

SCATTERING OF PLANE WAVE BY PEC AND PMC CYLINDER COATED WITH DIFFERENT MATERIALS

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Abstract

Electromagnetic scattering of an incident uniform plane wave from a perfect electric conductor (PEC) and perfect magnetic conductor (PMC) circular cylinder coated with different materials marble, dry soil and wood, is investigated theoretically. It is assumed that both PEC & PMC cylinders and the coating layers are infinite along the cylinder axis. We have studied the effect of the different above mentioned materials. Both parallel and perpendicular polarization cases are considered for the analysis. A comparison between the back scattering cross-section, of the cylinder coated with different materials, is presented. The numerical results are compared with the published literature, and comparison is found to be in good agreement..



INTRODUCTION

Scattering of electromagnetic waves from circular cylinders has been an interesting topic for the researchers [1, 2]. As Perfect electromagnetic conductor (PEMC) material introduced by Lindell [3], has attracted the attention of many researchers [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. Perfect electromagnetic conductor (PEMC) material is generalization of the PEC and PMC materials. The PEMC boundary conditions are

$$\vec{n} \times (\vec{H} + M\vec{E}) = 0 \quad (1)$$

$$\vec{n} \cdot (\vec{D} - M\vec{B}) = 0 \quad (2)$$

where $\vec{D} = \epsilon\vec{E}$ and $\vec{B} = \mu\vec{H}$, ϵ and μ being the permittivity and the permeability of the host medium

and M denotes the admittance of the PEMC boundary. It is obvious that PMC corresponds to $M = 0$, while PEC corresponds to $M = \pm\infty$. The problem of electromagnetic waves scattering from concentrically coated with different materials has been extensively studied [17, 18, 19, 20, 21, 22]. Scattering behavior becomes much more complicated if scattering obstacle is made of layers or sections of several materials. We are going to compare our study with scattering of electromagnetic plane waves by a conducting cylinder coated with different dielectric materials, is investigated and compared with Li and Shen [22].

In this paper, electromagnetic scattering from an infinite PEC and PMC circular cylinder coated with marble, dry soil and wood layer has been studied. It may be noted that for PEMC case, both co-polarized

and cross-polarized components of field are produced [8,14]. To simplify the problem, we have taken an infinite long PEC and PMC circular cylinder covered with a homogeneous layer of different materials of uniform thickness, and electric vector of the incident plane wave is taken parallel as well as perpendicular to the axis of the cylinder. The method of eigenfunction expansion is used in the theoretical study. The problem is formulated assuming fields in two regions, i.e., free space out side and the coating with different

material layer. Appropriate boundary conditions are applied at the two interfaces. The far scattered field patterns are calculated by using the large argument approximation of Hankel function. To verify the correctness of the analytical formulation and the numerical code, the numerical results are compared with the published work for the special cases. In present paper, we have used $e^{-j\omega t}$, time dependence and it is suppressed throughout the analysis.

Materials and methods

The geometry of the scattering problem is shown in Fig1. and Fig2. It contains a PEMC circular cylinder which has been coated by a material having marble, dry soil and wood permittivity and permeability. Through out the discussion, coated material has been termed as marble, dry soil and

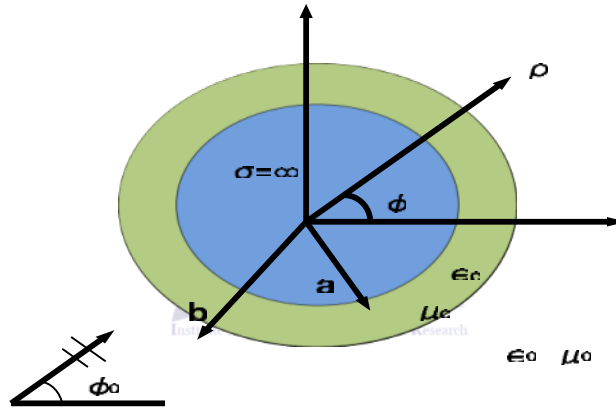


Fig.1. Plane wave scattered by materials coated PEC Cylinder.

wood aterial. Plane wave scattered by PEC Cylinder Coated with Different Materials. Plane wave scattered by PMC Cylinder for the admittance $M = 0$ Coated with Different Materials.

