Comparison of Scattering from Electrically Large PEC and PMC Targets Coated with Uniaxial Dielectric Medium based on Asymptotic Solution in Spectral Domain

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ABSTRACT:
In this paper, electromagnetic (EM) scatterings from electrically large Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) targets coated with Uniaxial Electric Anisotropic Medium (UEAM) layer are evaluated and compared. The effect of the coating layer's parameters including ε_u, ε_v and the thickness (d) are studied. It is shown that radar cross section (RCS) of a PMC with UEAM coating is less than that of PEC with the same coating. In some cases, about 20 dB reduction in RCS has been obtained for UEAM coated PMC plate.

1. INTRODUCTION

Scattering from various electrically large targets have been attracted much attention, specially, large PEC targets coated with dielectric layer are investigated to reduce or modify their RCS. There are several methods to reduce the RCS such as lossy resistive coating [1], utilizing chemical absorbing materials [2], creating discrepancies on the geometrical shape of the structure [3], and coating the target by anisotropic dielectric layer [4-7]. Among the above mentioned methods, anisotropic coating is applicable for both RCS reduction and RCS modification, without any additional lossy material or shape modification [8].

As it is well known, PEC and PMC structures reflect the whole incident EM wave, which this reflection results in larger RCS than other structures. In [9], it has been shown that while the Salisbury absorber which if it is designed on PEC surfaces has thickness of $\lambda/4$, it will be thin when PEC is replaced by PMC.

Since Sievenpiper introduced the first High Impedance Surface (HIS) as Artificial Magnetic Conductor (AMC) [10], AMCs have attracted the interests of researchers [11-13]. Therefore, applications of PMC which seemed to be unpractical for decades, attract interests of researchers again [14]-[16]. One of the most important applications of HIS-based AMC structures is RCS reduction in checkerboard configuration [17]. However, to the best of the authors' knowledge, RCS reduction of PMC plates using UEAM coating method is not studied in the literature. In this study, the challenge is that *"what is the effect of UEAM coating on RCS of PEC and PMC surfaces? Could it be said that for RCS reduction with thin UEAM coating, PMC is more successful than PEC?"*

It has been shown in the literature that UEAM coating can modify the RCS of a PEC target [8]. In this paper, both PEC and PMC targets coated with UEAM layer are studied and compared. Since most of commercial Electromagnetic softwares are not suitable for evaluation of scattering from electrically large PEC and PMC targets coated with UEAM layer, a numerical solution must be developed. In order to have fare comparison between RCS of UEAM coated PEC and PMC plates, the method introduced in [8] is developed for PMC in this paper. Also, acceptable accuracy besides less calculation time are two important factors in selecting the solution method.

The paper is organized as follows. In section 2, scattering from PMC coated with UEAM layer based on asymptotic solution in spectral domain is evaluated for the first time. The effects of UEAM coating parameters including ε_u, ε_v and the thickness on RCS of PEC and

PMC targets are studied and compared in section 3. It is shown that UEAM coating on PMC results in more RCS reduction than PEC. In some cases, about 20 dB reduction in RCS is obtained. The paper is closed with conclusions in section 4.
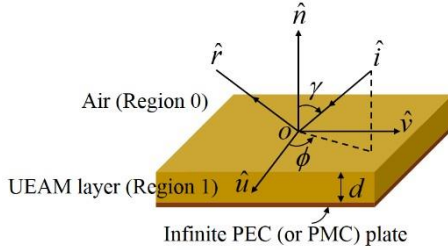

Fig. 1. Planarly stratified model of coated PEC (or PMC) plate.

