Characterisation And Modelisation Of Shielding Effectiveness Of Pani/PU Conducting Composite Multilayer At Microwave Frequency

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Abstract

Nowadays, the electromagnetic interference problem becomes more important to protect the electric, electronic devices. In this paper, the electromagnetic characterisation of Pani/PU in multi-layered structure was studied in order to optimize the shielding effectiveness at the microwave frequency. In the three-layered structure, the insulating layer increases not only the mechanical properties but also improve the shielding effectiveness. The three-layered Pani/Pu conducting composite with total thickness below 500μm *could answer many industrial or military shielding applications in microwave band (according to FCC 15, class B).*

1. Introduction

Nowadays, the electromagnetic interference (EMI) becomes more significant due to the proliferation of commercial, military, scientific electrical devices and equipments in high frequencies. To protect against the incoming and potentially disturbing radiation from penetrating into the equipment, electronic devices must be shielded.

The interaction mechanism of an electromagnetic wave with a material can be divided in three mechanisms: reflection, absorption and multiple reflections inside the material [1]. The first one, reflection, depends on the permittivity and conductivity of the material. The effect of this mechanism increases with permittivity and conductivity of shield. The second one of EMI shielding, absorption, requires the existence of mobile charge carriers (electrons or holes), which interact with the electromagnetic radiation. And the third one of EMI is the wave attenuation due to multiple reflections. This mechanism depends on physical properties and geometric structure of shielding material.

Having high conductivity, metal is usually used as the shielding material. In the recent years, new materials such as intrinsically conducting polymers (ICP) with high conductivities and lightweight structures appear as an alternative to metal. Among the ICP, Polyaniline (PAni) has lots of potential applications in electronic and micro-electronic industry such as opto-electronic devices, sensors, electrostatic discharge layers, printed circuit board [2,3] and electromagnetic interference shielding [4,5]…thanks to their good electric properties and environmental stability.

Lee *et al.* [6] presented the EMI shielding effectiveness of the mixtures of PAni and conducting powders like silver, graphite and carbon black in the frequency range from 10 MHz to 1 GHz. As an exemple, the shielding effectiveness of the mixture between doped PAni and Ag powder is about 46 dB at room temperature. The authors showed theoretically that the shielding effectiveness could be improved in three-layered structure. Makela *et al.* [7] measured the shielding effectiveness of two-layer structure composed of PAni-CSA, and found a SE of 39 dB at 1 GHz in the far-field regime. In this paper, the shielding theory of multilayer structure is studied and then the role of each layer in three layered is also investigated in order to concept an optimized EMI shielding material.

2. Shielding effectiveness theory

The electromagnetic shielding effectiveness (SE) of a material is defined by the ratio of the transmitted power (P_t) through the material to the incident power (P_i) of an electromagnetic wave [4]. In general SE is given in decibel (dB):

$$SE = -10\log\left(\frac{P_t}{P_i}\right) = -20.\log\left(\frac{E_t}{E_i}\right) = -20.\log\left(\frac{H_t}{H_i}\right) \quad (1)$$

Where $E_i(H_i)$ and $E_t(H_t)$ are the incident and transmitted field strength.

A theoretical model based on plan-wave and transmitted wave matrix field is proposed to study the far-field of multilayer materials. The reflection and the transmission of a normal EM wave on the N-layer structure were presented in the fig. 1. Consider that each layer is homogeneous and isotropic, the electromagnetic parameters of *i*-layer are noted: μ_i - permeability, δ_i - conductivity, ε_i- permittivity and d_i-thickness. The intrinsic impedance of i^{th}-layer Z_i depends on the frequency of incident wave,and given by:

$$Z_i = \left[\frac{\mu_i}{\varepsilon_i + \sigma_i / j\omega}\right]^{1/2} \quad (2)$$

