Theoretical Approach of Electromagnetic Shielding of Multilayer Conductive Sheets

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Abstract—This paper evaluates and compares the reflection loss, absorption loss and electromagnetic shielding effectiveness of a diverse range of shield. A design methodology is presented to yield these three quantities and propose a new relation of equivalent impedance for multilayer conductive sheets with considering the equivalence between single and the laminated structure. Analysis is carried out for the study of three shields: i) Polyaniline/polyurethane (PANI/PU), ii) Aluminum-Polyaniline/polyurethane-Aluminum (Al-(PANI/PU)-Al), iii) Nickel-Polyaniline/polyurethane-Aluminum (Ni-(PANI/PU)-Al) in the case of oblique incidence for electrical and magnetic polarization.

1. INTRODUCTION

Electromagnetic interference has become an important problem because the proliferation of commercial, military and scientific electrical devices must be shielded against incoming and potentially disturbing radiation. Electromagnetic shields are designed and developed to minimize the electromagnetic interference and improve compatibility of the circuit [1]. EMI shielding materials have been used to attenuate those unwanted electromagnetic energies, which is an important issue to be considered for both civil and military purposes. Therefore, considerable attention has been devoted to the development of effective EMI shielding technologies and materials [2, 3]. Due to their specific mass, easiness of synthesis, the possibility to modulate easily the electronic properties from insulating to conducting materials through chemical process, low cost and processability, conducting polymers are very promising for applications in electromagnetic interference shielding [4].

These materials are characterized by relatively high conductivities. So, compared to the metals (copper, aluminium, nickel...) or composite polymer (CPs) (Polypyrrole/Graphite oxide (PPy/GO) and Poly(3,4-ethylenedi-oxythiophene)/Graphite oxide (PEDOT/GO) [5]), intrinsically conducting polymers (ICPs), such as polyaniline/polyurethane (PANI/PU), have better properties: high conductivity and permittivity, lighter weight, good environmental stability and ease in synthesis which are considered desirable for shielding applications [6].

Several analytical and numerical models have been proposed and applied to estimate shielding effectiveness of plate shield and the effective EM properties of heterogeneous materials [7–10]. As for analytical method, there are mainly three kinds of methods to calculate plate shielding effectiveness. They are field distribution method, wave propagation and reflection method together with equivalent transmission line method [11–14].

As for the planar shielding case, there are a few publications [13, 15] which address the validity of transmission line (TL) modeling for shielding effectiveness for normal plane wave incidence. However, previous studies [11, 12] ignored that shielding effectiveness may vary widely with the direction of

both polarization and angle of incidence wave. The transfer matrix method is a method used in the propagation of electromagnetic wave through a stratified (layered) medium.

In this paper, we propose an approach to modulate and simulate the multilayered electromagnetic shielding constructed with the good conductor materials; this is to make the equivalence between single and laminated shields. This approach permits to have the formula of reflection loss, absorption loss, shielding effectiveness and suggests a new relation of the equivalent impedance of laminated shields. These three quantities (refection loss, absorption loss and shielding effectiveness) are calculated and analyzed as a function of the angle of incidence for transverse electrical and magnetic polarizations.

2. THEORETICAL BACKGROUND

The electromagnetic shielding effectiveness (SE) of a material is defined by the ratio of the incident and transmitted field of an electromagnetic wave [16, 17], which is given by:

$$SE\,(\text{dB}) = -20\log|T| = -20\log\left(\left|\frac{E_t}{E_{in}}\right|\right) \tag{1}$$

where E_{in} and E_t, respectively, are the incident and transmitted field strengths.

The shielding effectiveness given in (1) can be broken into the sum of three terms, each representing one of the phenomena of reflection loss, absorption loss, and multiple reflections. These factors are added by [16]:

$$SE\,(\text{dB}) = R\,(\text{dB}) + A\,(\text{dB}) + M\,(\text{dB}) \tag{2}$$

where $R\,(\text{dB})$ represents the reflection loss caused by reflection at the left and right interfaces and increases with increasing permittivity and conductivity of shield. $A\,(\text{dB})$ represents the absorption loss of the wave as it proceeds through the barrier, and $M\,(\text{dB})$ represents additional effects of multiple re-reflections and transmissions [18]. The $M\,(\text{dB})$ term is often negligible with respect to $R\,(\text{dB})$ and $A\,(\text{dB})$ terms, especially in the high frequency range [19].

