Simple Device for Electromagnetic Interference Shielding Effectiveness Measurement

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Abstract—The design, construction, and testing results of a simple flanged coaxial electromagnetic interference (EMI) shielding effectiveness (SE) tester are presented in this paper. This tester is a coaxial holder with uniform diameters that maintain 50 Ohm impedance throughout the length of the device. The ends of the tester are designed to directly attach 10 dB, 50 Ohm, attenuators with standard N-type connectors, which allow practical coupling of the device for installation and measurements. This device was primarily designed to overcome several shortcomings of the ASTM D4935-99 standard SE tester that besides having a relatively complex shape requires relatively large sample specimens for testing. Compared to the frequency band of operation, up to 1.5 GHz, of the ASTM D4935-99 standard coaxial EMI tester, the newly developed SE tester operates in a broader frequency range, theoretically up to 18.2 GHz. The tester was calibrated and the SE of common and new materials was determined through several experiments. The SE results were validated with expected theoretical outcomes.

Index Terms—carbon nanofiber composite, coaxial test holder, electromagnetic interference, reinforced polymer, shielding effectiveness.

I. INTRODUCTION

Electromagnetic interference (EMI) can become a problem when emitted electromagnetic fields interfere with the operation of other electronic equipment. Electromagnetic fields are radiated from sources such as equipment for television, cellular telephone, radio communication, computer, radar, and other devices [1]. EMI could also take place due to distant sources such as radio transmitters, antennas, and lightning, which make incident electromagnetic fields similar to plane waves [2]. Common examples of EMI include disturbances in television reception, mobile communication equipment, medical, military, and aircraft devices, in which interference could disturb or jam sensitive components, destroy electric circuits, and prompt explosions and accidents. For instance, there were five crashes of Blackhawk helicopters shortly after their introduction into service in the late 1980s [3], [4]. The cause of these accidents was found to be EMI in the electronic flight control system from very strong radar and radio transmitters [4]. Furthermore, pilots have reported anomalies with their navigation equipment that seem to be related to EMI generated by use of personal electronics in the airplane [5]. EMI has also been claimed as a possible cause for the TWA [6] and Harrier Jump Jet accidents where the pilot emergency ejector seat was triggered [7].

Given the rapid development in commercial, military, scientific electronic devices and communication instruments, there has been an increased interest in developing materials that could shield against electromagnetic radiation to prevent interference [2]. Current material options that provide effective shielding effectiveness are metals, metal powder, metal-fiber filled plastics, polyacrylonitrile (PAN) nickel coated reinforced polymers, aluminum structures, coatings, nickel and copper metalized fabrics, and, more recently, nanoreinforced polymer composites (NRPCs) [8], [9]. Typical limitations found with materials used for shielding to prevent EMI are associated with corrosion susceptibility, lengthy processing times, high equipment cost for production, difficulty of material utilization to build articles with complicated geometries, limited service life when using conductive layers due to peeling and wear, and high reinforcement concentration. NRPCs, like carbon nanofiber, carbon nanotube, and nanowire reinforced polymer matrices, seem to overcome some of these limitations because they are lightweight materials with design flexibility, corrosion resistance, and suitable for mass production through conventional plastic manufacturing technologies such as extrusion and injection molding.

Measuring reliable EMI SE data at a broad frequency range for newly developed materials is crucial to determine their properties and potential applications. Shielding effectiveness is defined for incident waves that are in transverse electromagnetic mode (TEM), that is, similar to plane waves caused by a distant source. In a coaxial line, a transverse electromagnetic mode (TEM) is present, meaning that the magnetic (H) and electric (E) field vectors are both perpendicular to the direction of current propagation [10]. New nano-engineered and nanoreinforced materials are relatively expensive; hence, the specimen size required for testing its properties should be as small as possible. Currently, there are numerous ways to conduct SE testing that depend on the type of materials being used and their applications [8]. Researchers can make use of several existing standards available to characterize the SE of materials, such as ASTM D4935-99, ASTM ES7-83, MIL-STD-188-125A, IEEE-STD-299-1991, MIL-STD-461C, and MIL-STD-462. It has been reported that using the ASTM D4935-99 standard coaxial holder to measure SE is convenient because of the relatively small specimens required for testing in comparison with military standards, which require 46 cm square samples [11]. However, because of their limited dynamic range and relatively large specimen dimensions, these standards may also be impractical and inadequate for testing some newly developed nanoreinforced materials. The ASTM D4935-99 standard tester and the required material samples are shown in Figure 1. Notice that the dimensions of the required specimens are relatively large.

