Laminated Electromagnetic Shielding Effectiveness of Non-Magnetic Materials

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***Abstract*—This paper presents a simple calculation of the electromagnetic shielding effectiveness of a laminated shield made of conductive non-magnetic sheets. The development of the calculation leads to a simple form of the transfer matrix and the electromagnetic shielding effectiveness shows that at low frequencies the latter is only dependent on the conductivity and the thickness of sheet. Analysis is carried out for the study of the multilayered shield constructed with (Copper-(PANI 44/PU) - Bronze - Aluminum).**

Keywords—Shielding effectiveness; Crossover frequency; non-magnetic material

I. INTRODUCTION

The electromagnetic shielding effectiveness (SE) of a material is defined by the ratio of the incident and transmitted field of an electromagnetic wave [1]–[2], it is usually given in decibels (dB) by:

$$SE = -20\log|T| = -20\log\left(\left|\frac{E_t}{E_{\text{in}}}\right|\right) \tag{7}$$

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

Many theoretical and numerical tools have been developed and applied to estimate the coefficient of transmission of plate shield of heterogeneous materials [3–6]. As for analytical method, the transfer matrix method is powerful tool for the analysis of the propagation of electromagnetic wave through multilayer shield with *n* slabs. This theoretical model is based on the association of each layer of thickness *d* and a transmitted wave matrix can be defined as [7]:

$$\mathrm{M_j} = \begin{bmatrix} \cosh\left((1+\mathrm{i})\frac{\mathrm{d_j}}{\delta_j}\right) & -\mathrm{Z_j}\sinh\left((1+\mathrm{i})\frac{\mathrm{d_j}}{\delta_j}\right) \\ -\frac{1}{\mathrm{Z_j}}\sinh\left((1+\mathrm{i})\frac{\mathrm{d_j}}{\delta_j}\right) & \cosh\left((1+\mathrm{i})\frac{\mathrm{d_j}}{\delta_j}\right) \end{bmatrix} \tag{1}$$

where δ_j is the skin depthof the conductive sheet ($\sigma_j \gg \omega\varepsilon$) given by:

$$\delta_j = \sqrt{1/(\sigma_j \mu_j \pi f)} \tag{2}$$

and $\mathrm{Z_j}$ is the intrinsic impedance of j^{th} layer, for a good conductor is given by[7]:

$$\mathrm{Z_j} = \frac{(1+\mathrm{i})}{\sigma_j \delta_j} \tag{3}$$

The characteristic matrix of the whole structure is given by:

$$\mathrm{M} = \prod_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{M_j} = \begin{bmatrix} \mathrm{M_{11}} & \mathrm{M_{12}} \\ \mathrm{M_{21}} & \mathrm{M_{22}} \end{bmatrix} \tag{5}$$

The coefficient of transmission for *n* layer can be writing as follows [8]:

$$T = \frac{2Z_{j-1}}{(\mathrm{M_{11}}Z_{j-1} - \mathrm{M_{12}}) + Z_{j+1}(\mathrm{M_{22}} - Z_{j-1}\mathrm{M_{21}})} \tag{6}$$

In this work, we propose simplified formula of the shielding effectiveness of multilayered electromagnetic shielding constructed with the good conductor non-magnetic materials. This simplification is based on the two frequency range: first, when the frequency is much lower than crossover frequency, the second, in the higher frequency range than crossover frequency.

II. RESULTS AND DISCUSSION

The characteristic matrix of multilayered structure constructed with *n* conductive sheets, $\mathrm{Z_0} \gg \mathrm{Z_j}$, in contact with two semi-infinite air media, so $\mathrm{Z_{j-1}} = \mathrm{Z_{j+1}} = \mathrm{Z_0} = 377\Omega$ is:

$$\mathrm{M} = \begin{bmatrix} 1 & 0 \\ -\sum_{\mathrm{j=1}}^{\mathrm{n}} \frac{\tanh\left((1+\mathrm{i})\frac{\mathrm{d_j}}{\delta_j}\right)}{\mathrm{Z_j}} & 1 \end{bmatrix} \prod_{\mathrm{j=1}}^{\mathrm{n}} \cosh\left((1+\mathrm{i})\frac{\mathrm{d_j}}{\delta_j}\right) \tag{8}$$

Expression of M has two limits of interest which can be taken as acceptable approximations, depending on whether the frequency is higher or lower than that at which the thickness, *d*, equals the skin depth δ. The crossover frequency is:

$$f_c = \frac{1}{\pi \sigma_j \mu_j \mathrm{d}_\mathrm{j}^2} \quad (9)$$

In the lower frequency range than $f_c(\delta \gg \mathrm{d})$, M reduces to:

$$\mathrm{M} = \begin{bmatrix} 1 & 0 \\ -\sum_{\mathrm{j}=1}^{\mathrm{n}} \sigma_\mathrm{j} \mathrm{d}_\mathrm{j} & 1 \end{bmatrix} \prod_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{e}^{\frac{\mathrm{d}_\mathrm{j}}{\delta_j}} \quad (10)$$

The shielding effectiveness of laminated conductive layer, using (7), reduces to:

$$SE = 20\log\left(\frac{Z_0}{2} \sum_{\mathrm{j}=1}^{\mathrm{n}} \sigma_\mathrm{j} \mathrm{d}_\mathrm{j}\right) + 8{,}66 \sum_{\mathrm{j}=1}^{\mathrm{n}} \frac{\mathrm{d}_\mathrm{j}}{\delta_\mathrm{j}} \quad (11)$$

Therefore, knowing that, at low frequencies, the skin depth can be neglected compared to the thickness, in addition to the impedance of vacuum, the shielding effectiveness depends only on the conductivity and thickness of the material. This indicates that there is no magnetic effect on the shielding effectiveness.