It is assumed that coating on PEC and PMC cylinder is of uniform thickness. The coated cylinder is supposed to be of infinite extent. Radius of the cylinder is a while radius of the cylinder with coating

is b . The external medium $\rho > b$, which is free space (μ_0, ϵ_0) , has been mentioned as region 0 in Fig. 2. The wave number of region 0 is $k_0 = \omega\sqrt{\mu_0\epsilon_0}$. The material region, $a < \rho < b$ and (μ_1, ϵ_1) , is named as region 1, with wave number $k_c = \omega\sqrt{\mu_c\epsilon_c}$. In the following two subsections the parallel and perpendicular polarizations of the incident plane wave, are discussed separately.

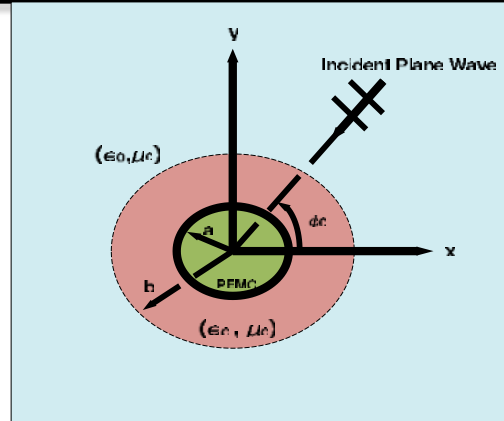


Fig. 2. Plane wave scattered by PMC Cylinder for the admittance $M = 0$ Coated with Different Materials

2.1 Parallel Polarization

When the polarization of the incident electric field is parallel to the axis of the cylinders, the incident electric field in terms of the cylindrical coordinates (ρ, ϕ) , can be expressed as

$$E_{0z}^{inc}(\rho, \phi) = E_0 e^{jk_0 \rho \cos \phi} \quad (3)$$

Using the wave transformation, the incident field may be written in terms of an infinite Fourier-Bessel series as

$$E_{0z}^{inc} = E_0 \sum_{n=-\infty}^{\infty} j^n J_n(k_0 \rho) e^{jn\phi} \quad (4)$$

Using Maxwell equation, the corresponding ϕ component of the magnetic field, is obtained as

$$H_{0\phi}^{inc} = 1 - j\eta_0 k_0 \partial E_{0z}^{inc}(\rho, \phi) / \partial \rho = -E_0 j\eta_0 \sum_{n=-\infty}^{\infty} j^n J_n'(k_0 \rho) e^{jn\phi} \quad (5)$$

where $\eta_0 = \sqrt{\mu_0 / \epsilon_0}$ is the free space impedance, $J_n(\cdot)$ is the Bessel function of first kind and prime denotes the derivative with respect to the whole argument. As the core material is a PEC & PMC cylinder. Hence the scattered fields in *region 0* using Maxwell's equation, can be written as using Maxwell's equation, can be written as

$$E_{0z}^s = E_0 \sum_{n=-\infty}^{\infty} j^n a_n^{TM} H_n^{(2)}(k_0 \rho) e^{jn\phi} \quad (6)$$

$$H_{0\phi}^s = -1j\eta_0 E_0 \sum_{n=-\infty}^{\infty} j^n a_n^{TM} H_n^{(2)'}(k_0 \rho) e^{jn\phi} \quad (7)$$

$$H_{0z}^s = -j\eta_0 E_0 \sum_{n=-\infty}^{\infty} j^n b_n^{TM} H_n^{(2)}(k_0 \rho) e^{jn\phi} \quad (8)$$

$$E_{0\phi}^s = -E_0 \sum_{n=-\infty}^{\infty} j^n b_n^{TM} H_n^{(2)'}(k_0 \rho) e^{jn\phi} \quad (9)$$

