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Performances of multilayer composite materials for broadband shielding

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Abstract—The paper investigates the shielding effectiveness (SE) of multilayers composite materials over a wide frequency band. First, several nanocomposite materials are characterized, and behavior laws are deduced up to several GHz. Then different arrangements involving conductive layers and composite layers are compared. Finally, a three-layer arrangement combining a magnetic material and a conductive sheet is shown to provide a high shielding effectiveness from DC to 10 GHz.

Keywords—composite materials, shielding effectiveness

I. INTRODUCTION

Composite materials are good candidates for electromagnetic shielding applications. Their light weight provides an important advantage over conducting alloys classically used in the automotive and aircraft industries. Various types of composite materials, including nanocomposites, are widely studied in the EMC community in view of the design of shielding boxes and/or electronic enclosures.

Carbon-based nanocomposites materials such as carbon nanotubes (CNTs), exfoliated graphite, graphene, are among the most popular ones [1,2,3,4]. They are generally dedicated to high frequencies, X-band for example (8 GHz -12 GHz) [5,6,7]. In [8] a flexible graphene-based paper was shown to provide a high shielding effectiveness (SE) over the frequency range 10 MHz - 18 GHz. Metal coating are also sometimes proposed to increase SE [3, 4, 12]. In some configurations local arrangements of multilayers combining conductive materials and composite materials may provide efficient solutions [7].

For low frequencies, some combinations of magnetic materials and alloys demonstrate strong capabilities. In [9,10] multilayer screens were proposed for building an enclosure and perform a shielding up to several tens of Hz. In [13] a bimetallic composite based on aluminum and steel proved to be very efficient up to 10 kHz.

It comes out from the literature that shielding sheets or walls are often designed either for low frequency applications (from 0 Hz to some ten of kHz) or for high frequency applications (from some ten of Hz to some GHz). The contribution of this paper is to design a shielding material for a wide band analysis (from 0 Hz to several GHz). In [11,12] the authors have shown that multilayers combinations of glass fiber-based nanocomposite materials lead to high

absorption rates and high shielding effectiveness over the X-band. To obtain a high SE over an extended frequency range, the work suggests to combine magnetic layers with conductive layers and investigates the capabilities of several composite (including nanocomposite) materials. The paper compares several multilayer arrangements of materials involving thin sheets. It is a first step in the design of enclosures where composite panels may replace standard conducting materials for electronic equipment.

II. MATERIALS AND EXPERIMENTAL CHARACTERIZATION

Glass fiber (GF) is widely used as structural composite reinforcement because of good mechanical properties, low density, and low price. High-performance structural absorbing composites can be achieved by surface treatment on GF or adding absorbing materials into the epoxy matrix. To improve the electromagnetic absorbing performances of GF reinforced composites, the combination of growing CNTs and depositing nickel layers (Ni) (GF-CNTs and GF-CNTs@Ni) have been performed on the surface of GF to get hybrids. The GF-CNTs hybrid, with different CNT contents, were prepared by a floating catalyst CVD (chemical vapor deposition) method. Fig. 1 illustrate these two composite materials.

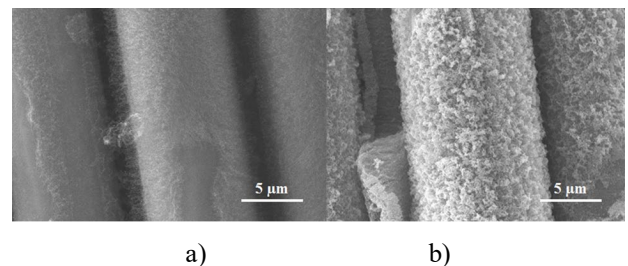


Fig. 1. SEM (scanning electron microscopy) images of the hybrids. a) GF-CNTs. b) GF-CNTs@Ni