The ASTM D4935-99 standard device has a complex shape and it is difficult to manufacture. It is a flanged circular coaxial transmission line, with internal conical shape that secures the

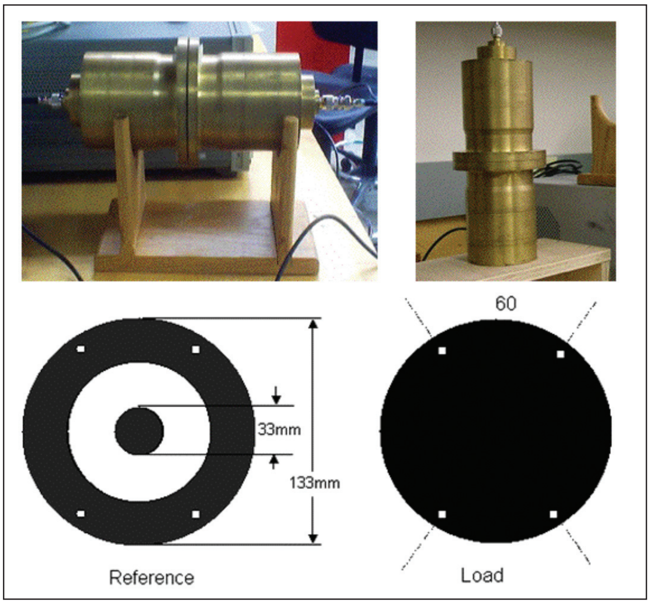

Fig. 1. Top: ASTM D4935-99 coaxial EMI SE tester; bottom: required specimens.

sample and capacitively couples the coaxial conductors. Measurement of insertion loss (IL) or SE using the ASTM D 4935-99 standard tester could also be used to estimate the electric conductivity and the near-field SE of electrically thin specimens [10]. The ASTM D4935-99 standard presents several shortcomings that could generate different results among different labs; some of these differences may be associated with variations in the tester fabrication, given the unclear explanation within the standard on some construction details, surface finish, and dimensions at the ends of the tester where connectors are attached. The dimensions of the ends of the standard device do not allow for a proper fit with standard connectors or attenuators [10]. Some other details that have resulted in slightly different manufactured standard SE testers deal with the coating of the outer surface (application, type, and amount of silver paint). As already mentioned, another issue with the current standard SE tester is the sample size; it requires a disk with a diameter of 133 mm, which seems to be a small sample size when compared to other SE testing methods, but, in the case of NRPC materials like nanowires and newly synthesized nanoparticles, the cost to prepare such size specimens for initial characterization could be prohibitive for research in both academia and industry. Besides that, the mass of the ASTM D4935-99 standard tester is about 18 kg, making it inconvenient for frequent handling during assembling and disassembling.

Due to such shortcomings of the ASTM D4935-99 standard tester, there was a need for an accurate, economical, and easy to manipulate tester that could address the current requirements for SE testing. Similar issues have also been recently addressed by other researchers such as Hong et al. [12] and Sarto et al. [13], who designed new coaxial SE testers and their performances were compared to the standard ASTM D 4935-99 tester. Their results are in agreement within the 50 MHz–1.5 GHz frequency range (working interval of the ASTM device). Hong et al. [13] have shown that by reducing the radius of the total flanged coaxial tester, its working frequency range could be extended to higher frequencies (up to 13.5 GHz in theory). Their tester performed well above 1.5 GHz, but, it seemed to have an awkward characteristic beyond 10 GHz. In Sarto et al. [13], measurements of SE of EMI were performed in the frequency range from 30 MHz to 8 GHz, with satisfactory results. Sarto et al. [14] developed a mathematical model and determined correction factors to consider resonance and other disturbing effects that emerged in the experimental data and that were not considered in their theoretical analysis. The correction factors seek to minimize the resonance peaks that occur when testing thin conducting films deposited on a thick dielectric substrate [13]. In the present study, a simple coaxial SE tester was developed using a similar idea to Hong et al. [13]; however, several improvements were made such us using different dimensions to increase its dynamic range and its ends were machined to couple standard N-type connectors to match commercially available filters and cables. The developed SE tester was calibrated and several materials were tested. Of particular interest is a sample of liquid crystal polymer (LCP) composite with a concentration of 15% weight of vapor grown carbon nanofibers (VGCNF), which was tested to identify its performance in comparison with other common materials.