2. REFLECTION FROM INFINITE COATED PMC PLATE

Fig. 1 shows the planarly stratified model of a coated PEC or PMC plate. Here, $\hat{i}$ and $\hat{r}$ specify the unit incident and reflection vectors, while γ and ϕ are the elevation and azimuth angles of incidence, respectively. The top surface of the coating is supposed to place at $n = 0$. In this study, the optic axis of the UEAM is $\hat{u}$ according to Fig. 1. Hence, the relative permittivity and permeability tensors of the UEAM are

$$\bar{\bar{\varepsilon}}_r = \begin{bmatrix} \varepsilon_u & 0 & 0 \\ 0 & \varepsilon_v & 0 \\ 0 & 0 & \varepsilon_v \end{bmatrix}, \bar{\bar{\mu}}_r = \bar{\bar{I}}. \tag{1}$$

As reported in the literature [17], there are two types of waves in anisotropic medias, type I and type II. In UEAM, both of them satisfy Maxwell's equations. General form of the EM fields in the UEAM layer (region 1), $\vec{E}_1(\vec{r})$ and $\eta_0 \vec{H}_1(\vec{r})$, are derived in [8] and are repeated here for the sake of completeness, as follows

$$\tilde{\vec{E}}_1(k_u,k_v,n) = (k_{nI}k_0\hat{v} - k_v k_0\hat{n})A_I^+ e^{jk_{nI}n}$$
$$+((k_u^2 - \varepsilon_v k_0^2)\hat{u} + k_u k_v \hat{v} + k_u k_{nII}\hat{n})A_{II}^+ e^{jk_{nII}n}$$
$$+(-k_{nI}k_0\hat{v} - k_v k_0\hat{n})A_I^- e^{-jk_{nI}n} \tag{2}$$
$$+((k_u^2 - \varepsilon_v k_0^2)\hat{u} + k_u k_v \hat{v} - k_u k_{nII}\hat{n})A_{II}^- e^{-jk_{nII}n}.$$

$$\eta_0\tilde{\vec{H}}_1(k_u,k_v,n) = (\varepsilon_v k_0 k_{nII}\hat{v} - \varepsilon_v k_0 k_v \hat{n})A_{II}^+ e^{jk_{nII}n}$$
$$+((\varepsilon_v k_0^2 - k_u^2)\hat{u} - k_u k_v \hat{v} - k_u k_{nI}\hat{n})A_I^+ e^{jk_{nI}n}$$
$$+(-\varepsilon_v k_0 k_{nII}\hat{v} - \varepsilon_v k_0 k_v \hat{n})A_{II}^- e^{-jk_{nII}n} \tag{3}$$
$$+((\varepsilon_v k_0^2 - k_u^2)\hat{u} - k_u k_v \hat{v} + k_u k_{nI}\hat{n})A_I^- e^{-jk_{nI}n}.$$

Where, the superscripts $+$, $-$ indicate the partial EM waves propagating in $-\hat{n}$ and $+\hat{n}$ directions, respectively. The amplitude of waves are denoted by A_i, $i = I, II$ to determine the type of waves. Furthermore, $\vec{k} = -k_u\hat{u} - k_v\hat{v} - k_n\hat{n}$ in which $k_{nI} = \sqrt{k_0^2\varepsilon_v - k_u^2 - k_v^2}$, $k_{nII} = \sqrt{k_0^2\varepsilon_u - (\varepsilon_u/\varepsilon_v)k_u^2 - k_v^2}$.

In Eqs. (2)-(3), by substituting the ε_u and ε_v by 1, and k_{nI} and k_{nII} by $k_{n0} = \sqrt{k_0^2 - k_u^2 - k_v^2}$, EM fields in the air (region 0) can be obtained. The result is reported in [8] and again it is represented here for the sake of completeness.

$$\tilde{\vec{E}}_0(k_u,k_v,n) = (k_{n0}k_0\hat{v} - k_v k_0\hat{n})A_{I0}^+ e^{jk_{n0}n}$$
$$+((k_u^2 - k_0^2)\hat{u} + k_u k_v \hat{v} + k_u k_{n0}\hat{n})A_{II0}^+ e^{jk_{n0}n}$$
$$+(-k_{n0}k_0\hat{v} - k_v k_0\hat{n})A_{I0}^- e^{-jk_{n0}n} \tag{4}$$
$$+((k_u^2 - k_0^2)\hat{u} + k_u k_v \hat{v} - k_u k_{n0}\hat{n})A_{II0}^- e^{-jk_{n0}n}.$$

$$\eta_0\tilde{\vec{H}}_0(k_u,k_v,n) = (k_0 k_{n0}\hat{v} - k_0 k_v \hat{n})A_{II0}^+ e^{jk_{n0}n}$$
$$+((k_0^2 - k_u^2)\hat{u} - k_u k_v \hat{v} - k_u k_{n0}\hat{n})A_{I0}^+ e^{jk_{n0}n}$$
$$+(-k_0 k_{n0}\hat{v} - k_0 k_v \hat{n})A_{II0}^- e^{-jk_{n0}n} \tag{5}$$
$$+((k_0^2 - k_u^2)\hat{u} - k_u k_v \hat{v} + k_u k_{n0}\hat{n})A_{I0}^- e^{-jk_{n0}n}.$$