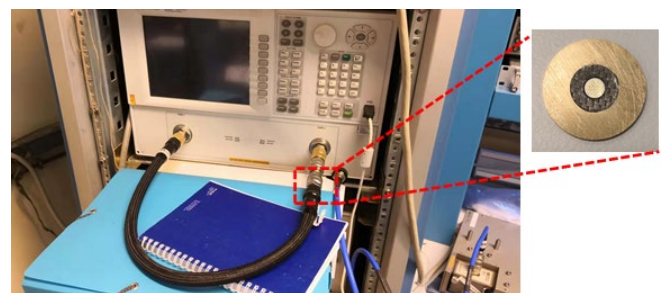


Fig. 2. Measurement for complex permittivity measurement 1MHz-18GHz

The shielding properties of nanocomposites were evaluated in the frequency range 1-18 GHz by a network analyzer (Keysight E8364C) (Fig. 2.). Samples with 7 mm in diameter and less than 1 mm in thickness were polished and placed in a metallic coaxial cell (Fig. 3.). From S-parameters measurements and following [14] the variation of dielectric and magnetic properties can be deduced. To illustrate, Fig. 4 shows the measured complex relative permittivity of GF-CNTs@Ni.

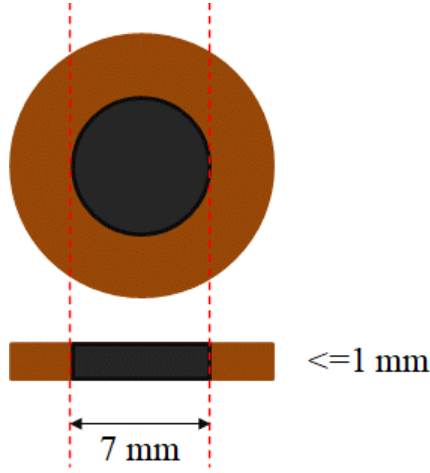


Fig. 3. Cross-section of the coaxial cell for S-parameters measurements

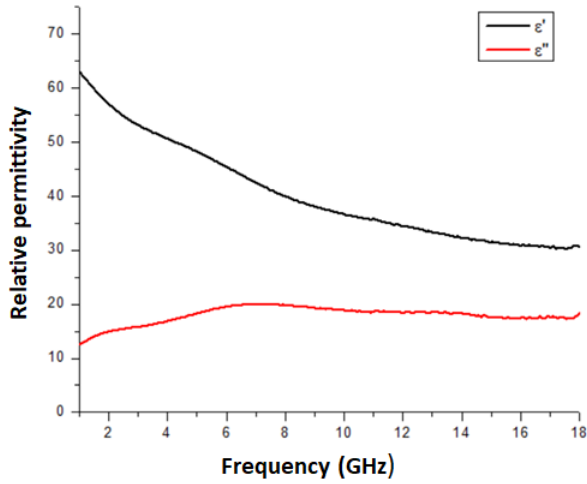


Fig. 4. Complex relative permittivity of GF-CNTs@Ni

To include the composite behavior laws in future 3D full wave computational softwares, it may be useful to describe the real inhomogeneous medium as an equivalent homogeneous material with a causal permittivity profile, approximated by analytical functions with poles. Such analytical expressions are of interest when looking for a relationship between material properties and shielding specifications.

Standard behavior laws for dielectric materials can be used: Debye, Cole-Cole, Cole-Davidson and Havriliak-Negami. For example, according to Havriliak-Negami model, the dielectric permittivity is given by :

$$\epsilon_{H-N} = \epsilon_{\infty} + \frac{\epsilon_S - \epsilon_{\infty}}{(1 + (j\omega\tau)^{\alpha})^{\beta}} \quad (1)$$

The Cole-Cole model is given by:

$$\epsilon_{C-C} = \epsilon_{\infty} + \frac{\epsilon_S - \epsilon_{\infty}}{1 + (j\omega\tau)^{\alpha}} \quad (2)$$

In (1) and (2), ϵ_{∞} is the permittivity at the high frequency limit, ϵ_S is the static permittivity, τ is the characteristic relaxation time, α , β are coefficients accounting for the asymmetry and broadness of the dielectric dispersion curve ($0 < \alpha, \beta < 1$).