II. THEORY AND SHIELDING EFFECTIVENESS TESTER DEVELOPMENT

An improved flanged coaxial EMI SE tester with a relatively simple design was constructed and tested in this study. It is a flanged coaxial tester with uniform diameters that maintain 50 Ω impedance throughout the length of the device. The two ends of the tester were designed to directly attach 10 dB, 50 Ω attenuators, with standard N-type connectors, in order to make it more practical and minimize the number of parts and connections in the entire SE testing setup.

A. Theory

The purpose of any shielding effectiveness (SE) test is to determine the insertion loss (IL) due to introducing a material between the source and signal analyzer. SE is determined by measuring the electric field strength levels with both reference (E_R) and load (E_L) specimens; this is without and with the shielding material, respectively:

$$SE = 20\log_{10}\left(\frac{E_R}{E_L}\right) = (dB)_R - (dB)_L \tag{1}$$

and it can also be determined by measuring power,

$$SE = 10\log_{10}\left(\frac{P_R}{P_L}\right). \tag{2}$$

The SE coaxial tester impedance of 50 Ω throughout its length matches the impedance of the signal analyzer, cables, connectors, and attenuators. This impedance was achieved by choosing the diameters "D" and "d" according to (3) to compute the characteristic impedance, Z_0, of a coaxial line:

$$Z_0 = \left(\frac{\eta_0}{2\pi\sqrt{\varepsilon_r}}\right)\ln\left(\frac{D}{d}\right), \tag{3}$$

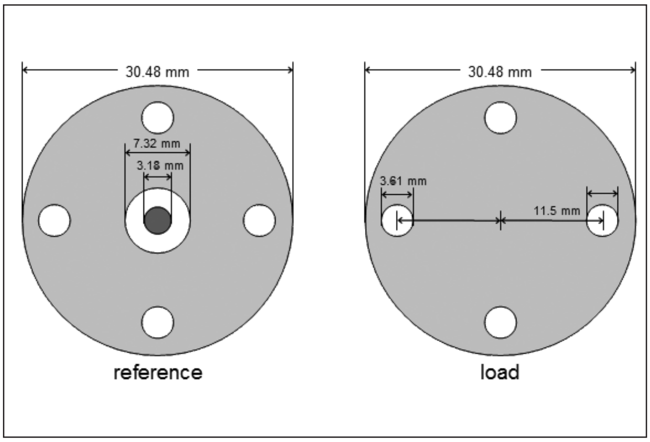

Fig. 2. Reference and load specimens for the newly developed EMI SE tester.

where, η_0 is the free space wave impedance, approximately equal to 377 Ω, "D" is the inner diameter of the outer conductor, "d" is the diameter of the inner conductor, and ε_r is the real part of the relative permittivity of the dielectric material between conductors, which for air (without material) is equal to 1. Applying the previous equation to the coaxial holder and having air as the dielectric material, it is determined that the impedance of the holder is only a function of its dimensions "D" and "d":

$$Z_0 = 60\ \ln(D/d). \tag{4}$$

The upper frequency limit for pure transverse electric mode (TEM) operation is the cutoff frequency f_c of the first higher order mode, which can be computed using equation (5), as explained in [10]:

$$f_c = \left(\frac{n}{\pi}\right)\left(\frac{2c}{D+d}\right), \tag{5}$$

where n is a positive integer, and is equal to 1 for the principal mode, and c is the speed of light, equal to 3×10^8 m/s. Also, for the new SE tester, the following dimensions were chosen to match the dimensions of female N-type connectors of 10 dB, 50 Ω attenuators:

$$D = 7.32\ mm; \quad d = 3.18\ mm. \tag{6}$$

Therefore, it was determined that the characteristic impedance of the tester is 50.0 Ω with a theoretical cutoff frequency of 18.2 GHz.

Figure 2 presents the dimensions of the reference and load specimens required to perform SE tests using the newly developed tester; it requires specimens with outer diameter of 30.48 mm and the inner conductor has a diameter of 3.18 mm. The reference measurement requires two pieces of material, one matching the diameter of the inner conductor, and the other matching the cross sectional area of the flanged section. The load measurement only requires a disk of material with diameter equal to the diameter of the flanges. In both cases, holes were made to pass nylon bolts to attach the two flanged connectors.