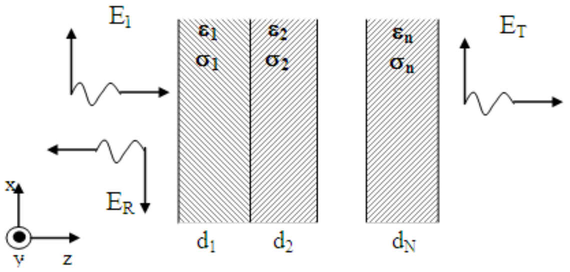

Figure 1. The reflection and the transmission of a normal EM wave on the N-layer structure

The characteristic matrix presented by Kong [10] was used to calculate the coefficients of reflection and transmission of an electromagnetic wave through a multi-layers structure. Therefore, for i^{th}-layer we have:

$$[M_i] = \begin{bmatrix} \cos(k_i d_i) & -jZ_i \sin(k_i d_i) \\ -\frac{j}{Z_i}\sin(k_i d_i) & \cos(k_i d_i) \end{bmatrix} \quad (3)$$

Where: $k_i = \frac{2\pi}{\lambda_0}\left[\left(\varepsilon_i' + \sigma_i /(j\varepsilon_0\omega)\right) - (\lambda_0/\lambda_c)^2\right]^{1/2}$ and λ_0 is the wavelength in the air and λ_c is the cut-off wavelength of the TE_{01} mode in the waveguide.

The characteristic matrix of the whole structure presented:

$$[M] = [M_1].[M_2]....[M_N] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \quad (4)$$

N-layers structure is in contact with two semi-infinite air media, so $Z_0 = Z_N = 377$ (Ω).

The coefficients of reflection R and transmission T were calculated according to Naishadham [4]:

$$R = \frac{(M_{11}Z_0 - M_{12}) - Z_1(M_{22} - M_{21}Z_0)}{(M_{11}Z_0 - M_{12}) + Z_1(M_{22} - M_{21}Z_0)} \quad (5)$$

$$T = \frac{2[M_{22}(M_{11}Z_0 - M_{12}) + M_{12}(M_{22} - M_{21}Z_0)]}{(M_{11}Z_0 - M_{12}) + Z_1(M_{22} - M_{21}Z_0)} \quad (6)$$

From equation (1), consider that the incident field equal one unit, so the SE is given by:

$$SE = -20.\log|T| \quad (7)$$

3. Experimental

3.1. Conducting composite

3.1.1. Freestanding Pani/Pu conducting composites

The freestanding Pani/PU films were prepared as described in our work [8]. The permittivity and conductivity of the samples were measured by using the open ended coaxial probe for different weight ratio of Pani: Pani0.2/PU, Pani0.5/PU and Pani1/PU films [9]. Electrical properties of the composites were presented in the table I (DC measurement)

Table 1. Characteristics of the freestanding films of Pani/PU

Material	**d(µm)**	**ε**	**σ(S/m)**
Pani0.2/PU	150	7.5	0.2
Pani0.5/PU	150	8.2	0.3
Pani1/PU	150	19	4
Pani4.7/PU	160	-	235
Pani8.8/PU	155	-	792
Pani16/PU	145	-	2456
Pani44/PU	130	-	11500

The use of the Scanning Electron Microscope (SEM) teachnique permits to analyse the morphology of freestanding and thee-layered PAni/PU films in profil section. In the fig. 2, it can't distinguish the PAni, doping and PU phases. It shows that the film is homogeneous.

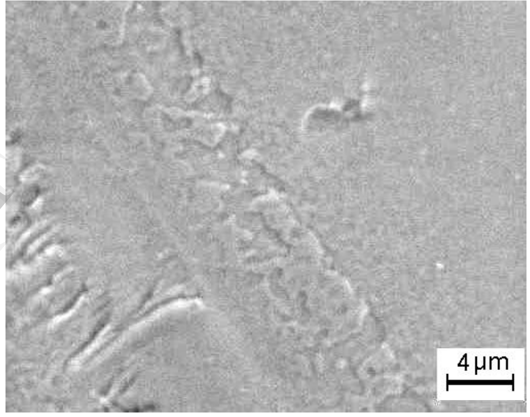

Figure 2. Scanning Electron Microscope of PAni0.5/PU in profil section

3.1.2. Thee-layered Pani/PU conducting composite

The three-layered conducting composite was structurized by Pani/PU as the first and the third layer and the Kapton film as the middle layer (fig. 3). The conductivity of Pani/PU varies from insulating state (10^{-8} S/m) to conducting state (10^{4} S/m). The Kapton slide is insulating material with 3.1 of relative permittivity.

