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EM Analysis of Metamaterial Based Radar Absorbing Structure (RAS) for Millimeter Wave Applications

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Abstract: The EM performance analysis of a multilayered metamaterial based radar absorbing structure (RAS) has been presented in this paper based on transmission line transfer matrix (TLTM) method for millimeter wave applications. The proposed metamaterial-RAS consists of cascaded DPS and MNG layers of identical configurations. It exhibits extremely low reflection ($<$ 42 dB) at 95 GHz and absorbs more than 95% power of incident wave over the frequency range of 90.4-100 GHz without metal backing for both TE and TM polarizations. In view of aerospace applications, the reflection, transmission, and absorption characteristics of the proposed metamaterial-RAS are also studied at different incident angles (0°, 30°, and 45°) for both polarizations.

Keywords: Metamaterial, Radar absorbing structure, Metamaterial-RAS, Transmission line transfer matrix method, Millimeter wave.

1 Introduction

The radar absorbing materials (RAM) and structures (RAS) are widely used for various applications such as stealth technology, electromagnetic shielding of high reflection surfaces and metal surfaces. The stealth technique is the most typical application of electromagnetic (EM) wave absorption technology. Using this technique, the aircraft and warships can evade detection by reducing their radar cross-section (RCS). Actually, the stealth phenomenon can be achieved in two ways; one is to optimize the shape of the body so that incident EM wave is scattered to yield minimum reflection, and the other is by the use of EM absorption materials or structures such as RAM and RAS (Vinoy and Jha, 1996). The second method is reported to be a better choice for RCS reduction. The common radar absorbing materials are made up of dielectrics, magnetic layers etc., e.g. Dallenbach, Salisbury screen (Chambers, 1994), and Jaumann surfaces, which are narrowband resonant

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absorbers. However, the analysis of lossy materials with non-unity permeability is difficult to achieve at microwave frequencies.

The radar absorbing structures are also realized by Zhao *et al*. (2009) and Singh *et al*. (2012) based on FSS technology, which provides thin design but shows satisfactory EM performance only at low incidence angle. Recently, metamaterial have many potential applications such as metamaterial based RAM/ RAS (Chen *et al*., 2009; Varadan, 2011), metamaterial-FSS (Narayan *et al.*, 2012), metamaterial invisibility cloak (Choudhury *et al.*, 2013), and wireless power transfer via metamaterial (Stevens, 2013), due to its negative permittivity and permeability characteristics. By tuning electric and magnetic resonances of unit cells, a metamaterial structure can be impedance-matched to free-space to achieve perfect absorption through it.

In view of this, a metmaterial based radar absorber with metal-backed plate was proposed by Zhu *et al.* (2010). Further, single and dual-band metamaterial absorbers were realized by Singh *et al*. (2011) on flexible polyimide substrate with metal-backed plate. However, these absorbers may be disadvantageous for stealth applications. In order to avoid the metal-backing plate in absorbers, multiple split-ring resonator (SRR) bases with resonant-magnetic inclusion were employed by Alici *et al.* (2010). Recently, Lee and Lee (2012) presented a double negative metamaterial absorbers with a periodic array composed of a split-ring resonator (SRR) and two open complementary split-ring resonators (OCSRRs) for microwave applications.

In this paper, a novel metamaterial based RAS is proposed without metallic backing plate for stealth applications in millimeter wave frequency region. The EM analysis has been carried out based on transmission line transfer matrix method. The proposed structure exhibits excellent absorption ($> 95\%$) over the frequency range of 90.4-100 GHz for both TE and TM polarizations without metal backing.

2 Theoretical Considerations

The side view of a six-layered metamaterial based RAS is shown in Figure 1, where the EM wave is first incident on DPS (double positive) layer at angle θ_{inc} and finally transmit through the MNG (mu-negative) layer. According to TLTM method, a multilayered metamaterial structure is represented as multiple sections of transmission line, where each section is described by characteristic impedance and propagation constant, which depends on the incidence angle, frequency, and polarization of the incidence wave. In this method, the reflection coefficient at the surface of each layer is obtained by starting the calculation from the previous layer, using the impedance matching concept. Finally, the reflection and transmission coefficients of the entire structure are determined for different polarizations.