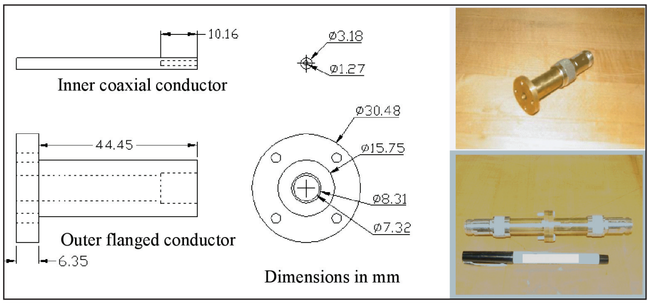

Fig. 3. Manufacturing drawings and photos of the newly developed SE tester.

According to the ASTM D 4935-99 standard [10], an electrically thin material must have a thickness, t_m, less than 0.01 times the electrical wavelength, λ, of the signal transmitted through the specimen being tested. The electrical wavelength is the speed of light divided by the frequency of the signal. If a material is not electrically thin, measurements of SE should be performed throughout the frequency range of interest. Electrically thin materials that are isotropic, and whose electrical properties are independent of the frequency, might require SE measurements at only a few frequencies since their EMI SE characteristics are independent of the frequency [10]. Also, it is known that the transition between near-field and far-field occurs at about $\lambda/(2\pi)$ from a dipole source. Table 1 presents the maximum thickness of a specimen to be considered electrically thin at the specified frequencies. Tests with coaxial SE testers are in the far-field region because the distance between the source and receiver is more than a quarter of the wavelength of the highest frequency used in the tests. If needed, near-field SE can be determined from far-field data for electrically thin materials [12]. With the newly developed simple EMI SE tester, a specimen that is 0.165 mm thick or less will be considered a thin material at frequencies up to 18.2 GHz.

B. Manufacture of a Simple EMI SE Device

The new electromagnetic interference SE device consists of two identical flanged parts that are clamped together, to hold the outer part of the testing specimen, and two concentric rods that hold the circular central part of the reference specimen. The

TABLE 1. ELECTRICALLY THIN MATERIAL, WAVELENGTH, AND NEAR-TO-FAR-FIELD TRANSITION.

Frequency f (GHz)	Maximum thickness to be an electrically thin material, t_m(mm)	Wavelength λ (mm)	Near-to-far-field transition (mm)
1	3.000	300.0	47.75
5	0.600	60.0	9.55
13.5	0.222	22.2	3.54
18.2	0.165	16.5	2.62

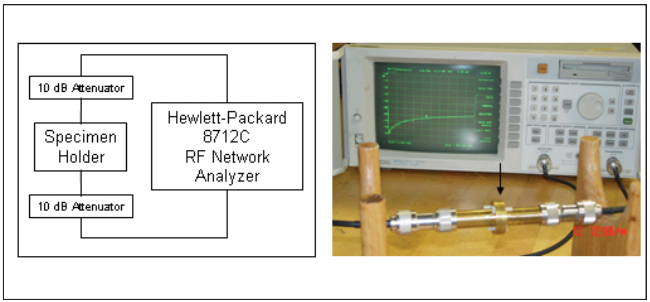

Fig. 4. Setup of EMI SE testing system.

flanged conductors are attached using four nylon bolts. Figure 3 presents the drawings and pictures of the SE tester, showing the 10 dB attenuators attached to it. The flanged parts have threaded ends designed to couple standard N-type connectors, like the ones of the attenuators and cables. Manufacturing of the tester was performed using alloy 360 brass rods.

The manufacturing process of this new EMI SE tester was much simpler than the ASTM D 4935-99 standard device shown in Figure 1, its dynamic range is much higher, it is lighter, less costly, and easier to manipulate by the researcher [15].

Figure 4 presents a diagram and picture of the setup used to conduct experiments. A vector network analyzer is attached to the ends of 10 dB attenuators connected at both ends of the tester. All testing was conducted with attenuators unless otherwise specified.