The transmission line theory is used for determination of shielding effectiveness of multilayered structure. Multilayer shield with n slabs is modeled as a non-uniform transmission line which is segmented into n sections [10]. We consider that each layer is homogeneous and isotropic, with constitutive parameters: permittivity ε_j, permeability μ_j, conductivity σ_j and thickness d_j [20].

The intrinsic impedance of jth layer for a good conductor is given by [16]:

$$\eta_j = (1 + i)\,(\mu_j\omega/2\sigma_j)^{1/2} \tag{3}$$

The impedance of the shield is varied according to the polarization as follows:

$$Z_j = \begin{cases} \frac{\eta_j}{\cos\theta_j} & \text{Transverse electrical polarization} \\ \eta_j\cos\theta_j & \text{Transverse magnetic polarization} \end{cases} \tag{4}$$

The angle of refraction, θ_j, can be calculated using the Snell's law [20]:

$$\cos\theta_j = \left[1 - \left(\frac{k_{in}}{k_j}\sin\theta_{in}\right)^2\right]^{1/2} \tag{5}$$

where θ_{in} and k_{in} are, respectively, the angle of incidence and the wave number in the free space.

And k_j is the wave number jth layer given by:

$$k_j = (1 - i)\sqrt{(\sigma_j\mu_j\omega)/2} \tag{6}$$

For each layer, we associate a matrix which gives the electric (E_{j-1}) and magnetic (H_{j-1}) fields according to the electric (E_j) and magnetic (H_j) fields [20].

$$\begin{bmatrix} E_{j-1} \\ H_{j-1} \end{bmatrix} = M_{j-1}\begin{bmatrix} E_j \\ H_j \end{bmatrix} \quad (j = 1, 2, 3, \ldots, N) \tag{7}$$

where M_{j-1} is given by [4]:

$$M_{j-1} = \begin{bmatrix} \cosh\left(ik_{j-1}d_{j-1}\right) & -Z_{j-1}\sinh\left(ik_{j-1}d_{j-1}\right) \\ -\frac{1}{Z_{j-1}}\sinh\left(ik_{j-1}d_{j-1}\right) & \cosh\left(ik_{j-1}d_{j-1}\right) \end{bmatrix} \tag{8}$$

The characteristic matrix of the whole structure is given by:

$$M = [M_1] \cdot [M_2] \dots [M_N] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{9}$$

According to Naishadham [18, 20, 21], the coefficient of transmission T of laminated structure is:

$$T = \frac{2Z_{j+1}}{(M_{11}Z_{j-1} - M_{12}) + Z_{j+1}(M_{22} - Z_{j-1}M_{21})} \tag{10}$$

3. RESULTS AND DISCUSSIONS

In this work, the effects of the angle, polarization and frequency of the incidence wave on the reflection loss, absorption and shielding effectiveness are analyzed for two kinds of shields: single and multilayer's shields. The analysis is carried out, and the thickness of the multilayer shields is equal to the thickness of the polymer used in a single shield. The materials selected for shielding in combination with the conductive polymer were aluminum and nickel. The material parameters conductivity, relative permeability and thickness of the considered materials and conducting polymer are listed in Table 1.

Table 1. Conductivity, relative permeability and thickness of selected materials.

Materiel	Conductivity (S·m^{-1})	Relative Permeability	Thickness (mm)
(PANI 44/PU)	$1.15\ 10^4$	1	0.1
Aluminum	$3.538\ 10^7$	1	0.1
Nickel	$1.16\ 10^7$	100	0.1

3.1. Single Shield

For a single layer of a good conductor, $Z_0 \gg Z_N$, in contact with two semi-infinite air media (Figure 1), so $Z_{N-1} = Z_{N+1} = Z_0 = 37\,\Omega$.