It is obvious that A_{I0}^+ and A_{II0}^+ describe the incident wave, while A_{I0}^-, A_{II0}^- determine the complex amplitudes of scattered waves from the whole structure into the air. By applying the boundary conditions at both sides of the coating, the amplitude of scattered fields (A_{I0}^-, A_{II0}^-) can be deduced.

The scattered waves from the PEC coated with UEAM are obtained in [8]. To find the scattered waves from the PMC coated with UEAM, the boundary conditions are as follows

$$\hat{n} \times \left(\tilde{\vec{E}}_0(k_u,k_v,0) - \tilde{\vec{E}}_1(k_u,k_v,0)\right) = 0$$
$$\hat{n} \times \left(\eta_0\tilde{\vec{H}}_0(k_u,k_v,0) - \eta_0\tilde{\vec{H}}_1(k_u,k_v,0)\right) = 0 \tag{6}$$
$$\hat{n} \times \eta_0\tilde{\vec{H}}_1(k_u,k_v,-d) = 0.$$

After some calculations, the scattered wave amplitudes in terms of the incident wave amplitudes are obtained as follows

$$\begin{bmatrix} A_{II0}^- \\ A_{I0}^- \end{bmatrix} = \bar{\bar{M}} \cdot \begin{bmatrix} A_{II0}^+ \\ A_{I0}^+ \end{bmatrix} \tag{7}$$

Where

$$\bar{\bar{M}} = \begin{bmatrix} \dfrac{-\alpha^2 + (\beta+\chi)(\beta-\delta)}{\alpha^2+(\beta+\chi)(\beta+\delta)} & \dfrac{-2\alpha\beta}{\alpha^2+(\beta+\chi)(\beta+\delta)} \\[2mm] \dfrac{2\alpha\beta}{\alpha^2+(\beta+\chi)(\beta+\delta)} & \dfrac{-\alpha^2+(\beta-\chi)(\beta+\delta)}{\alpha^2+(\beta+\chi)(\beta+\delta)} \end{bmatrix}$$

$$\alpha = -k_u k_v k_0^2 (\varepsilon_v - 1) \quad , \quad \beta = k_{n0} k_0 (k_u^2 - \varepsilon_v k_0^2)$$

$$\chi = k_0 k_{nI} (k_u^2 - k_0^2) \frac{(1+e^{-j2k_{nI}d})}{(1-e^{-j2k_{nI}d})}$$

$$\delta = \varepsilon_v k_0 k_{nII} (k_u^2 - k_0^2) \frac{(1-e^{-j2k_{nII}d})}{(1+e^{-j2k_{nII}d})}.$$

According to [8], the reflection matrix ($\bar{\bar{R}}$) of the structure can be obtained and by determining $\bar{\bar{R}}$, the scattered fields can be calculated. For the sake of brevity, the details are avoided to be represented here. Considering that

$$\begin{bmatrix} E_u^r(\vec{r}_c) \\ E_v^r(\vec{r}_c) \\ E_n^r(\vec{r}_c) \end{bmatrix} = \bar{\bar{R}} \cdot \begin{bmatrix} E_u^i(\vec{r}_c) \\ E_v^i(\vec{r}_c) \end{bmatrix}, \qquad \bar{\bar{R}} = \begin{bmatrix} R_{uu} & R_{uv} \\ R_{vu} & R_{vv} \\ R_{nu} & R_{nv} \end{bmatrix}. \tag{8}$$

In which, $\vec{r}_c$ is the origin of discretized facet on the surface,

$$\bar{\bar{R}} = \bar{\bar{P}} \cdot \bar{\bar{M}} \cdot \bar{\bar{Q}}^{-1}. \tag{9}$$

