

# Enhanced electromagnetic interference shielding through the use of functionalized carbon nanotube-reactive polymer composites

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**Abstract**— We report on a new principle yielding enhanced electromagnetic shielding, using as an example, a composite comprised of carbon nanotubes (CNT) integrated with a Reactive Ethylene Terpolymer (RET). Such composites were synthesized through the chemical reaction of the functional groups on the CNT with the epoxy linkage of the RET polymer. The main advantages of these composites incorporate good dispersion with low electrical percolation volume fractions (~0.1 volume %), yielding outstanding microwave shielding efficiency for EMI applications. The shielding effectiveness was characterized for both single-walled and multi-walled CNT based composites and was much enhanced in the former. The specific roles of absorption and reflection in determining the total shielding, as a function of the nanotube filling fraction, is also discussed.

**Index Terms**— Carbon nanotubes, polymer composites electromagnetic interference shielding, functionalization

## I. INTRODUCTION

THE advent of carbon nanotubes (CNTs) and recent studies in polymer-CNT composites[1] has motivated study of their use for Electromagnetic Interference (EMI) applications as light-weight, high shielding efficiency materials. At the very outset, in EMI shielding, the effects of both reflection and absorption of the incident EM radiation have to be considered[2]. The intensity of the reflected radiation (R) is related to the difference of the characteristic impedances (Z) of the incident medium (i.e., air of impedance  $Z_a$ ) and the material ( $Z_m$ ) through  $R = \left(\frac{Z_a - Z_m}{Z_a + Z_m}\right)^2$ . The absorption (A) is

quantified through the skin depth ( $\delta$ ), the extent to which the radiation, of frequency  $f$ , penetrates the material, through  $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$ , where  $\mu$  is the magnetic permeability and

$\sigma$  the electrical conductivity. Consequently, while metallic materials (with low  $Z_m$  and high  $\sigma$ ) are obviously efficient shielding materials, issues such as cost and bulk preclude their wide scale application. Such issues have encouraged the use of polymers where the intrinsic poor conductivity could be compensated through the use of filler materials which form a conducting network. (It is to be noted that electrically conducting polymers are currently expensive, difficult to process, and need considerable improvement in their mechanical properties[3]).

While carbon based materials, such as carbon black and fibers, have previously been used in polymer composites[4], their widespread use is limited due to a maximum loading capability, beyond which there is embrittlement. CNTs are then more attractive candidates for filler materials in composites, primarily due to their large aspect ratio and tunable electrical conductivity, which enables electrical percolation to be achieved with *very small* amounts of nanotubes. For example, we have calculated from the excluded-volume percolation theory of rod-like systems [5, 6] (Figure 1a) that single walled CNTs (SWNTs) with an aspect ratio of ~ 5000 (which corresponds to a length of 5  $\mu$ m and a diameter of ~ 1 nm), when dispersed uniformly into a non-conducting polymer enable a conducting pathway at a volume fraction of ~ 0.01 %. Our results on SWNT-RET polymers, which we report in this paper, yield values very close to the optimal considerations (as indicated by the ★ in Fig. 1a).

In our experiments, we have also observed higher values of the EMI shielding efficiency (SE) at a lower loading fraction of SWNTs (i.e., ~ 30 dB at 4.5 vol % of functionalized SWNTs) compared with literature. A few examples of the SE values from literature include: (i) < 17 dB with 15 vol % SWNTs in SWNT/epoxy composites[7, 8] (ii) < 20 dB with 11.6 vol % SWNTs in SWNT/polyurethane composites at 8 GHz[9], (iii) ~ 20 dB with 8 vol % SWNTs in SWNT/vinyl acetate based composites at 8 GHz[10]. The superior performance of our particular composites could possibly be due to the uniformity of dispersion obtained through functionalization along with a larger aspect ratio. Additionally, our values are comparable to those obtained in CNT films, of ~ 28 dB at 10 GHz[11]

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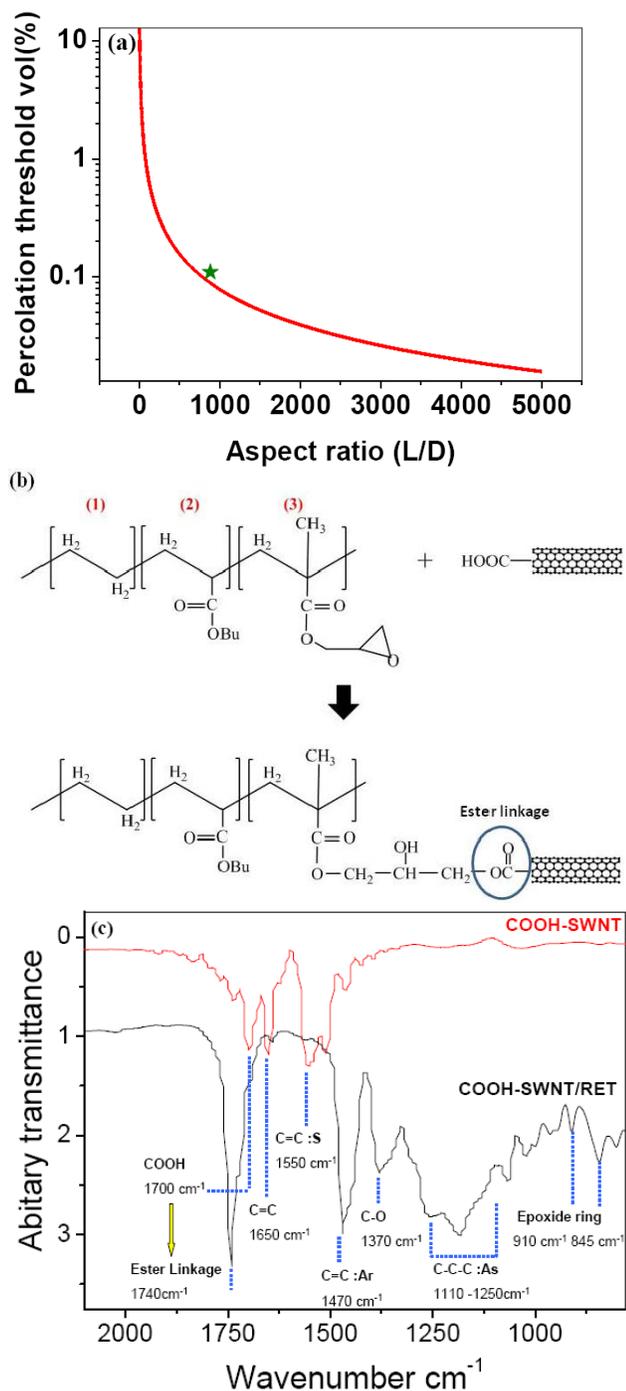