In the higher frequency range than $f_c(\delta \ll \mathrm{d})$, M becomes:

$$\mathrm{M} = \begin{bmatrix} 1 & 0 \\ -\sum_{\mathrm{j}=1}^{\mathrm{n}} \frac{\sigma_j \delta_\mathrm{j}}{1+\mathrm{i}} & 1 \end{bmatrix} \prod_{\mathrm{j}=1}^{\mathrm{n}} \frac{\mathrm{e}^{\frac{\mathrm{d}_\mathrm{j}}{\delta_j}}}{2} \quad (12)$$

This matrix can be yet simplified if the materials for electromagnetic interference shielding are non-magnetic: $\mu_1 = \mu_2 = \cdots = \mu_0$, where $\mu_0 = 4\pi\ 10^{-7}\mathrm{kg.m.A^{-2}.s^{-2}}$ is the permeability of free space. In this case, we can write the characteristic matrix of multilayered structure constructed with *n* non-magnetic conductive sheets as:

$$\mathrm{M} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{(1+\mathrm{i})\sqrt{\mu_0 \pi f}} \sum_{\mathrm{j}=1}^{\mathrm{n}} \sqrt{\sigma_j} & 1 \end{bmatrix} \prod_{\mathrm{j}=1}^{\mathrm{n}} \frac{\mathrm{e}^{\frac{\mathrm{d}_\mathrm{j}}{\delta_j}}}{2} \quad (13)$$

Therefore, in this frequency range, the shielding effectiveness of laminated non-magnetic shied, is as follows:

$$SE = 96{,}52 + 20\log\left(\frac{1}{2^{\mathrm{n}} f} \sum_{\mathrm{j}=1}^{\mathrm{n}} \sqrt{\sigma_j}\right) + 0{,}0172\sqrt{f} \sum_{\mathrm{j}=1}^{\mathrm{n}} d_j \sqrt{\sigma_j} \quad (14)$$

From (14), we conclude that the shielding effectiveness is uniquely linked to the thick and the conductivity of non-magnetic materials and to electromagnetic wave frequency.

III. APPLICATIONS

Using the expressions that we obtained, we will plot the shielding effectiveness of laminated conductive non-magnetic sheets according to the frequency of the incidence wave. The materials selected for shielding are; conductive polymer (PANI 44/PU [9]), copper, aluminum and bronze. The material parameters conductivity and the thickness of the considered materials were listed in the Table 1.

TABLE 1
CONDUCTIVITY AND THICKNESS OF SELECTED MATERIALS

Materiel	Conductivity ($\mathrm{S.m^{-1}}$)	Thickness (mm)
(PANI 44/PU)	11500	0.1
Copper	$5.8\ 10^7$	0.1
Aluminum	$3.53\ 10^7$	0.1
Bronze	$1.044\ 10^7$	0.1

Figures 1 and 2 are plotted using, respectively, equation (11) and (14), they show that the shielding effectiveness is frequency independent at lower frequency and, at higher frequency, it increases with increasing frequency.

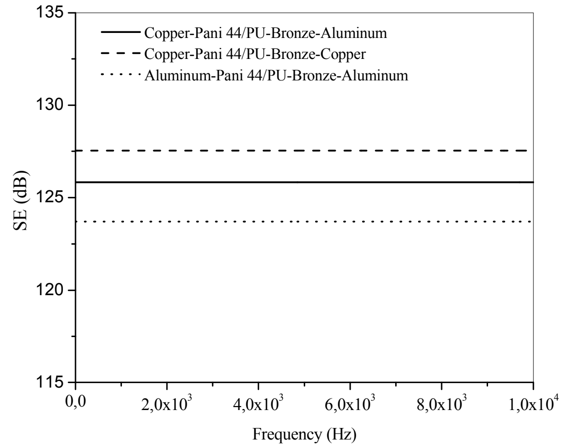

Fig. 1. Dependence of the shielding effectiveness on frequency ($f \ll f_c$)

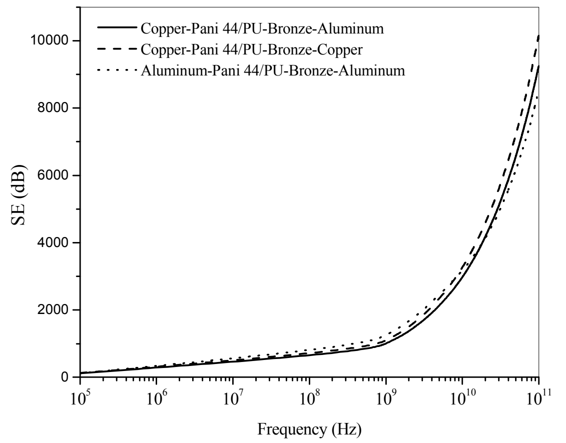

Fig. 2. Variation of the shielding effectiveness as function of frequency ($f \gg f_c$)

IV. CONCLUSIONS

In this study, a simple calculation of the shielding effectiveness expression of multilayered conductive non-magnetic sheets is presented. In the lower frequency range, the formula of the effectiveness shielding is the same, this regardless of the type of materials; magnetic or non-magnetic and depends only on the conductivity and thickness of the material. In the higher frequency range, the simplification of the shielding effectiveness expression shows that it is uniquely linked to the thick and the conductivity of non-magnetic materials and to electromagnetic wave frequency.

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