From the measured permittivity and using a fitting or an optimization algorithm the parameters in (1) and (2) can be easily obtained. To illustrate the accuracy of fitting, Fig. 5 and Fig.6 show the approximation of the measured permittivity with a Havriliak-Negami expression for the GF-CNTs@Ni nanocomposite and for a commercial composite material reinforced by CNTs from Nanocyl SA, Belgium. In the case of GF-CNTs@Ni, a similar agreement is obtained with a Cole-Cole fitting. In case of Nanocyl composite, Havriliak-Negami was shown to provide a better accuracy and so this model was chosen for the shielding effectiveness prediction.

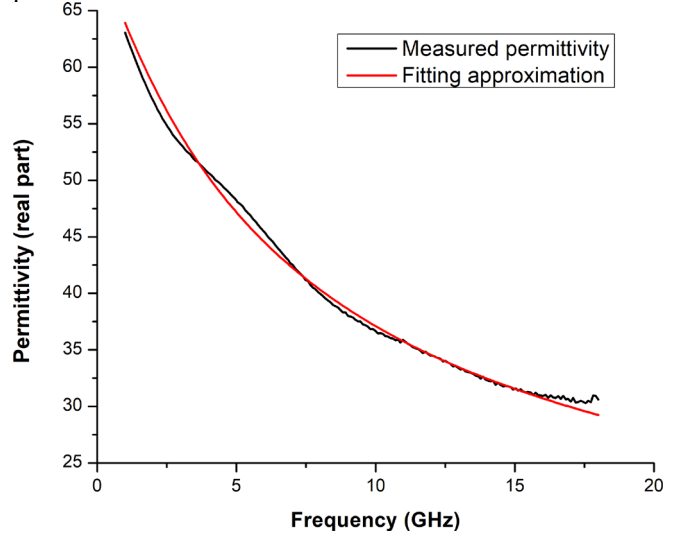


Fig. 5. Real part of complex relative permittivity of GF-CNTs@Ni

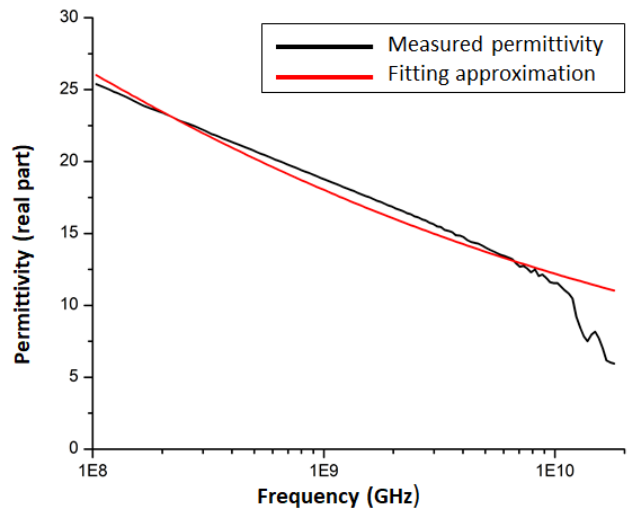


Fig. 6. Real part of complex relative permittivity of Nanocyl composite

The shielding effectiveness of the material sample can be deduced from the S-parameters determined in the coaxial cell (Fig. 3). The theoretical value in this case of TEM mode propagation corresponds to the standard definition of shielding effectiveness obtained in case of a planar sheet illuminated by a plane wave in normal incidence:

$$SE = -20 \log|S_{21}| \quad (3)$$

Fig. 7 shows the shielding effectiveness of an infinite planar 2 mm slab corresponding to three types of nanocomposites. The two composites based on GF-CNTs are compared to the commercial one reinforced by CNTs from Nanocyl SA, Belgium. For each one, SE obtained with the measured permittivity is compared with SE obtained with the permittivity represented with (1). The corresponding fitting parameters are shown in Table I. Same results have been obtained with an analytical solution (plane wave against a planar sheet) and a numerical method. A good agreement between predictions and measures is reached over the range 1 GHz – 10 GHz. Clearly the nickel coating gives to the better performances. It should be mentioned that the discrepancies related to Nanocyl material at high frequencies are probably due to the characterization of the permittivity, as it already appears on Fig. 6. The thickness of the sample (less than 1 mm) may also impact the accuracy of the measures at high frequencies.