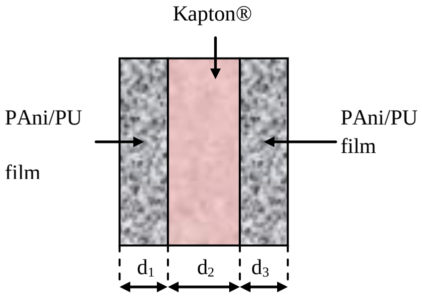

Figure 3. Three-layered conducting composite

A three-layered Pani/Pu conducting film was realized and presented in the table 2.

Table 2. Three-layered Pani/Pu film

Sample TS88	Material	Thickness (µm)
First layer	*Pani8.8/PU*	93
Second layer	*Kapton*	125
Third layer	*Pani8.8/PU*	360

A good interaction between the Pani/Pu and the Kapton film is observed under SEM technique in micro scale (fig. 4)

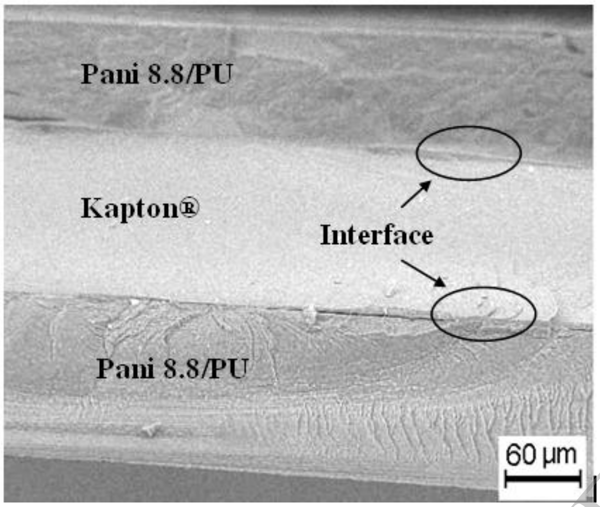

Figure 4. Scanning Electron Microscope of three-layered PAni 8.8/PU film in profil section

3.2. Shielding effectiveness measurement in far-field

The technique measurement of the EMI shielding effectiveness in the far-field of a conducting material consists of placing the test material between a source of plane waves and a detector. The shielding effectiveness can be measured by using the TEM cell (50MHz to 1GHz), the rectangular waveguides (8.2GHz to 18GHz) and antenna (to 110GHz)[11].

Two sections of the measuring cell were connected to the vector network analyser (VNA) via two coaxial-to-waveguide adapters. Before performing measurements, the VNA was calibrated by using the calibration kits with the full two-port calibration method provided by Hewlett Packard Corporations. The shielding effectiveness is extracted from modules of the transmitted coefficients S_{21}.

4. Results and discussions

In the previous work [8], the shielding effectiveness model was validated by modeling the shielding effectiveness of Pani/PU freestanding and three-layered films. In this paper, shielding effectiveness behaviours of the material versus thickness and conductivity are investigated in order to work out an optimal shielding material in far-field.

The effect of thickness on shielding effectiveness of Pani0.2/PU, Pani0.5/PU and Pani1/PU at 4GHz was shown in figure 5. It is obvious that, at this frequency the shielding effectiveness increases with the conductivity but the effect of thickness does not follow the same trend. With the small amounts of Pani (corresponding to 0,2 and 0,5 of weight ratio), a resonance of shielding effectiveness is visualized at the thickness of 7mm with the value of 5dB. Otherwise, the shielding effectiveness of the freestanding film containning the highest ratio of Pani (1%) increases with the thickness in quasi-linear way in logarithimic scale, and this behavior is found to be similar to that of conducting material.