Shielding effectiveness can be obtained from the transmission measurements of the load and the reference specimens, and it equals the transmission of the reference (dB) minus the transmission of the load (dB) specimens, as indicated in (1). The reference and load specimens need to be of the same material and thickness. Therefore, it is imperative that SE testing be performed using both the reference and the load specimens. Several reports consider using air as the reference material. However, doing so yields an insertion loss of 0 dB for the reference; therefore, the SE of the sample is the negative of the transmission of the load specimen. As a consequence, this practice does not provide accurate results for absolute SE measurements.

Using the newly developed SE tester, the transmission readings without material (air) between the flanges are shown in Figure 5. It can be observed in the figure that readings of −20 dB and 0 dB were obtained with and without attenuators, respectively, indicating good performance of the SE tester with an expected impedance match of 50 Ω. The results indicate proper operation up to approximately 11 GHz. However, there is a resonance peak at about 12 GHz, which closely corresponds to the expected resonance frequency for a radial transmission line mode in the space between the flanges. Consequently, the newly developed simple EMI SE tester seems to perform satisfactorily up to 11 GHz.

C. Calibration of the EMI SE Tester

A commercial conductive gold film, AGHT-4, with thickness of 0.18 mm, with 4.5 ohms/square surface resistivity, was used to calibrate the SE tester. In the case of a sample with thickness t, conductivity σ, complex permeability $\mu = \mu' - j\mu''$, and complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$, which is also coated on each side with conducting thin films of resistance per square R_A and R_B, the shielding effectiveness (SE) in decibels at normal incidence can be computed from transmission line theory as:

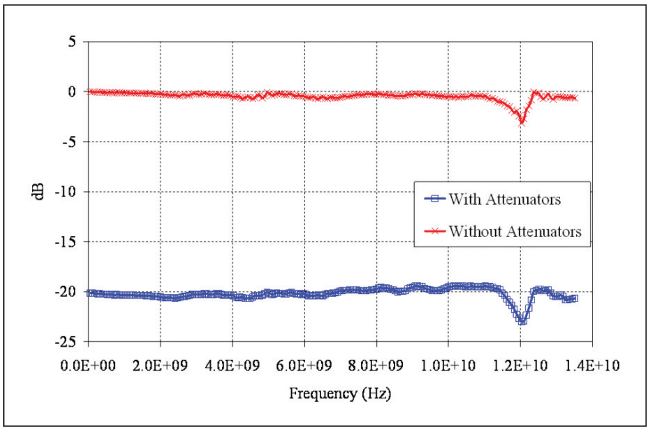

Fig. 5. Transmission readings without sample material (air between flanges).

$$SE = 10\log_{10}\left(\frac{P_{inc}}{P_{trans}}\right) = -20\log_{10}\left|\frac{(1+\Gamma_i)Z_L}{Z_L\cosh\gamma t + \eta\sinh\gamma t}\right|, \tag{7}$$

where

$$Z_L = \left(\frac{1}{R_B} + \frac{1}{\eta_0}\right)^{-1} \tag{8}$$

is the combined wave impedance of free space and the second thin film,

$$\Gamma_i = \frac{Z_i - \eta_0}{Z_i + \eta_0} \tag{9}$$

is the electrical field reflection coefficient at the front surface,

$$\gamma = \sqrt{j\omega\mu\sigma - \omega^2\mu\varepsilon} \tag{10}$$

is the complex propagation factor of the bulk material making up the layer,

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\,\Omega \tag{11}$$

is the wave impedance of free space, and

$$\eta{=}\sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \tag{12}$$

is the complex wave of the bulk material. The quantity

$$Z_i = \left(\frac{1}{R_A} + \frac{1}{\eta}\,\frac{\eta\cosh\gamma\ t + Z_L\sinh\gamma\ t}{Z_L\cosh\gamma\ t + \eta\sinh\gamma\ t}\right)^{-1} \tag{13}$$

is the wave impedance looking into the front surface. In many cases, several simplifications can be made; for instance, when the thin film coatings are absent, the $1/R_A$ and $1/R_B$ terms can