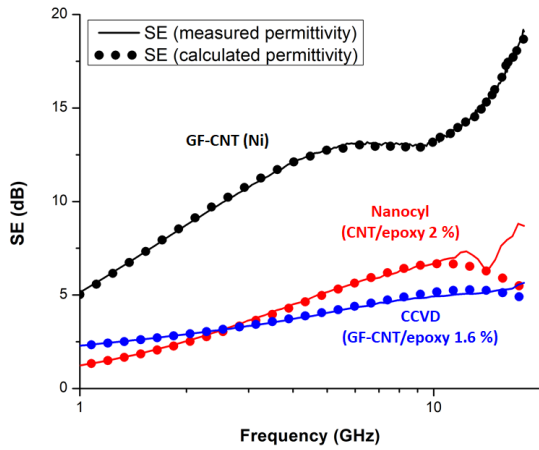


Fig. 7. Shielding effectiveness obtained with three nanocomposite materials

TABLE I. FITTING PARAMETERS

Fitting parameters	GF-CNT (Ni)	Nanocyl	GF-CNT /epoxy
ϵ_s	70.6	86.7	4355
ϵ_{zp}	1.04	1.	6.08
α	0.767	0.255	0.991
β	0.585	0.779	0.685
$f_c=1/(2 \pi \tau)$	4.1 GHz	600 kHz	238 kHz

III. MULTILAYERED COMPOSITE SHIELDS

As mentioned in the introduction, the composites presented in the previous sections can be combined to provide a high shielding. Such multilayer arrangements have demonstrated a significant absorption efficiency in the X-band

[12]. At low frequencies, as shown in Fig. 7, SE decreases and then, a combination of conductive layers with such composite layers may significantly improve SE.

Here, the GF-CNTs composite is associated with conductive layers in different arrangements (Fig.8). Using both analytical solutions and numerical simulation, Fig. 9 shows, in case of sheet with 2 mm thick, a comparison between the corresponding values of SE, above 1 GHz. As expected, for the same total thickness of the sheet (2 mm), a doubled conductive sheet presents a better efficiency than a single one.

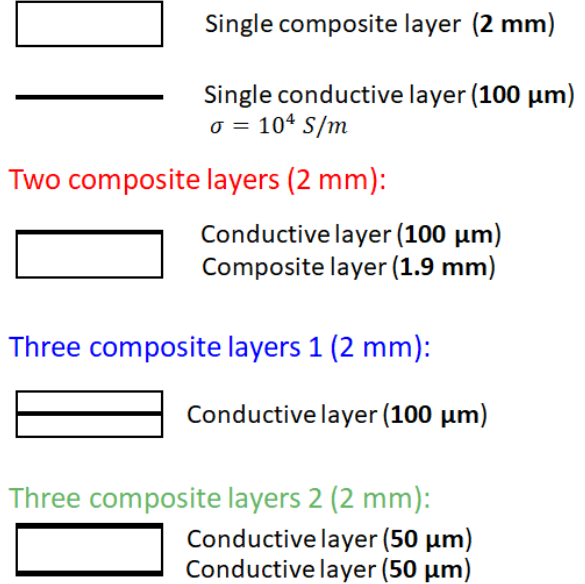


Fig. 8. Different arrangements mixing glass fiber composite and conductive layers