And *region 1* is a material coating of uniform thickness and is bounded by two interfaces at $\rho = a$ and $\rho = b$, the fields in this region can be expressed in the form

$$E_{1z} = E_0 \sum_{n=-\infty}^{\infty} j^n [c_n^{TM} J_n(k_c \rho) + d_n^{TM} Y_n(k_c \rho)] e^{jn\phi} \quad (10)$$

$$H_{1\phi} = -1j\eta_c E_0 \sum_{n=-\infty}^{\infty} j^n [c_n^{TM} J_n'(k_c \rho) + d_n^{TM} Y_n'(k_c \rho)] e^{jn\phi} \quad (11)$$

$$H_{1z} = -j\eta_c E_0 \sum_{n=-\infty}^{\infty} j^n [e_n^{TM} J_n(k_c \rho) + f_n^{TM} Y_n(k_c \rho)] e^{jn\phi} \quad (12)$$

$$E_{1\phi} = -E_0 \sum_{n=-\infty}^{\infty} j^n [e_n^{TM} J_n'(k_c \rho) + f_n^{TM} Y_n'(k_c \rho)] e^{jn\phi} \quad (13)$$

where in all the above expressions $J_n(x)$ and $N_n(x)$ are the Bessel functions of first and second kinds, and

$H_n^{(1)}(x) = J_n(x) + iN_n(x)$ and $H_n^{(2)}(x) = J_n(x) - iN_n(x)$. Also in the above expressions $a_n^E, b_n^E, c_n^E, d_n^E, e_n^E$, and f_n^E are the six unknown scattering coefficients in case of the TM incident plane wave which are to be determined. These unknowns can be found by using appropriate boundary conditions at the interfaces $\rho = a$ and $\rho = b$. The boundary conditions at the interface $\rho = a$ are

$$H_{1z} + ME_{1z} = 0, \quad \rho = a, 0 \leq \phi \leq 2\pi \quad (14)$$

$$H_{1\phi} + ME_{1\phi} = 0, \quad \rho = a, 0 \leq \phi \leq 2\pi \quad (15)$$

And the boundary conditions at the interface $\rho = b$, are

$$E_{0z}^{inc} + E_{0z}^s = E_{1z}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (16)$$

$$H_{0\phi}^{inc} + H_{0\phi}^s = H_{1\phi}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (17)$$

$$H_{0z}^s = H_{1z}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (18)$$

$$E_{0\phi}^s = E_{1\phi}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (19)$$

Applying these boundary conditions at $\rho = a$ and $\rho = b$, we obtain a linear matrix equations. Then we find out the unknown scattering coefficients by taking the inverse of the matrix. The solution of this matrix equation yields the values of all the unknowns scattering coefficients of the above equations.

Using the values of a_n^E and b_n^E in equations (6) and (9), we get the scattered fields radiated by the coated PEC and PMC cylinder, respectively. Far-zone scattered fields result when the asymptotic form of Hankel functions is used. As the backscattering cross-section is defined as the ratio of the total power scattered by the scatterer to the incident power per unit area on the scatterer, given as

$$\sigma = 2\pi\rho W^{sca}W^{inc} = 2\pi\rho |E^s|^2 |E^{inc}|^2 \quad (20)$$

where W^{inc} , the incident power density and W^{sca} , is the power density of the far-zone scattered field. By using the large argument approximation of Hankel function, the normalized bistatic echo width in the case of TM plane wave incidence, can be written in the form:

$$\sigma_{co}/\lambda_0 = 2\pi \left| \sum_{n=-\infty}^{\infty} a_n^{TM} e^{jn\phi} \right|^2 \quad (21)$$

$$\sigma_{cross}/\lambda_0 = 2\pi \left| \sum_{n=-\infty}^{\infty} b_n^{TM} e^{jn\phi} \right|^2 \quad (22)$$

where a_n^{TM} and b_n^{TM} , are the scattering coefficients of the co- and cross-polarized field components respectively.