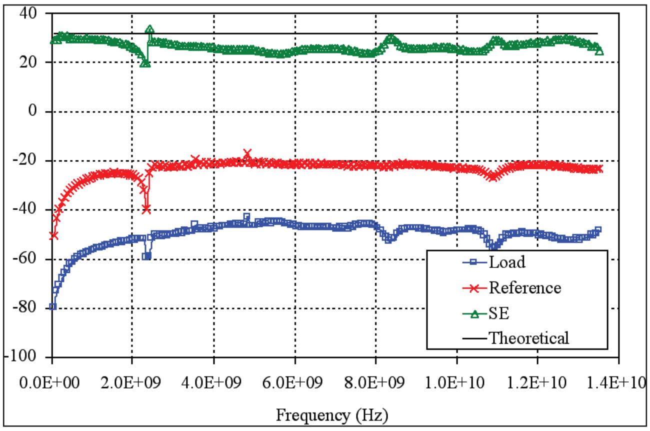

Fig. 6. EMI SE results for AGHT-4.

be omitted; for nonmagnetic dielectric materials, the permeability reduces to $\mu = \mu_0$.

In the case of a single thin film alone, with sheet resistance R_A, the thickness of the film and any supporting substrate is insignificant compared to the wavelength, t can be set to zero, and the above equations reduce to

$$SE = -20 \log_{10} \left| \frac{2R_A\eta_0}{2R_A\eta_0 + \eta_0^2} \right| . \qquad (14)$$

In the case of the gold film with a value of R_A equal to 4.5 ohms/square, used for the calibration, a value of 32.6 dB SE is theoretically expected, computed using (11) and (14). The EMI SE specifications of the AGHT-4 film according to the manufacturer, CPFilms Inc., are in the range between 24 and 44 dB. A film AGHT-4 from CPFilms Inc. was tested using the developed simple EMI SE tester and the results are presented in Figure 6.

Except at a frequency of about 2.4 GHz where a resonance peak occurs, in all the range of frequencies up to 13.5 GHz the SE of the film was in the 24–40 dB interval specified by the manufacturer. Therefore, acceptable EMI SE values were obtained with the new SE tester using an AGHT-4 film for calibration. It should be noted that up to 1.5 GHz (upper limit of the ASTM D 4935-99) the SE value is 32 dB.

D. Experiments

Different samples were prepared to further elucidate the potential of the developed tester. The following list presents the materials that were prepared and tested to determine their EMI SE:

a) Low-density polyethylene (LDPE) sheet with thickness of 1.5 mm.
b) Mylar (PET) with thickness of 0.18 mm.
c) Aluminum foil with thickness of 0.015mm.
d) 15% weight VGCNF liquid crystal polymer (LCP) sheet with thickness of 1.25 mm.

In the case of the LDPE (HXM-50100) sample, pellets with a density of 948 kg/m^3 and a melting temperature of 135°C were provided by Chevron Phillips Chemical Company. The pellets were hot pressed using a hydraulic press into sheets of 1.5 mm thickness. Commercial Mylar and aluminum foil were used with the provided thickness. In the case of the VGCNF reinforced LCP sample, VGCNFs (Pyrograph III PR-19-from Applied Sciences Inc.) with diameters ranging from 100 to 200 nm and lengths from 30 to 100 μm were used. Since the as received CNFs contain impurities such as metal catalyst and amorphous carbon, CNFs were purified using the method developed by Lozano et al. [16]. The thermo tropic liquid crystalline polymer (LCP), Vectra® A950 was supplied by Ticona. The preparation of the composite material consisted of mixing the nanofibers with the LCP in a Haake Rheomixer 600 miniaturized internal mixer. The mixing was performed at 285°C and 90 rpm for 15 min. Then, the composites were pressed at 300°C at a pressure of 4000 psi for 1.5 min. Samples with a thickness of 1.45 mm were obtained [15]. Reference and load samples were then cut as illustrated in Figure 2.

III. RESULTS AND DISCUSSION

Figure 7 shows the SE of a low density polyethylene (LDPE) sheet ($t = 1.5$ mm). It can be observed that the reference reading is much lower than the -20 dB attenuation generated by the two attenuators, which indicates that assuming 0 dB for the reference reading generates incorrect results. For example, assuming 0 dB for the reference reading in Figure 7, a SE of -30 dB would be reported, which is an incorrect value because it is known that the SE of LDPE is approximately 0 dB since it is transparent to electromagnetic interference.

Also, as shown in Figure 7, the EMI SE of a Mylar (PET) sheet ($t = 0.18$ mm) is close to 0 dB, as theoretically expected, indicating the transparency of Mylar to EMI. This is another example that shows why the reference value has to be measured in order to determine correct absolute SE values. The SE value of 35 dB for pure PET reported by Glatkowski, et al. [9] was probably obtained by assuming a zero value for transmission reference reading (air reading).