The shielding effectiveness can be written:

$$SE = 20\log\left|\frac{Z_0 \sinh\left(ik_N d_N\right)}{2Z_N}\right| \tag{11}$$

The relation (11) can be developed to:

$$SE\,(\text{dB}) = 20\log\left|\frac{Z_0}{4Z_N}\right| + 20\log\left|2\cosh\left(ik_N d_N\right)\right| + 20\log\left|[\tanh\left(ik_N d_N\right)]\right| \tag{12}$$

By identification with relation (2), we can write the reflection loss $R\,(\text{dB})$, absorption loss $A\,(\text{dB})$ and internal multiple reflections $M\,(\text{dB})$:

$$R\,(\text{dB}) = 20\log\left|\left[\frac{Z_0}{4Z_N}\right]\right| \tag{13}$$

$$A\,(\text{dB}) = 20\log\left|2\cosh\left(ik_N d_N\right)\right| \tag{14}$$

$$M\,(\text{dB}) = 20\log\left|[\tanh\left(ik_N d_N\right)]\right| \tag{15}$$

Figures 2 and 3 depict the angle and polarization dependencies of: 2(a) the reflection loss, 2(b) the shielding effectiveness, 3(a) the absorption loss and 3(b) the internal reflection of the single shield (PANI 44/PU), using, respectively, Equations (14), (15), (16) and (12). The reflection loss and shielding effectiveness increase with angle of incidence for transverse electrical polarization and decrease for magnetic polarization. The absorption loss and internal reflection are independent of the angle and polarization of the wave.
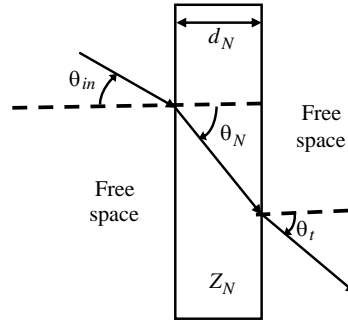
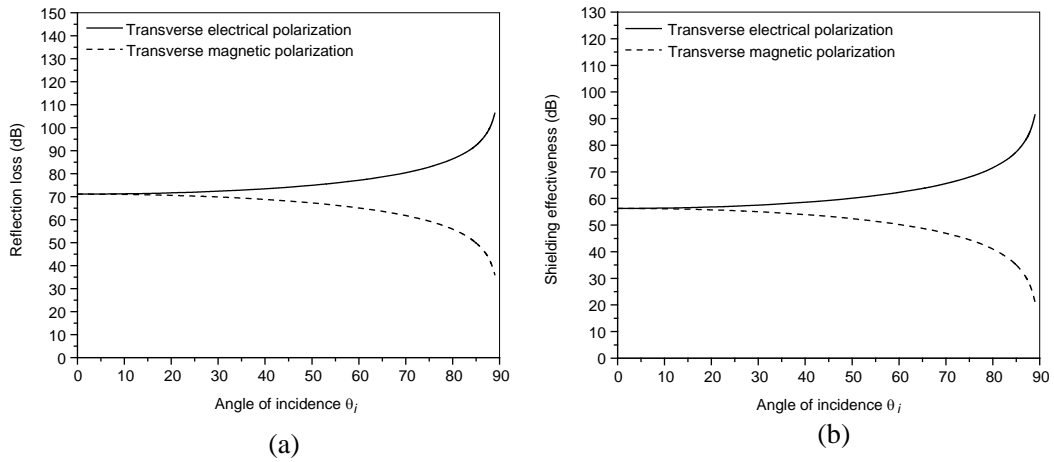**Figure 1.** Scheme of the single shield.

Figure 2. Variation of: (a) reflection loss and (b) shielding effectiveness with angle and polarization of incidence wave (0.3 mm thin sheet of Pani44/PU at 1 MHz).
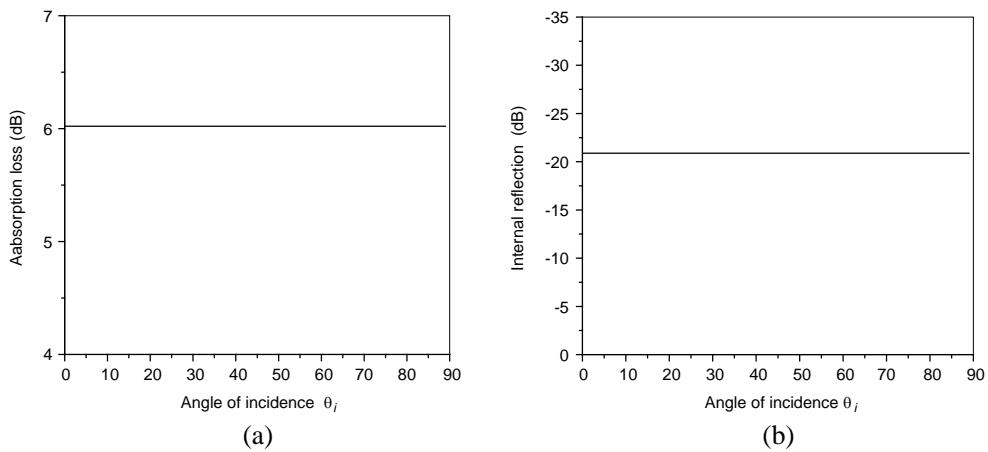

Figure 3. Variation of: (a) absorption loss and (b) internal reflection with angle and polarization of incidence wave (0.3 mm thin sheet of Pani44/PU at 1 MHz).