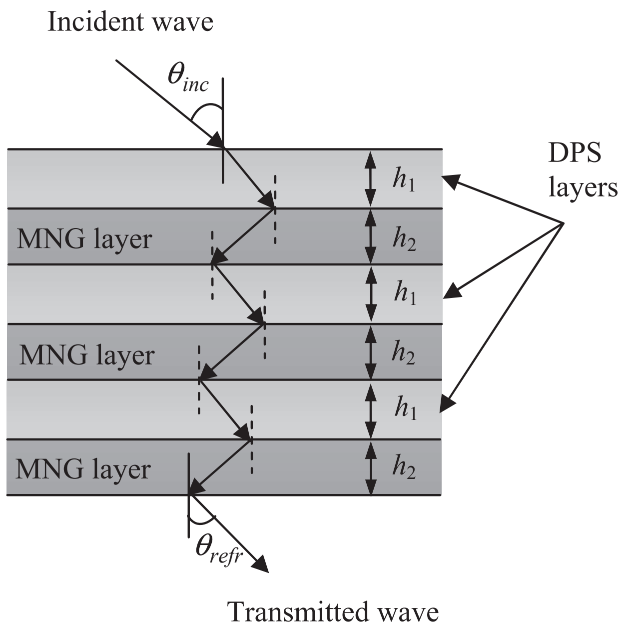

Figure 1: Side view of six-layered metamaterial-RAS

The propagation constant (γ_{lz}) of section l of the transmission line, which is identical for both TE and TM polarizations, is given by Oraizi and Afsahi (2007) as

$$\gamma_{lz} = j\omega\sqrt{\mu_l \varepsilon_l}\cos\theta_l \tag{1}$$

where, μ_l and ε_l are the permeability and the permittivity of the l^{th} layer, respectively. ω represents the angualar frequency. θ_l is the angle of incidence at the l^{th} layer.

The angle of incidence at each layer can be computed by using the Snell's law for l^{th} and $(l+1)^{th}$ layers as

$$\gamma_l \sin\theta_l = \gamma_{(l+1)} \sin\theta_{(l+1)} \tag{2}$$

The intrinsic impedance of the l^{th} layer is obtained by

$$\eta_l = \sqrt{\frac{\mu_l}{\varepsilon_l}} \tag{3}$$

The transfer matrix of a multilayered structure can be expressed as

$$[T]_{(l+1)l} = [L]_{(l+1)}\,[I]_{(l+1)l}\,,\ \ l = 0,\,1,\,\ldots.\,(N-1) \tag{4}$$

where N represents the number of layers. The wave amplitude matrix $[L]_{(l+1)}$ and discontinuity transfer matrix $[I]_{(l+1)l}$ can be determined using the expressions given in Oraizi and Afsahi (2007).

The transmission coefficient (t) and reflection coefficients (r) of the whole structure can be expressed by

$$\begin{bmatrix} t \\ 0 \end{bmatrix} = [T]_{(N+1)0} \begin{bmatrix} 1 \\ r \end{bmatrix} \tag{5}$$

where

$$[T]_{(N+1)0} = [T]_{(N+1)N}\,[T]_{N(N-1)} \cdots\cdots [T]_{(l+1)l} \cdots\cdot [T]_{10} \tag{6}$$

Solving the above equation, we get

$$r \ = \ -\frac{T_{21}}{T_{22}} \tag{7}$$

$$t \ = \ T_{11} \ + \ r\,T_{12} \tag{8}$$

Finally, the power reflection R, and the power transmission T, of the proposed metamaterial-RAS can be computed by

$$R = rr^{*} \tag{9}$$

$$T = tt^{*} \tag{10}$$

The proposed metamaterial-RAS consists of three alternate layers of DPS-MNG sequence, where DPS layer is a lossy dielectric material having dispersion relation according to equation (11)

$$\varepsilon_c = \varepsilon^{'}\left[1 - j\left(\tan\delta + \frac{\sigma}{\omega\varepsilon^{'}}\right)\right] \tag{11}$$

where $\varepsilon^{'}$ is the real part of complex permittivity. σ and $\tan\delta$ are the conductivity and loss tangent of the dielectric material. While the MNG layer consists of *circular split ring resonators* (CSRRs) and its complex effective permeability is determined by Lorentz and Resonance model given in Pendry *et al.* (1999)

$$\mu_{eff} = 1 - \frac{\left(f_{mp}^{2} - f_{m0}^{2}\right)}{f^{2} - f_{m0} - j\Gamma_{m} f} \tag{12}$$

where f_{mo} and f_{mp} are the magnetic resonant frequency and magnetic plasma frequency of the SRR, respectively. Γ_m represents the magnetic damping factor, which is expressed in terms of periodicity p, of the SRR, and the radius of the ring a, as