The EMI SE of aluminum foil resulted in about 40 dB, and it is also presented in Figure 7. An aluminum plate was also tested; but, its SE was out of the operating range of the VNA and measurements became meaningless. The reason for this is that the resistivity of aluminum plate is $R_A = 2.85 \times 10^{-8}$ ohms/square and yields a SE of 196 dB.

Figure 7 also shows the SE of a liquid crystal polymer (LCP) composite with a concentration of 15% weight of vapor grown carbon nanofibers (VGCNF). The thickness of the VGCNF/LCP was 1.25 mm and the SE obtained is close to 30 dB, indicating a performance similar to the aluminum foil. This nanotechnology material has good EMI SE properties which potentially make it suitable for EMI applications.

As mentioned above, the transmission of the reference sample readings are critical when experimentally obtaining SE values. Figure 8 shows reference sample readings for the materials tested. Reference sample readings have a strong dependence on thickness and conductivity. For example, as shown in Figure 8, the non-conductive LDPE with a thickness of 1.5 mm has a smaller reference value as compared to non-conductive PET with a thickness of 0.18 mm. Likewise in the case of the aluminum plate (1.53 mm thickness) which has a smaller reference value when compared to the aluminum foil. However, an exception occurs with the 15% weight nanofiber reinforced liquid crystalline polymer. This sample has a surface resistivity