Where

$$\bar{\bar{P}} = \begin{bmatrix} k_u^2 - k_0^2 & 0 \\ k_u k_v & -k_0 k_{n0} \\ -k_u k_{n0} & -k_0 k_v \end{bmatrix}, \bar{\bar{Q}} = \begin{bmatrix} k_u^2 - k_0^2 & 0 \\ k_u k_v & k_0 k_{n0} \end{bmatrix}. \tag{10}$$

That $k_u = k_0 \sin\gamma \cos\phi$ and $k_v = k_0 \sin\gamma \sin\phi$.

## 3. STUDY OF UEAM COATING PARAMETERS ON RCS OF PEC AND PMC PLAES

The monostatic RCS of a $10\lambda_0 \times 5\lambda_0$ PEC plate coated with UEAM layer is compared with that of the PMC plate with the same coating. In the whole paper, from here onwards, it is assumed that the incident wave is ϕ polarized and $\phi = 0$. The other incident angle (γ) is in the range ($0, 90°$).

Fig. 2 (a) shows the RCS of the PEC plate coated with $0.1\lambda_0$ thick UEAM layer, with $\varepsilon_v = 1$ for several values of ε_u. It can be seen that by increasing the value of ε_u, RCS is increased, too. The differences between RCSs are seen mostly for γ in ($40°, 60°$).

RCS of the PEC plate coated with $0.25\lambda_0$ thick

UEAM layer, with $\varepsilon_v = 1$ for several values of ε_u is shown in Fig. 2 (b). Although RCS variation is somehow irregular due to the large thickness of the coating, RCS is decreased by increasing ε_u. The RCS of the structure with $\varepsilon_u = 10$ is about 15 dB less than that of $\varepsilon_u = 2$ for γ in ($50°, 60°$).

Fig. 2 (c) and (d) indicate the RCSs of PMC plates coated with UEAM layer, with $\varepsilon_v = 1$ for several values of ε_u with $0.1\lambda_0$ and $0.25\lambda_0$ thick coating layers, respectively. For $d = 0.1\lambda_0$, increase in ε_u results in decrease in RCS. The difference of RCSs for $\varepsilon_u = 10$ and $\varepsilon_u = 2$ is more than 8 dB for γ in $(46°, 61°)$. For $d = 0.25\lambda_0$, variation is not regular, again, due to the thicker coating. However, by increasing ε_u, decrease in RCS is seen in general. The comparison results of the above discussions are summarized in Table 1.
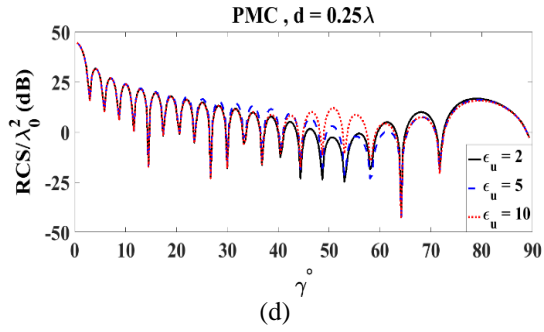

(a)

(b)

(c)