$$\Gamma_m = \frac{2pR}{a\mu_0} \tag{13}$$

The resonance of the structure depends on the resonance of the SRRs and its resonance frequency is given by

$$\omega_{m0} = c\sqrt{\frac{3p}{\pi \ln\left(\frac{2w}{d}\right) a^3}} \tag{14}$$

where w is the width of the rings and d is the spacing between the rings. c represents the speed of light. The magnetic plasma frequency of the SRR is given as

$$\omega_{mp} = \frac{\omega_{m0}}{\sqrt{1-F}} \tag{15}$$

where $F = \pi\left(a/p\right)^2$ is the fractional volume occupied by the unit cell.

3 EM Design Aspects of Six-layer Metamaterial RAS

In the present work, a six-layered metamaterial-RAS structure is considered (Fig. 2), which consists of cascaded DPS and MNG layers of identical configurations. The MNG layer is composed of circular split ring resonator with ε_r = 1.15 (foam). The schematic of unit cell of circular SRR is shown in Figure 3, where p represents periodicity, a represents the radius of inner ring, d represents the separation between the rings, and w denotes the width of each ring. The optimized design parameters of the circular SRR is given in Table 1. The complex effective permeability of the circular SRR is computed using equation (12). The frequency response of effective permeability of CSRR is shown in Figure 4. It is observed that the proposed SRR resonates at 120 GHz and beyond it exhibits negative permeability. The magnetic resonant frequency and magnetic plasma frequency of the circular split ring resonator is computed by using the relation (14) and (15), respectively.

Here, the circular split ring resonator is designed for the magnetic resonant frequency f_{0m} = 120 GHz, magnetic plasma frequency f_{mp} = 148.8 GHz, and magnetic damping factor Γ_m = 0.357 GHz. For each DPS layer, the relative permittivity, conductivity, and dielectric loss tangent are considered to be 3.5, 1 mho, and 0.06, respectively. The thickness of the metamaterial layers is optimized to be 0.5 mm for each MNG layer and 1.69 mm for each DPS layer.

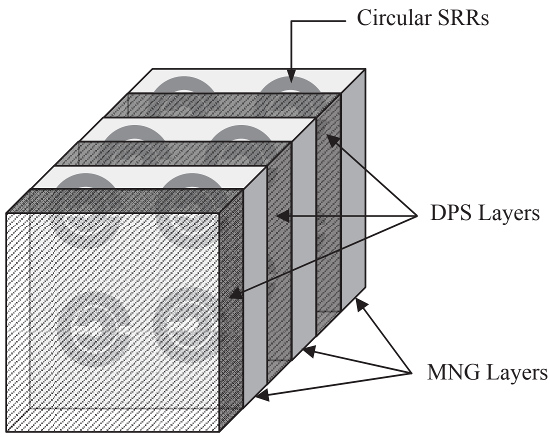

Figure 2: Schematic of Six-layer metamaterial RAS structures

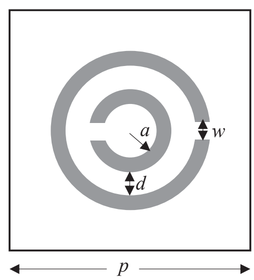

Figure 3: Schematic of unit cell of circular SRR

Table 1: Designed parameters of unit cell of circular SRR

Sl. No.	Design Parameters	Dimension (mm)
1.	Periodicity	0.8
2.	Separation between the rings	0.00024397
3.	Inner ring radius	0.26702
4.	Width of the ring	0.07

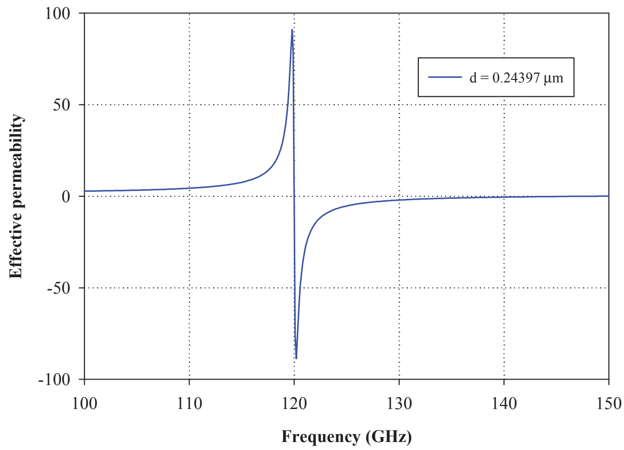

Figure 4: Effective permeability of designed SRR unit cell for the proposed metamaterial-RAS

4 EM Performance Analysis

In the present work, the EM performance of metamaterial based RAS has been investigated for both TE and TM polarization using the TLTM method. The reflection characteristics of proposed metamaterial-RAS are investigated at normal as well higher incidence angle (30° and 45°) for both TE and TM polarizations as shown in Figures 5 and 6.