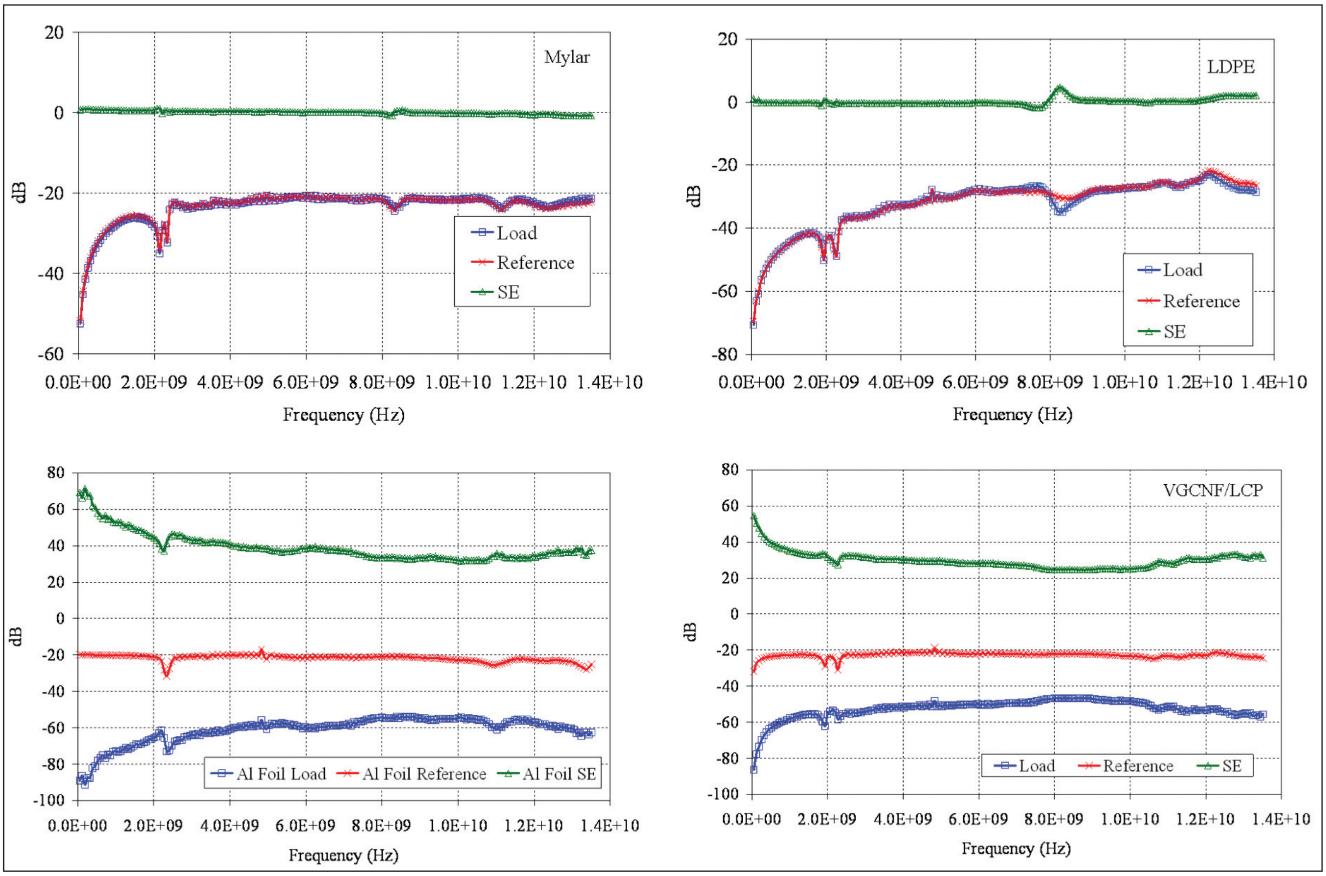

Fig. 7. Reference and load measurements and SE of several materials.

of 410 ohm/sq and a thickness of 1.25 mm. The surface resistivity of the AGHT-4 is 4.3 ohm/sq with a thickness of 0.17 mm. Given the thickness and the resistivity value of the VGCNF/LCP sample, a lower reference value was expected, but Figure 8 shows that the VGCNF/LCP sample has a higher reference reading than the AGHT-4. As explained by Yang et al. [15], in the case of nano-reinforced polymers, a strong contribution from the multiple reflection mechanism is observed, which increases the overall SE of the material.

As shown in Figure 8, only air and aluminum foil have a reference reading of 0 dB. This observation summarizes the need to perform the reference sample test instead of assuming 0 dB for reference when measuring the SE of any material.

Several resonance effects are observed in the region of 2.2 GHz and 4.4 GHz which correspond to the total length of $\lambda/2$ and λ for the flanged tester measured from the interfaces with the N-type connectors. This indicates that there is an impedance discontinuity at the interfaces of the connectors, which needs to be compensated for in future designs. Future work consists on researching the EMI SE characteristics of numerous nanoreinforced materials and developing an understanding of the SE mechanisms involved in nano-reinforced materials.

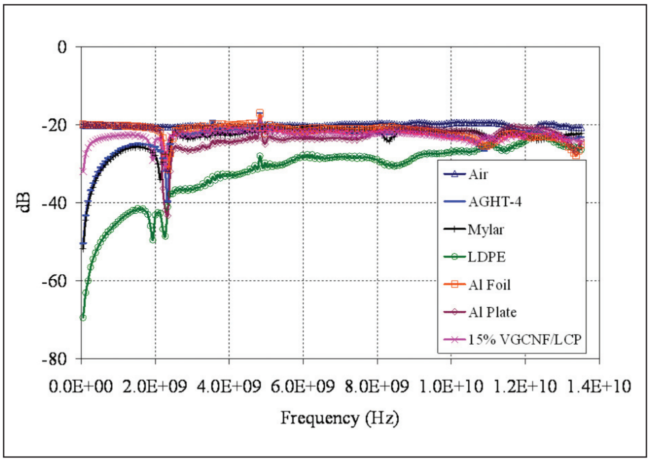

Fig. 8. Reference measurements for different materials.

IV. CONCLUSIONS

The design, construction, and testing results of a simple flanged coaxial electromagnetic interference (EMI) shielding effectiveness (SE) tester was developed in this study. The tester was primarily designed to overcome several shortcomings of the ASTM D4935-99 standard tester, such as its relatively large sample dimensions, complexity of testing fixture, and handling difficulty. Theoretically, the new tester could operate up to 18.2 GHz, but it was experimentally tested up to 13.5 GHz. Measures of SE with the newly developed simple EMI SE tester were satisfactory to identify materials with potential use in electromagnetic interference or similar applications. This simple EMI SE tester requires sample specimens with relatively small size, making it attractive in research applications where the testing material is expensive or difficult to obtain. Having developed, constructed, calibrated, and tested a simple EMI SE tester in this study will allow additional research in EMI SE characterization of new materials already available or currently being developed.

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BIOGRAPHIES

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Manuscript received on August 26, 2008. Support from AFOSR/SPRING program under grant number 9550-06-1-0419 is gratefully acknowledged.

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