The Comparison between the normalized bistatic echo widths of the different material coated PEMC core that behaves likes PEC core for the admittance $M = \infty$ in both TM and TE polarizations.

Comparison between the normalized bistatic echo widths of the different material coated PEMC core that behaves likes PEC core for the admittance $M = \infty$ in both TM and TE polarizations. In this figure, ($\epsilon_c = 8, \mu_c = 1$) used as coating material with, $f = 1\text{GHz}$, and $\lambda = 0.3$, for PEMC core in the both TM and TE modes

PEC core for TM case has ben shown, the material coated PEMC core behaves here as PEC core for the admittance $M = \infty$ with $f=1\text{GHz}$, $a = 50\text{cm}$, $b = 100\text{cm}$ and $\mu = 1$.

2.2 Perpendicular Polarization

When the incident field is polarized in a direction perpendicular to the axes of the cylinders, then the incident magnetic field can be expressed as

$$H_{0z}^{inc}(\rho, \phi) = H_0 e^{jk_0 \rho \cos \phi} \quad (23)$$

where H_0 , is amplitude of the incident magnetic field. Wave transformation of the incident magnetic field into an infinite Fourier-Bessel series, results in

$$H_{0z}^{inc}(\rho, \phi) = H_0 \sum_{n=-\infty}^{\infty} j^n J_n(k_0 \rho) e^{jn\phi} \quad (24)$$

Using Maxwell equation, the corresponding ϕ component of the magnetic field, is obtained as

$$E_{0\phi}^{inc}(\rho, \phi) = 1jk_0/\eta_0 \partial H_{0z}^{inc}(\rho, \phi) \partial \rho = -j\eta_0 H_0 \sum_{n=-\infty}^{\infty} j^n J_n'(k_0 \rho) e^{jn\phi} \quad (25)$$

In response to this incident magnetic field, the scattered field in region 0, may be expressed as

$$H_{0z}^s = H_0 \sum_{n=-\infty}^{\infty} j^n a_n^{TE} H_n^{(2)}(k_0 \rho) e^{jn\phi} \quad (26)$$

$$E_{0\phi}^s = -j\eta_0 H_0 \sum_{n=-\infty}^{\infty} j^n a_n^{TE} H_n^{(2)'}(k_0 \rho) e^{jn\phi} \quad (27)$$

$$E_{0z}^s = j\eta_0 H_0 \sum_{n=-\infty}^{\infty} j^n b_n^{TE} H_n^{(2)}(k_0 \rho) e^{jn\phi} \quad (28)$$

$$H_{0\phi}^s = -H_0 \sum_{n=-\infty}^{\infty} j^n b_n^{TE} H_n^{(2)'}(k_0 \rho) e^{jn\phi} \quad (29)$$

And the fields in the bounded region 1, can be written in the form

$$H_{1z} = H_0 \sum_{n=-\infty}^{\infty} j^n [c_n^{TE} J_n(k_c \rho) + d_n^{TE} Y_n(k_c \rho)] e^{jn\phi} \quad (30)$$

$$E_{1\phi} = -j\eta_1 H_0 \sum_{n=-\infty}^{\infty} j^n [c_n^{TE} J_n'(k_c \rho) + d_n^{TE} Y_n'(k_c \rho)] e^{jn\phi} \quad (31)$$

where a_n^{TE} , b_n^{TE} , c_n^{TE} , d_n^{TE} , e_n^{TE} , and f_n^{TE} are the six unknown scattering coefficients in case of perpendicularly polarized incident plane wave. These are determined using the boundary conditions at the two interfaces i.e. at $\rho = a$ and at $\rho = b$. The boundary conditions at the interface $\rho = a$ are