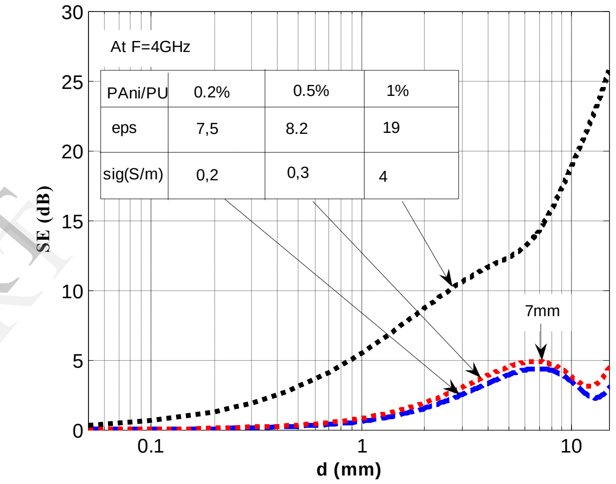

Figure 5. Shielding effectiveness of Pani/PU films versus thickness at 4GHz with different concentrations

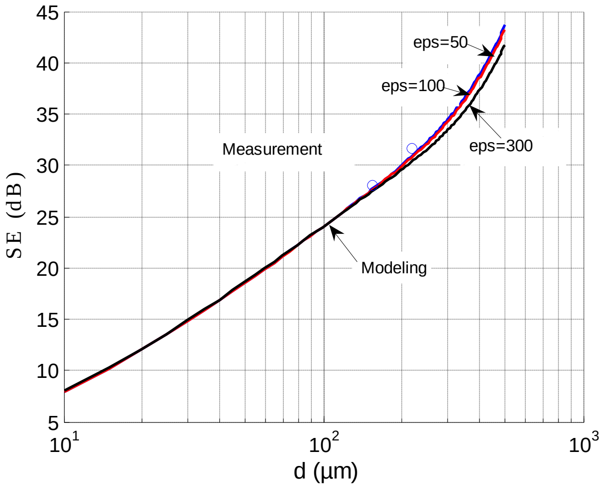

Figure 6. Shielding effectiveness of Pani8.8/PU versus thickness at 10GHz with different permittivities

Figure 6 depicted the results of measurements which were performed on Pani8,8/PU (792S/m of conductivity) with the relative permittivity of 50, 100 and 300 respectively. As the shielding effectiveness keep almost constant in the microwave band, the data at 10GHz was used to analyse. The modeling curves according to equation (7) were also illustrated in the figure, and they described very well the behaviours of the material. It is observed that the shielding effectiveness of such a high conductivity material is independent of their permitivity, the curve corresponding to the permittivity of 300 slightly deviates from the others at the thickness above 200µm. This behaviour is due to the insignificant value of permittivity in comparison with the conductivity ($\varepsilon << \sigma/\omega$). In other words, the value of permittivity is so small that it can be neglected in the intrinsic impedance expression (2). This observation is in accordance with that was recorded in [8,9] wherein the permittivity can be negligeable in shielding effectiveness calcalation if the static conductivity of material is superior to 10S/m.

By changing the conductivity of the sample of 0,15mm thick at 1GHz, the shielding effectiveness of the material versus the conductivity is plotted in the figure 7. This curve will be used to elaborate conducting material having desired shielding effectiveness by knowing their conductivity.

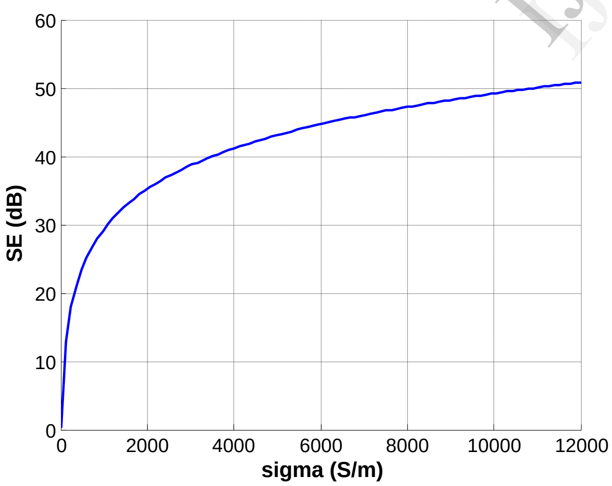

Figure 7. Shielding effectiveness versus conductivity at 1GHz of the thickness d=0.15mm

It can also be observed that the SE of three-layered TS88 film (in table 2) present high attenuation about 41dB corresponding to 99.99% of incident radiation (figure 8). In the multilayered material, the middle layer has a significant role to improve the SE level as well as very good mechanical properties.