3.2. Multilayered Shield

In this section, the relations of the reflection loss, absorption loss and shielding effectiveness are established for n conductive sheets. The first and last layers are in contact with semi-infinite air (Figure 4).
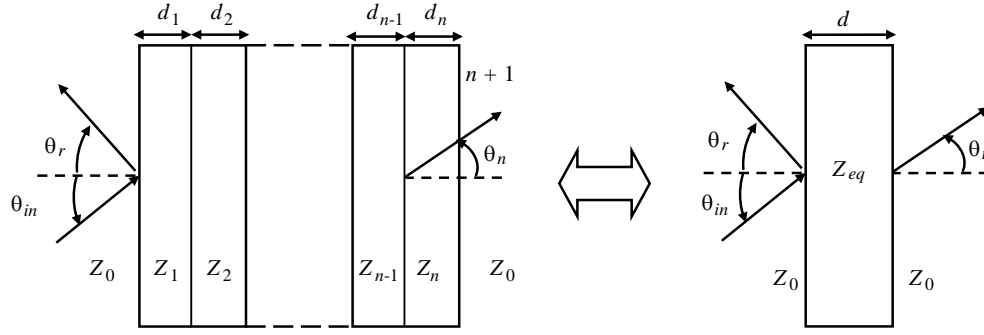
Figure 4. The equivalence between single and laminated shield.

The shielding effectiveness of multilayered structure bounded the free space can be expressed as:

$$SE = 20 \log \left| \frac{(M_{11}Z_0 - M_{12}) + Z_0 (M_{22} - Z_0 M_{21})}{2Z_0} \right| \tag{16}$$

Using the input-output relationship of the transmission coefficient [19], we can express SE of a multilayer shield, with negligible the internal multiple reflections, as:

$$SE = 20 \log \left| \frac{Z_0}{2^{n+1} Z_1} \prod_{j=2}^{n} \frac{(Z_j + Z_{j-1})}{Z_j} \prod_{j=1}^{n} 2^n \cosh(ik_j d_j) \right| \tag{17}$$

Shielding effectiveness SE is composed by reflection loss and absorption loss, which are respectively:

$$R \, (\text{dB}) = 20 \log \left| \frac{Z_0}{2^{n+1} Z_1} \prod_{j=2}^{n} \left[\frac{(Z_j + Z_{j-1})}{Z_j} \right] \right| \tag{18}$$

$$A \, (\text{dB}) = 20 \log \left| \prod_{j=1}^{n} 2^n \cosh(ik_j d_j) \right| \tag{19}$$

The laminated shield can be converted to the single shield by determining the equivalent impedance and wave number of multilayered shield (Figure 4).

$$k_{eq} = \frac{1}{d} \sum_{j=1}^{n} d_j k_j \tag{20}$$

and

$$Z_{equivalent} = 2^{n-1}(1 + i) \left(\frac{\mu_1 \omega}{2\sigma_1} \right)^{\frac{1}{2}} \prod_{j=2}^{n} \left[1 + \left(\frac{\sigma_j \mu_{j-1}}{\sigma_{j-1} \mu_j} \right)^{\frac{1}{2}} \right]^{-1} \tag{21}$$

This relation can be simplified if the materials for electromagnetic interference shielding are non-magnetic ($\mu_1 = \mu_2 = \ldots = \mu_0$, where $\mu_0 = 4\pi 10^{-7} \, \text{kg·m·A}^{-2}\text{·s}^{-2}$) and reduces to:

$$Z_{equivalent} = 2^{n-1}(1 + i) \left(\frac{\mu_0 \omega}{2\sigma_1} \right)^{\frac{1}{2}} \prod_{j=2}^{n} \left[1 + \left(\frac{\sigma_j}{\sigma_{j-1}} \right)^{\frac{1}{2}} \right]^{-1} \tag{22}$$