$$E_{1z} = j\eta_1 H_0 \sum_{n=-\infty}^{\infty} j^n [e_n^{TE} J_n(k_c \rho) + f_n^{TE} Y_n(k_c \rho)] e^{jn\phi} \quad (32)$$

$$H_{1\phi} = -H_0 \sum_{n=-\infty}^{\infty} j^n [e_n^{TE} J_n'(k_c \rho) + f_n^{TE} Y_n'(k_c \rho)] e^{jn\phi} \quad (33)$$

$$H_{1z} + ME_{1z} = 0, \quad \rho = a, 0 \leq \phi \leq 2\pi \quad (34)$$

$$H_{1\phi} + ME_{1\phi} = 0, \quad \rho = a, 0 \leq \phi \leq 2\pi \quad (35)$$

And the boundary conditions at the interface $\rho = b$, are

$$H_{0z}^{inc} + H_{0z}^s = H_{1z}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (36)$$

$$E_{0\phi}^{inc} + E_{0\phi}^s = E_{1\phi}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (37)$$

And the boundary conditions at the interface $\rho = b$, are

$$H_{0z}^{inc} + H_{0z}^s = H_{1z}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (38)$$

$$E_{0\phi}^{inc} + E_{0\phi}^s = E_{1\phi}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (39)$$

$$E_{0z}^s = E_{1z}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (40)$$

$$H_{0\phi}^s = H_{1\phi}, \quad \rho = b, 0 \leq \phi \leq 2\pi \quad (41)$$

Applying Boundary conditions Using the values of the incident and scattered field components in the above set of boundary conditions, we get a matrix of linear equations.

The solution of the matrix gives the unknown scattering coefficients by taking the inverse.

The normalized bistatic echo width, in the case of TE plane wave incidence, can be written in the form:

$$\sigma_{co}/\lambda_0 = 2\pi \left| \sum_{n=-\infty}^{\infty} a_n^H e^{jn\phi} \right|^2 \quad (42)$$

$$\sigma_{cross}/\lambda_0 = 4\pi \left| \sum_{n=-\infty}^{\infty} b_n^H e^{jn\phi} \right|^2 \quad (43)$$

where a_n^H and b_n^H , are the scattering coefficients of the co- and cross-polarized field components respectively, when a perpendicularly polarized incident field excites the proposed configuration.

3 Numerical results and discussion

In this section we have presented the numerical results, scattering back scattering cross section of a PEC and PMC circular cylinder coated with materials. In order to verify the analytical formulation and the numerical code, the results obtained are compared with the results given in published literature.

Comparison is found to be in excellent agreement. In all plots the radius of the PEC and PMC cylinder and the radius of the coating, are taken as $a = 5\text{cm}$ and $b = 10\text{cm}$, respectively. While the frequency of the incident field is taken as $f = 1\text{GHz}$. Moreover, the PMC and PEC circular cylinder coated with different materials dry soil, marble and wood. In order to verify the analytical formulation and the numerical results obtained are compared with the results given in published literature. Comparison is found to be in excellent agreement. In all plots the radius of the PEMC cylinder and the radius of the various material coated PEMC cylinder taken as $a = 5\text{cm}$ and $b = 10\text{cm}$, respectively. While the frequency of the incident field is taken as $f = 1\text{GHz}$.

In Fig 3, three different coating materials (wood, marble and dry soil with their respective parameters ($\epsilon_c = 2.1, \mu_c = 1$), ($\epsilon_c = 8, \mu_c = 1$), and ($\epsilon_c = 3.4, \mu_c = 1$)), a comparison effect on the PEC core for TM case has been shown, the material coated PEMC core behaves here as PEC core for the admittance $M = \infty$ with $f=1\text{GHz}$, $a = 50\text{cm}$, $b = 100\text{cm}$ and $\mu = 1$

In Fig 4, three different coating materials (wood, marble and dry soil with their respective parameters ($\epsilon_c = 2.1, \mu_c = 1$), ($\epsilon_c = 8, \mu_c = 1$), and ($\epsilon_c = 3.4, \mu_c = 1$)), a comparison effect on the PEC core for TE case has been shown.