It is observed that the proposed MTM-RAS exhibits very low reflection (< 42 dB) at 95 GHz for both polarizations at normal incidence. Further, the absorption characteristics are studied at different incident angles (0°, 30°, and 45°) for TE and TM polarizations (Figures 7 and 8). It is observed that the metamaterial based RAS absorbs more than 98% power of incidence wave at 95 GHz for both polarizations. Moreover, it absorbs more than 95% power of incidence wave over the frequency range of 90.4-100 GHz for TE and TM polarizations at incident angles 0°, 30°, and 45°.

The transmission characteristics of proposed structure are also studied at different incident angles (0°, 30°, and 45°) for TE and TM polarizations as shown in Figures 9 and 10. It is observed that the transmission through the MTM-RAS is extremely low (< 18 dB) over the frequency of interest. It is to be noted that these excellent characteristics of metamaterial-RAS are obtained without using metal-backing plate, which enables proposed metamaterial-RAS for stealth applications.

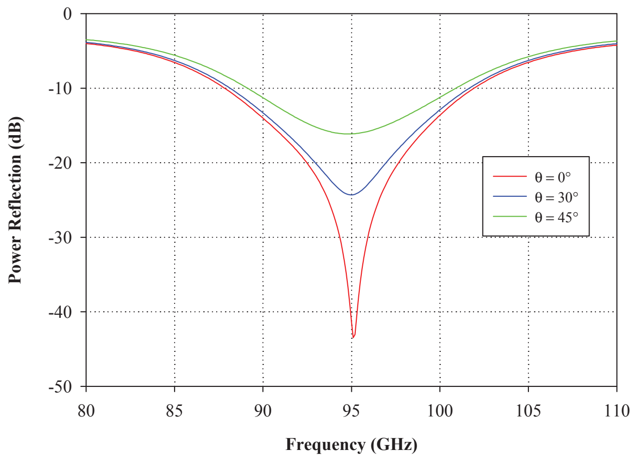

Figure 5: Power reflection characteristics of metamaterial-RAS for TE polarization at different incident angles

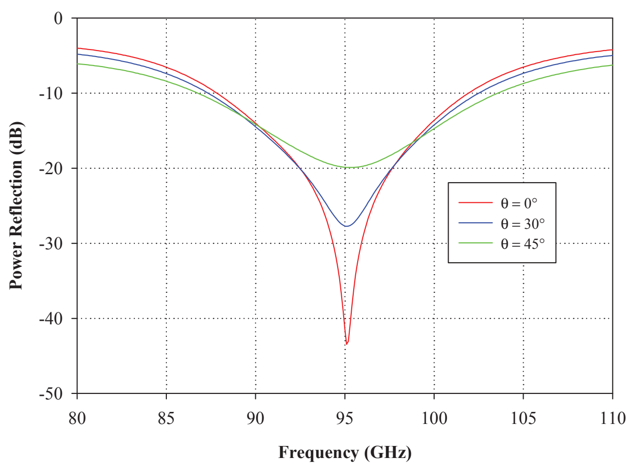

Figure 6: Power reflection characteristics of metamaterial-RAS for TM polarization at different incident angles

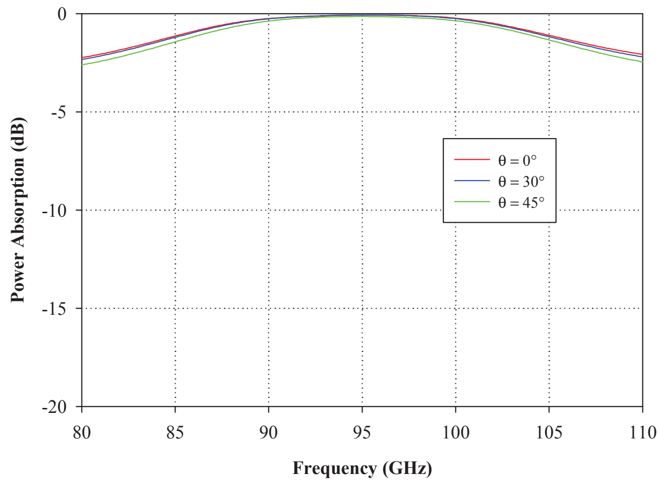

Figure 7: Power absorption characteristics of metamaterial-RAS for TE polarization at different incident angles