Finally, the reflection loss, absorption loss and shielding effectiveness of multilayered conductive sheets in contact with two semi-infinite air media can be calculated using, respectively, relations (18), (19) and (17), such as:

$$R \, (\text{dB}) = 20 \log \left| \left[\frac{Z_0}{4Z_{eq}} \right] \right| \tag{23}$$

$$A \, (\text{dB}) = 20 \log \left| 2 \cosh(idk_{eq}) \right| \tag{24}$$

$$SE \, (\text{dB}) = 20 \log \left| \frac{Z_0}{2Z_{eq}} \cosh(idk_{eq}) \right| \tag{25}$$

Figure 5 show respectively, (a) the reflection loss, (b) the absorption loss and (c) the effectiveness shielding evolution of multilayer's shields (Nickel-Pani44/PU-Aluminum) using, respectively, Equations (23), (24) and (25) for both types of polarizations as a function of the angle of incidence. It is observed that the reflection loss and shielding effectiveness increase with angle of incidence for perpendicular polarization and decrease for parallel polarization. Better reflection loss and shielding
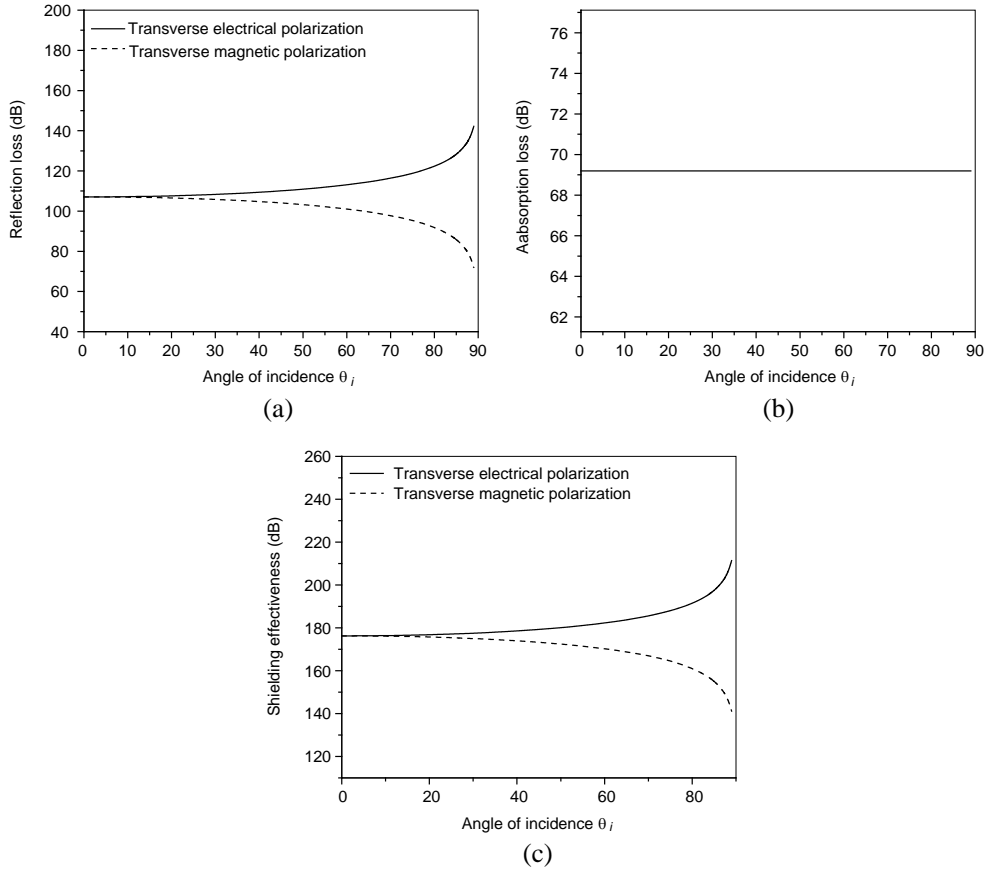