In Fig 5, three different coating materials (wood, marble and dry soil with their respective parameters ($\epsilon_c = 2.1, \mu_c = 1$), ($\epsilon_c = 8, \mu_c = 1$), and ($\epsilon_c = 3.4, \mu_c = 1$)), a comparison effect on the PMC core for TM case has been shown.

In Fig 6, three different coating materials (wood, marble and dry soil with their respective parameters ($\epsilon_c = 2.1, \mu_c = 1$), ($\epsilon_c = 8, \mu_c = 1$), and ($\epsilon_c = 3.4, \mu_c = 1$)), a comparison effect on the PMC core for TE case has been shown.

CONCLUSION

This study developed analytical formulations and conducted numerical simulations to analyze electromagnetic wave scattering by a perfect electromagnetic conductor PEC and PMC cylinder coated with materials such as marble, dry soil, and wood. The theoretical framework and formulations presented are applicable to any perfect conductor cylinder, including PEC and PMC. The scattering coefficients were derived in simplified forms. To validate the accuracy of the analytical approach and numerical implementation, the results were compared with previously published works under specific scenarios. The monostatic and bistatic echo widths for the co-polarized and the cross-polarized fields have been computed for various material coated perfect electromagnetic conductor (PEMC) cylinder. Echo widths for the special cases of PEC (perfect electric conductor) ($M\eta_c = \infty$), and PMC (perfect magnetic conductor) ($M\eta_c = 0$) cores have been computed and compared to the PEMC coated cylinder. The coated PEMC has a reduced radar cross-section (RCS) as compared to the similarly coated PEC and PMC cylinders. The comparisons of the computed results of the presented formulations with the published results of some special cases confirm the validity and accuracy of the presented analysis.

CONFLICT OF INTEREST

The authors have no conflict of interest.

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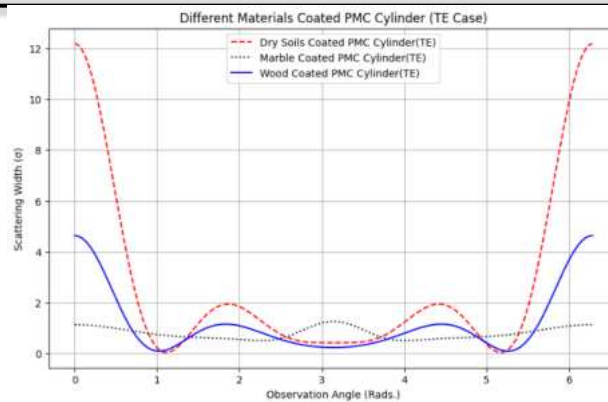


Fig. 6. In this Fig6, three different coating materials (wood, marble and dry soil with their respective parameters ($\epsilon_c = 2.1, \mu_c = 1$), ($\epsilon_c = 8, \mu_c = 1$), and ($\epsilon_c = 3.4, \mu_c = 1$)), a comparison effect on the PMC core for TE case has been shown, the material coated PEMC core behaves here as PMC core for the admittance $M = 0$ with $f=1\text{GHz}$, $a = 50\text{cm}$, $b = 100\text{cm}$ and $\mu = 1$.