(d)
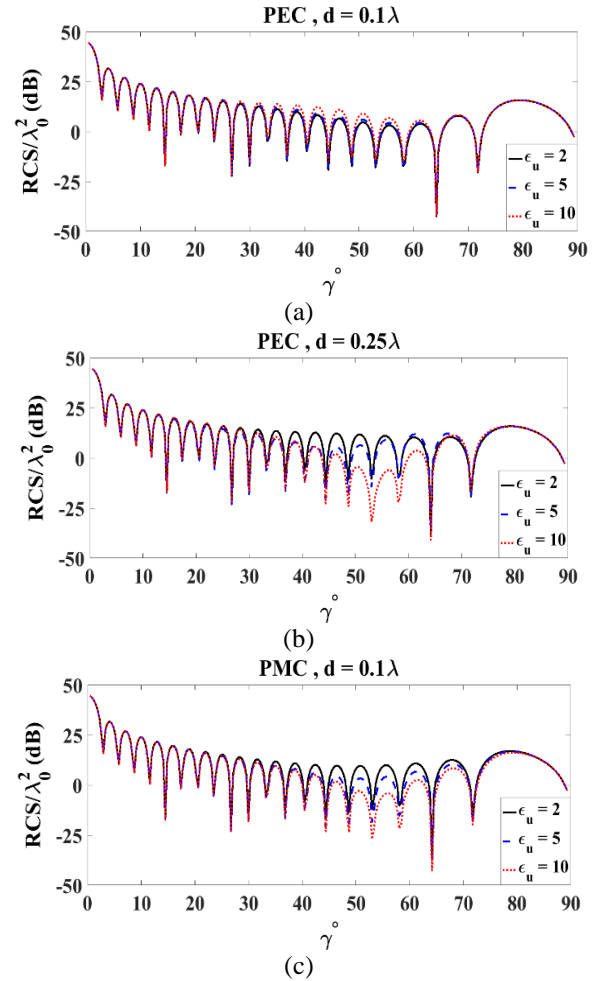
Fig. 2. RCS of a $5\lambda_0 \times 10\lambda_0$, ($\varepsilon_u = \{2,5,10\}$, $\varepsilon_v = 1$),(a) PEC plate, $d = 0.1\lambda_0$, (b) PEC plate, $d = 0.25\lambda_0$, (c) PMC plate, $d = 0.1\lambda_0$, (d) PMC plate, $d = 0.25\lambda_0$.
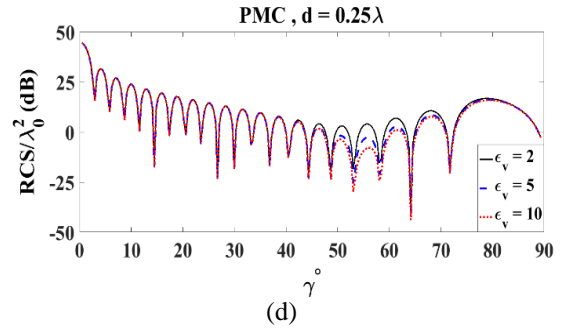
Fig. 3 (a)-(d) illustrate the RCSs of PEC and PMC Plates coated with $\varepsilon_u = 1$ for several values of ε_v, with $0.1\lambda_0$ and $0.25\lambda_0$ coating thicknesses, respectively. The results show that except for the case of PMC with 0.25λ coating thickness, RCS of PEC and PMC plates do not change when ε_v varies. At this case, RCS is reduced more than 5 dB for γ in $(50°, 62°)$ by increase in ε_v.

(a)

(b)

(c)

(d)

Fig. 3. RCS of a $5\lambda_0 \times 10\lambda_0$, ($\varepsilon_u = 1$, $\varepsilon_v = \{2,5,10\}$), (a) PEC plate, $d = 0.1\lambda_0$, (b) PEC plate, $d = 0.25\lambda_0$, (c) PMC plate, $d = 0.1\lambda_0$, (d) PMC plate, $d = 0.25\lambda_0$.
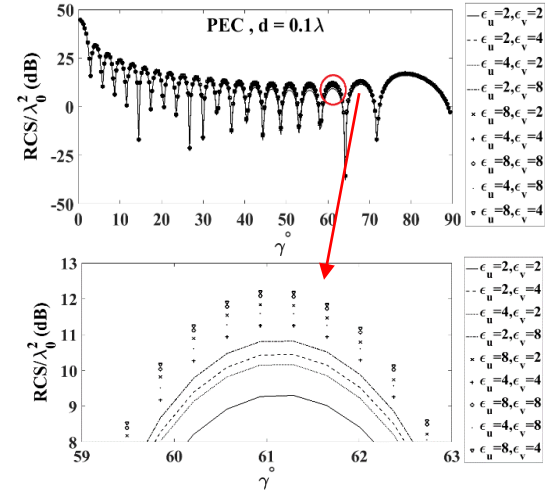