Figure 5. Variation of: (a) the reflection loss, (b) the absorption loss, and (c) the shielding effectiveness of (Nickel-Pani44/PU-Aluminum) with angle of incidence wave at 1 MHz.
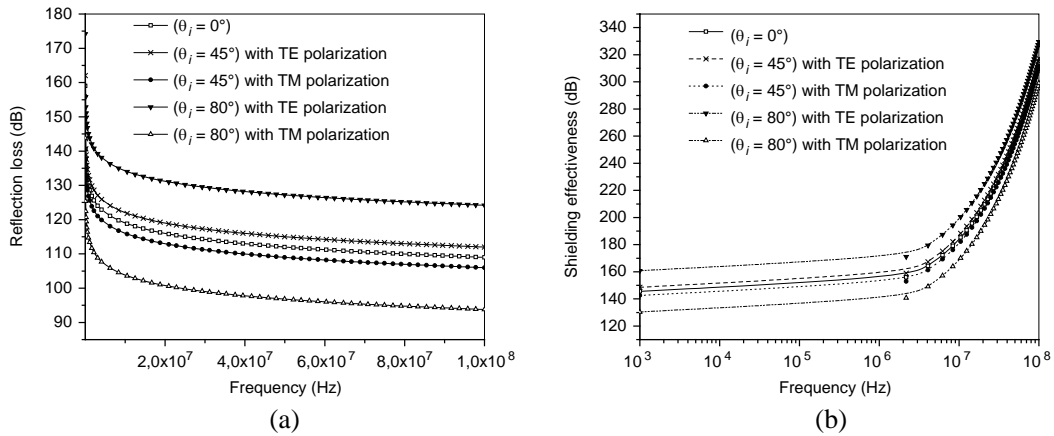

Figure 6. The variation of: (a) the reflection loss and (b) the shielding effectiveness of (Aluminum-Pani44/PU-Aluminum) as a function of frequency.

effectiveness can be obtained if we associate the magnetic and conductor material to conductive polymer.

The reflection loss and shielding effectiveness of multilayer's shield (Aluminum-Pani44/PU-Aluminum) with using, respectively, equations (23) and (25) are plotted as a function of frequency, respectively, in Figures 6(a) and 6(b) at normal (0°) and oblique (45° and 80°) incidence. The shielding effectiveness is frequency independent up to some limiting frequency, after which it increases with increasing frequency.

4. COMPARISON WITH LITERATURE

In this part, the approach presented in this paper is compared to the results used by [22, 23]. The frequency dependence of the shielding effectiveness SE for three-layer laminate of nickel, conductive polymer (Pani44/PU) and aluminium is plotted in Figure 7 using equations employed by [22, 23] (solid line) and Equation (25) of this paper (dash line). At low frequencies, a slight difference is observed between the two curves due to the neglect of the internal reflection which can be more significant in this range of frequency. On leaving that area, the coincidence of two curves validates the correctness of the approach presented in this paper.
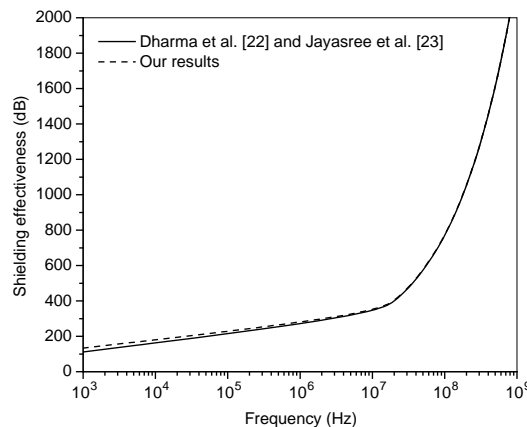

Figure 7. The variation of the Shielding effectiveness with frequency of (Nickel-Pani44/PU-Aluminum) at normal incidence.

5. CONCLUSIONS

In this paper, an approach is presented for modelling and simulates the reflection loss, absorption loss and electromagnetic shielding effectiveness of multilayer conductive sheets. This approach allows to have a new expression of the equivalent impedance of laminated structure which can be simplified if the materials shields are non-magnetic.

The presented results show that the increasing incidence angle increases reflection loss and shielding effectiveness for electrical polarization. In the case of a magnetic polarization, the presented results show that increasing incidence angle decreases reflection loss and shielding effectiveness. This indicates a positive influence of the angle of incidence on the reflection and shielding effectiveness for electrical polarization and a negative influence for a magnetic polarization. For absorption, we can say that it is independent of the type of polarization and the angle of incidence. The shielding effectiveness, reflection loss and absorption loss of the conductive polymer can be improved by combining with other classical materials (copper, aluminium, nickel. . .).

ACKNOWLEDGMENT

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