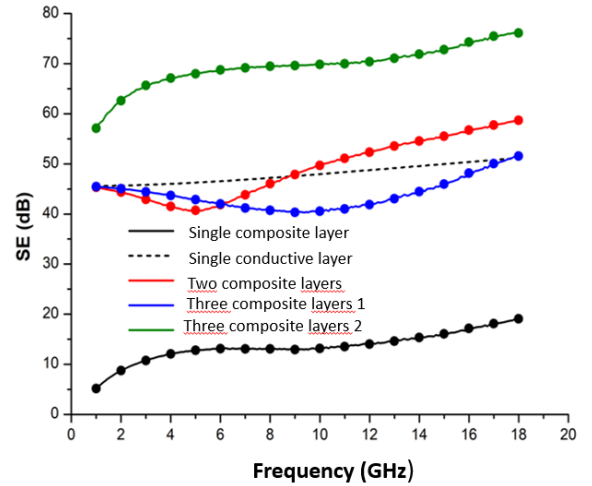


Fig. 9. Shielding effectiveness obtained for the arrangements in Fig.8 (dots : analytical method ; continuous line : numerical method)

Below 1 GHz, eddy currents in the conductive layers of the previous arrangements are not sufficiently high to shield the fields. The skin depth becomes larger than the thickness of the conductive layers. As a consequence a magnetic layer has to be added. Fig. 10 shows the SE of one single 100 μm magnetic layer (case 1) or two 50 μm magnetic layers located at a distance of 1.9 mm (case 2). These results

are obtained either from the analytical solution of a closed loop above a planar shield [16] but could also be deduced from a numerical axi-symmetric 2D model. For this frequency range, no difference exists between case 1 and case 2. The relative permeability is 200. Clearly, for this frequency range, SE does not depend on the electrical conductivity and such a thin magnetic layer is sufficient to shield at low frequency.

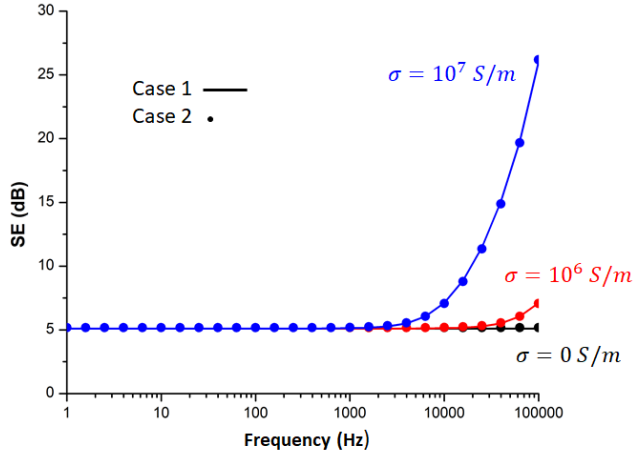


Fig. 10. Shielding effectiveness of magnetic layers ; Case 1 : single 100 μm magnetic layer. Case 2 : two 50 μm magnetic layers

IV. BROADBAND SHIELDING LAYER

Based on the previous considerations and to design a composite sheet that joins lightness and capacity to shield a large frequency band, a tri-layer arrangement is proposed (Fig. 11). It includes a support layer (SL) used for mechanical strength, a metallic magnetic layer (ML) for low-frequency shielding (red in Fig. 11), and a conductive layer (CL) for high-frequency shielding (blue in Fig.11).

The SL, CL, and ML refer to a glass-fiber-reinforced epoxy composite, a graphene sheet, and a mu-ferro sheet, respectively. Mu-ferro is the commercial name for a soft magnetic metal with a relative permeability within 10,000 and 25,000 at direct current [15]. The properties of these materials are resumed in Table II. [17].

TABLE II. PROPERTIES OF THE TRILAYER COMPOSITE MATERIALS

Layer	Conductivity (S/m)	Relative permeability	Relative permittivity
SL (glass fiber/epoxy)	1e-12	1	5
CL (graphene)	6.8e5	1	1
ML (mu-ferro)	4.8e5	14 200 (1 Hz) 1 340 (1 MHz) 1 (> 1 MHz)	1

Trilayer



Fig. 11. Three-layer 2 mm composite shield

The shielding effectiveness of the arrangement is performed with COMSOL software. A suitable homogenization method, described in [17] allows to take into

account such thin sheet in future 3D computations. It is based on an energetic approach [13] and AMSL method [18], considering the trilayer composite as a homogenized layer with effective conductivity and permeability. The computed SE is plotted in Fig. 12 and Fig. 13.

