in 2013. Currently she is associated with the Centre for Electromagnetics, CSIR- NAL as project scientist. Her research interest include the topics; computational electromagnetics, FSS, and metamaterials.