Fig. 4. RCS of a $5\lambda_0 \times 10\lambda_0$ PEC plate ($d = 0.1\lambda_0$, $\varepsilon_u = \{2,4,8\}$, $\varepsilon_v = \{2,4,8\}$).
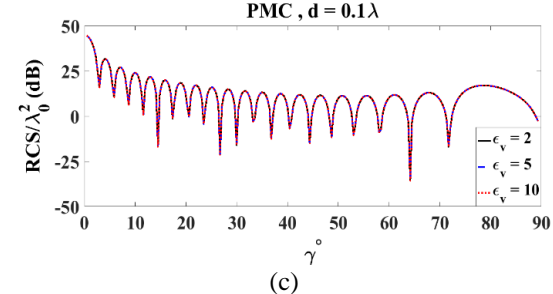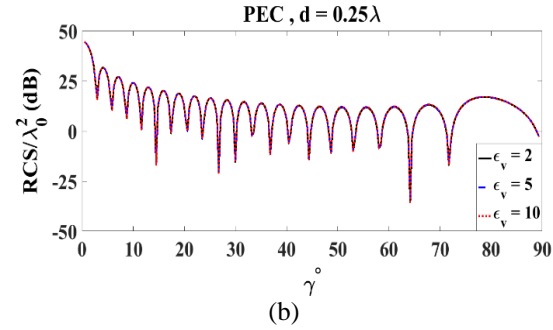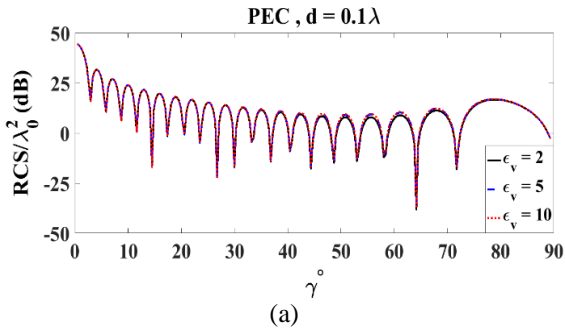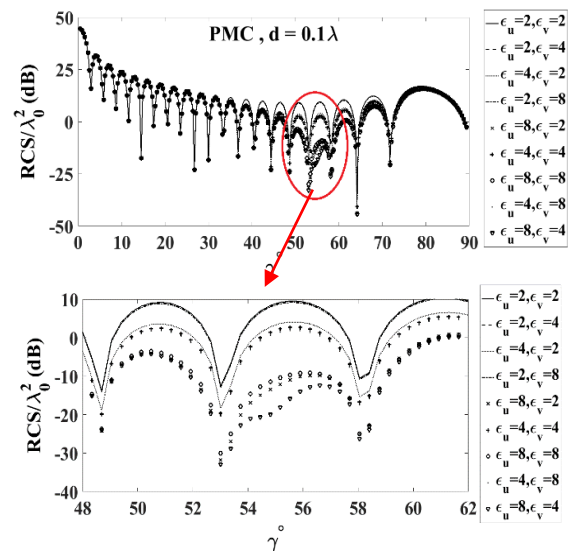

Fig. 5. RCS of a $5\lambda_0 \times 10\lambda_0$ PMC plate ($d = 0.1\lambda_0$, $\varepsilon_u = \{2,4,8\}$, $\varepsilon_v = \{2,4,8\}$).
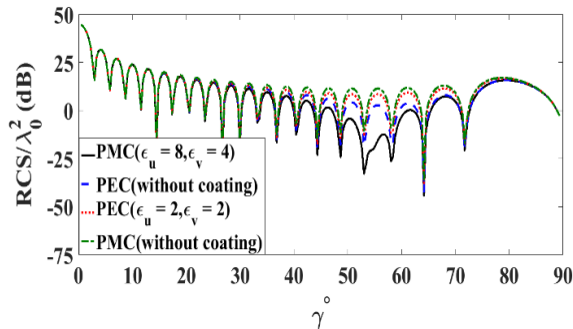
Fig. 6. Comparison of minimum RCS of $5\lambda_0 \times 10\lambda_0$ PEC and PMC plates.

Table 2 summarizes the comparison results of Figs. 3 (a)-(d).