At low frequency, thanks to a high relative permeability, the mu-ferro layer has a SE of 17.6 dB from 1 Hz to 10 kHz that then decreases to 9.5 dB at 1 MHz. The trilayer composite shows both interesting behaviors with the capacity to shield at low frequency thanks to the mu-ferro layer. Above 20 kHz, the decrease of SE with the frequency is compensated by an increase thanks to the graphene layer. At high frequencies, as both graphene and mu-ferro layers are conductive, their SE is high enough. By combining both layers, the SE of the trilayer composite is greater than 75 dB for the whole high frequency range. It should be noted that the value of SE around 1 MHz is not the same on both Fig. 12 and Fig. 13 because the respective electromagnetic problems are not the same: One, in near field, involves a current loop (low frequencies) and the other, in far field, involves a plane wave (high frequencies) [17].

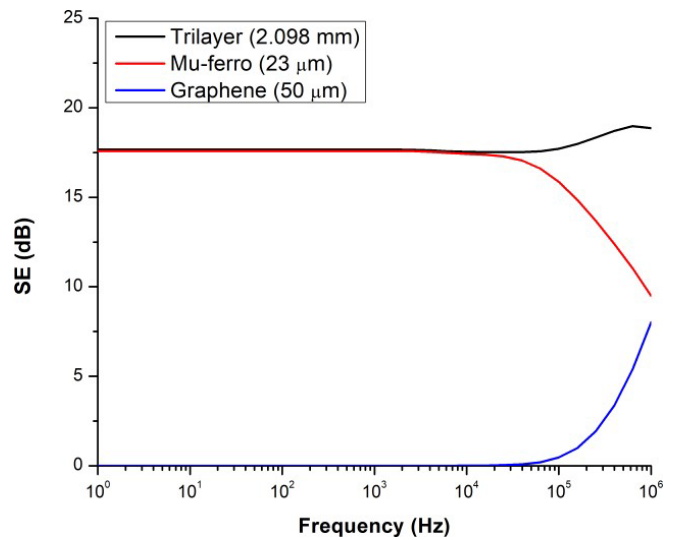


Fig. 12. SE of the three-layer composite (below 1 MHz)

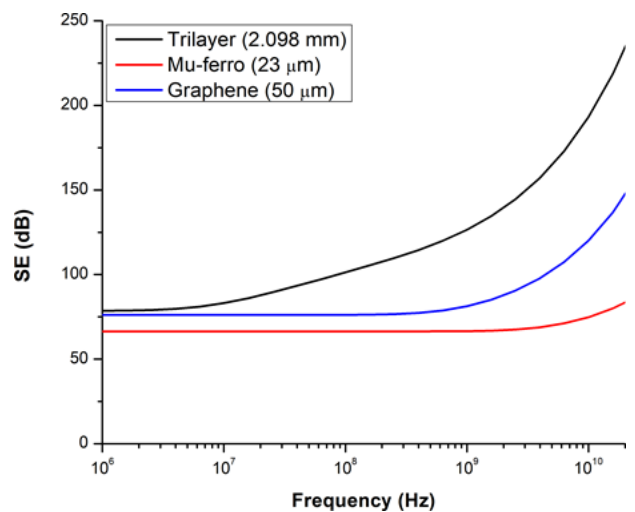


Fig. 13. SE of the three-layer composite (above 1 MHz)

V. CONCLUSION

The work investigated the shielding effectiveness of different composite materials arrangements including nanocomposites. It was shown that a tri-layer combination of glass fiber composites with a magnetic layer and a conductive layer provides a high SE higher than 17 dB above 1 Hz and higher than 75 dB above 1 MHz. An enclosure partially covered by such panels, including the tri-layer arrangement, is being built and preliminary measures will be presented in the conference.

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