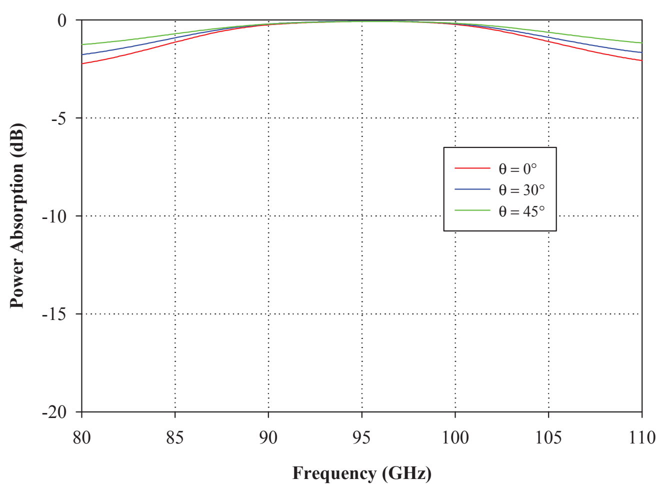

Figure 8: Power absorption characteristics of metamaterial-RAS for TM polarization at different incident angles

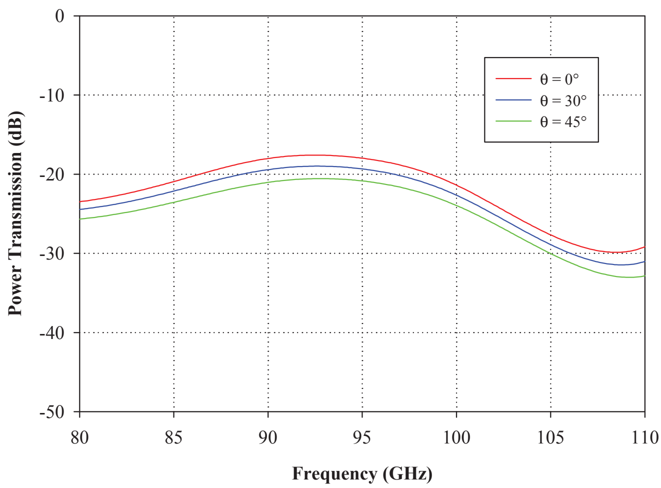

Figure 9: Power transmission characteristics of metamaterial-RAS for TE polarization at different incident angles

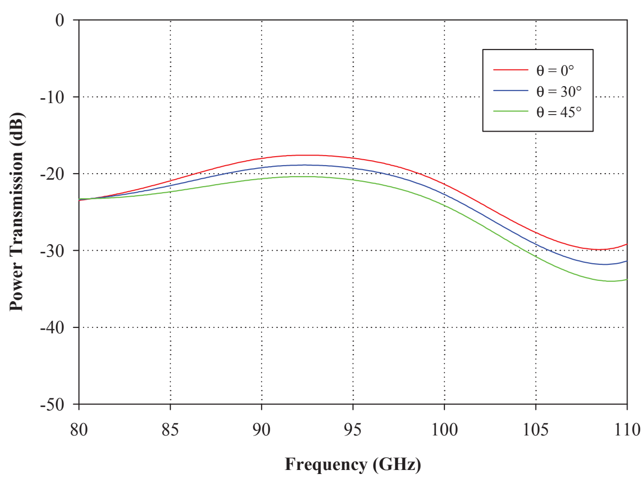

Figure 10: Power transmission characteristics of metamaterial-RAS for TM polarization at different incident angles

5 Conclusions

The EM analysis of six-layered metamaterial based radar absorbing structure (RAS) has been carried out in this work using TLTM method for TE and TM polarizations. The proposed metamaterial based RAS showed extremely low reflection ($<$ 42 dB) at 95 GHz and excellent absorption ($>$ 95%) over the frequency range of 90.4-100 GHz without metal backing, which is a desirable frequency range for defense applications. It also showed very low ($<$ 18 dB) transmission over the frequency of interest for both TE and TM polarizations. The proposed metamaterial-RAS can be used in millimeter wave frequency regime for stealth applications in strategic area.

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