Here, the modelling results are in good agreement with measurement values as we have ±5dB of measurement uncertainties induced by the calibration procedure, the conductivity and the thickness measurements of each film.

Following the Federal Communications Commission, for many commercial shielding applications, the SE had to be greater than 40dB, so this material can be used for these applications.

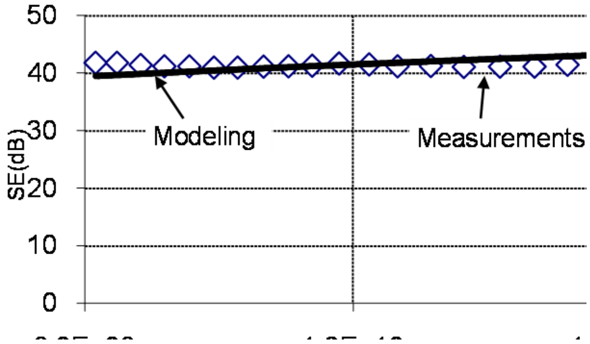

Figure 8. Shielding effectiveness of TS88 film in X and Ku bands

Table 3 summarizes mechanical and electrical properties of two-layer and three-layer material with the same total thickness of conducting layers (125µm). The material was structuralized as described 3.1.1. and 3.1.2. Data in the table were used to simulate the shielding effectiveness of the material.

Table 3. Mechanical and electrical properties of two and three-layered materials

	1st layer	**2nd layer**	**3rd layer**
Two layer	σ=2456 S/m d=80um	σ=5700 S/m d=55um	
Three-layer	σ=2456 S/m d=80um	Kapton ε=3.1,d=125um	σ=5700 S/m d=55um

The figure 9 compares the shielding effectiveness between two-layered and three-layered structures versus frequency. It is observed that the three-layered structure shows more interesting behaviour at high frequency than the two-layer one, especially at very high frequency. Although the structure did not influence on the shielding effectiveness at 1GHz, but 5dB of difference was observed between two structures at 10GHz. Since Kapton possesses very good mechanical properties, the three-layered structure will find more application in EMI shielding than the two-layered one.

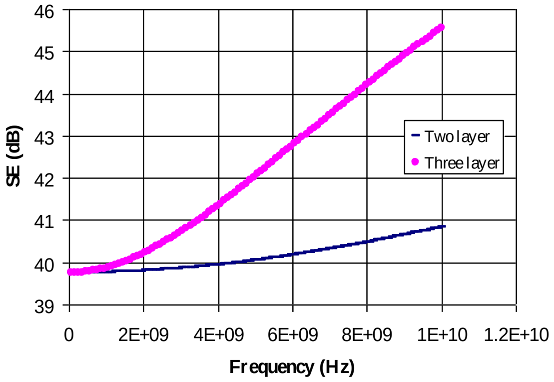

Figure 9. Shielding effectiveness two-layered and three-layered structure versus frequency

5. Conclusion

In this work, numerous parameters were changed in order to obtain an optimal shielding material. The shielding effectiveness increases in exponential scale with the thickness of material despite a resonance peak appears at low concentration of Pani. Permittivity has negligible effect on shielding effectiveness in the whole range of thickness. In the goal of elaborating a conducting material with desired shielding effectiveness based on Pani concentration, a curve which illustrates the dependence of shielding to the conductivity was built. The three-layered conducting structure was found to have better electrical and mechanical properties than the two layered one, especially at high frequency. Because of very thin dimension, the material can be compatible with aeronautic applications.

10. References

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