The variations of RCS of the coated PEC and PMC plates with $d = 0.1\lambda_0$ while none of ε_u and ε_v are 1, are shown in Fig. 4 and Fig. 5, respectively. It is observed that while any increase in each of UEAM parameters results in increase of the PEC plate RCS, the RCS of PMC plate reduces. Furthermore, the RCS variation for PEC are almost negligible, while for PMC, RCS reduction is considerable, especially for γ in the range $(40^\circ, 70^\circ)$. The details of RCS variations with respect to each parameter are represented in Table 3.

In order to clarify the differences of RCS for PEC and PMC cases, the minimum RCSs of each case at this study are plotted together in Fig. 6 and are compared with RCS of PEC and PMC plates without coating. More than 5 dB reduction in RCS is obtained for γ in $(43^\circ, 64^\circ)$ and 23 dB reduction at $\gamma = 55^\circ$ as the smallest RCSs of coated PEC and PMC plates (in this study) are compared.

Table 1. Effect of $d = 0.1\lambda_0$ thick UEAM coating parameters on RCS of PEC and PMC plates.

$d = 0.1\lambda_0$	RCS (PEC)	RCS (PMC)
$\varepsilon_u \uparrow$, $\varepsilon_v = 1$	$\uparrow$	$\downarrow$
$\varepsilon_u = 1$, $\varepsilon_v \uparrow$	$\uparrow$ (with small variations)	$\downarrow$ (almost no variation)

Table 2. Effect of $d = 0.25\lambda_0$ thick UEAM coating parameters on RCS of PEC and PMC plates.

$d = 0.25\lambda_0$	RCS (PEC)	RCS (PMC)
$\varepsilon_u \uparrow$, $\varepsilon_v = 1$	$\downarrow$ (irregular)	$\uparrow$ (irregular)
$\varepsilon_u = 1$, $\varepsilon_v \uparrow$	$\uparrow$ (almost no variation)	$\downarrow$

Table 3. Effect of $d = 0.1\lambda_0$ thick UEAM coating parameters on RCS of PEC and PMC plates ($\varepsilon_u = \{2,4,8\}$, $\varepsilon_v = \{2,4,8\}$).

$d = 0.1\lambda_0$	RCS (PEC)	RCS (PMC)
$\varepsilon_u = 2$, $\varepsilon_v \uparrow$	$\uparrow$	$\downarrow$
$\varepsilon_u \uparrow$, $\varepsilon_v = 2$	$\uparrow$	$\downarrow$
$(\varepsilon_u = \varepsilon_v) \uparrow$	$\uparrow$	$\downarrow$
$\varepsilon_u = 4$, $\varepsilon_v \uparrow$	$\uparrow$	$\downarrow$
$\varepsilon_u \uparrow$, $\varepsilon_v = 4$	$\uparrow$	$\downarrow$
$\varepsilon_u = 8$, $\varepsilon_v \uparrow$	Irregular	Irregular
$\varepsilon_u \uparrow$, $\varepsilon_v = 8$	$\uparrow$	$\downarrow$

At $\gamma = 55^\circ$, also, the minimum RCS of PMC coated plate is 27 dB less than RCS of the uncoated PMC plate, while the minimum RCS of PEC coated plate is 5.5 dB more than RCS of the uncoated PEC plate. As the results show, UEAM dielectric coating on PEC plate, can modify the RCS, but it does not reduce it, while for PMC, it can reduce the RCS very well.

It should be noted that although the method used in this study has the capability to consider lossy coating layer, too, we have avoided lossy materials as coating. As it is well known, lossy materials can result in RCS reduction of the target by attenuating the scattered EM waves. Hence, in order to see the pure effect of UEAM dielectric coating on PEC and PMC plates, only the lossless values for ε_u and ε_v have been considered.

4. CONCLUSION

In this paper, EM scatterings from electrically large PEC and PMC targets coated with UEAM layer have been evaluated and compared. The effects of the coating layer's parameters including ε_u, ε_v and the thickness (d) have been studied. It is shown that any increase in parameters of thin UEAM coating results in RCS reduction of PMC plates. More than 5 dB reduction in RCS is obtained for γ in $(43^\circ, 64^\circ)$ and 23 dB reduction at $\gamma = 55^\circ$ as the smallest RCSs of coated PEC and PMC plates (in this study) have been compared.

5. ACKNOWLEDGMENT

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