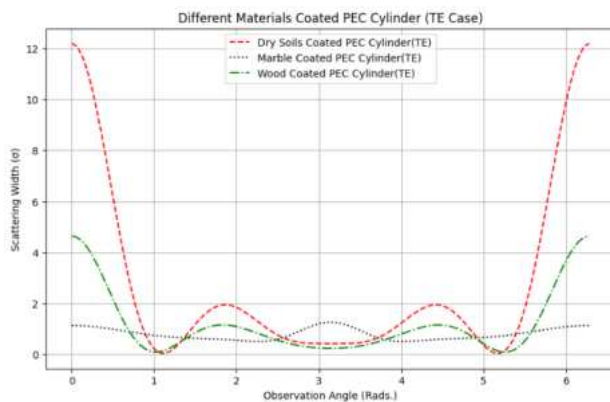


Fig. 4. In this Fig5, three different coating materials (wood, marble and dry soil with their respective parameters ($\epsilon_c = 2.1, \mu_c = 1$), ($\epsilon_c = 8, \mu_c = 1$), and ($\epsilon_c = 3.4, \mu_c = 1$)), a comparison effect on the PEC core for TE case has been shown, the material coated PEMC core behaves here as PEC core for the admittance $M = \infty$ with $f=1\text{GHz}$, $a = 50\text{cm}$, $b = 100\text{cm}$ and $\mu = 1$.

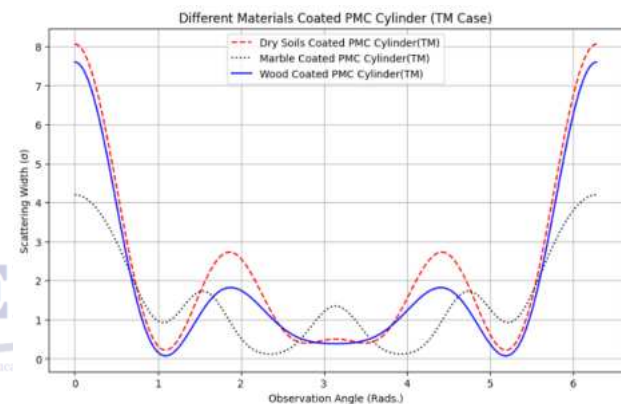


Fig. 5. In this Fig5, three different coating materials (wood, marble and dry soil with their respective parameters ($\epsilon_c = 2.1, \mu_c = 1$), ($\epsilon_c = 8, \mu_c = 1$), and ($\epsilon_c = 3.4, \mu_c = 1$)), a comparison effect on the PMC core for TM case has been shown, the material coated PEMC core behaves here as PMC core for the admittance $M = 0$ with $f=1\text{GHz}$, $a = 50\text{cm}$, $b = 100\text{cm}$ and $\mu = 1$.

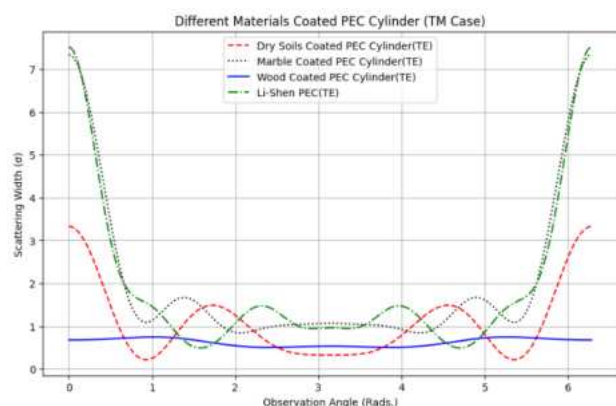


Fig. 3. In this Fig5, three different coating materials (wood, marble and dry soil with their respective parameters $(\epsilon_c = 2.1, \mu_c = 1)$, $(\epsilon_c = 8, \mu_c = 1)$, and $(\epsilon_c = 3.4, \mu_c = 1)$), a comparison effect on the PEC core for TM case has been shown, the material coated PEMC core behaves here as PEC core for the admittance $M = \infty$ with $f=1\text{GHz}$, $a = 50\text{cm}$, $b = 100\text{cm}$ and $\mu = 1$.