Fig. 1. (a) A high aspect ratio, pertinent to carbon nanotubes, enables very low threshold volume fractions for electrical percolation. The threshold-aspect ratio curve, for uniformly dispersed nanotubes, has been simulated from percolation theory where the \* indicates results from our experimental measurements.

(b) Schematic diagram of the reaction between functional groups on the CNT with the epoxy groups of the Reactive Ethylene Terpolymer (RET) constituted from (1): polyethylene, (2) methyl-methacrylate, and (3) epoxide functional groups. While (1) and (2) contributes to the mechanical robustness, (3) is used for forming ester linkages to the -COOH groups on the functionalized nanotubes for enhanced bonding and dispersion.

(c) Fourier Transform Infrared (FT-IR) Spectrographs comparing the (i) bare -COOH functionalized SWNT (COOH-SWNT) with the (ii) functionalized single walled CNT-RET (COOH-SWNT/RET) composites. The evidence of esterification, and bonding, between the functionalized nanotubes and the RET is seen in the energy up shift of the 1700 cm<sup>-1</sup> peak to 1740 cm<sup>-1</sup> (Ar: Aromatic, S: Symmetric, As: Antisymmetric)

## II. EXPERIMENTAL PROCEDURE

For large scale processing, it is desirable[1] to ensure effective *mixing* and dispersion of the CNTs within the polymer. The consequent enhanced nanotube-polymer interactions which are obtained, for example, through chemical functionalization, enable low critical volumes for electrical percolation. In this paper, we tackle such issues in detail and also consider the relative influences of both single walled and multi-walled carbon nanotubes in terms of their shielding efficiency.

We chose for our experiments, a composite of CNTs and a Reactive Ethylene Terpolymer (RET: Elvaloy 4170, density 0.94g cm<sup>-3</sup>) constituted from (1) polyethylene, (2) a polar methyl-methacrylate group, and (3) epoxide functional groups – Fig. 1b. While (1) and (2) contribute to the mechanical characteristics (e.g., elastomeric properties) and corrosion resistance underlying the utility of RET as a hot-melt adhesive and coating, the epoxy group has high reactivity[12] and is amenable for effective anchoring of the ring bonds with functional groups(e.g. -OH, COOH, -NH<sub>2</sub> etc.) on the CNTs. The underlying rationale is that the epoxide ring rupture [13] on the RET would be facilitated by the -COOH groups on the functionalized nanotubes (Figure 1b) and then contribute to bonding of the COOH on the SWNT with the epoxy group of the RET.

The effects of both pristine and carboxyl functionalized SWNTs (average diameter 1-2 nm, length 5-20 μm, 90% purity, and density 2.1g cm<sup>-3</sup>) and multi-walled carbon nanotubes (MWNTs, average diameter 140 nm, length 5-9 μm, 90% purity, and density 1.7g cm<sup>-3</sup>) were examined. A mixture of sulfuric and nitric acids (in a 3:1 ratio) was used both for nanotube surface functionalization, with -COOH groups, and for removing impurities[12]. Subsequently, the CNTs were rinsed with deionized water, and then dried at 60 °C for 10 hours. The MWNTs and SWNTs were then dispersed in toluene with sonication for 20 minutes. (It was typically seen, through atomic force microscopy characterization that the above procedure, including sonication, reduces the average length of the SWNTs to ~ 4.3 μm, with a bundle diameter ~4.8 nm, resulting in an aspect ratio of ~ 880. On the other hand, the MWNTs have an average length of 5.6 μm, with a bundle diameter ~190 nm, yielding an aspect ratio of ~ 30). The RET was then added to toluene solvent with heating to ~ 60 °C for 2 hours and subsequent stirring. The CNT dispersion was then added to the RET solution and sonicated again for ~ 50 minutes. To remove excess solvent, the mixture was stirred, at 60 °C for 3 hours, poured into glass dishes and then evacuated in vacuum (10<sup>-3</sup> Torr) for 12 hours. Subsequently, a hot press was used to fabricate the composites into desired thickness.

Fourier Transform Infrared (FT-IR) Spectroscopy (Nicolet Magna-IRTM Spectrometer 550) was used to provide proof of covalent bonding [14] between the CNTs and the RET as evidenced by the energy up-shift of the C=O stretch (at 1700 cm<sup>-1</sup>) - due to the carboxyl group of the -COOH functionalized SWNT- to 1740 cm<sup>-1</sup> due to the formation of an ester linkage (Fig. 1c). The exact location of the functional groups would depend on the defect density on the nanotubes and can be manipulated[15].

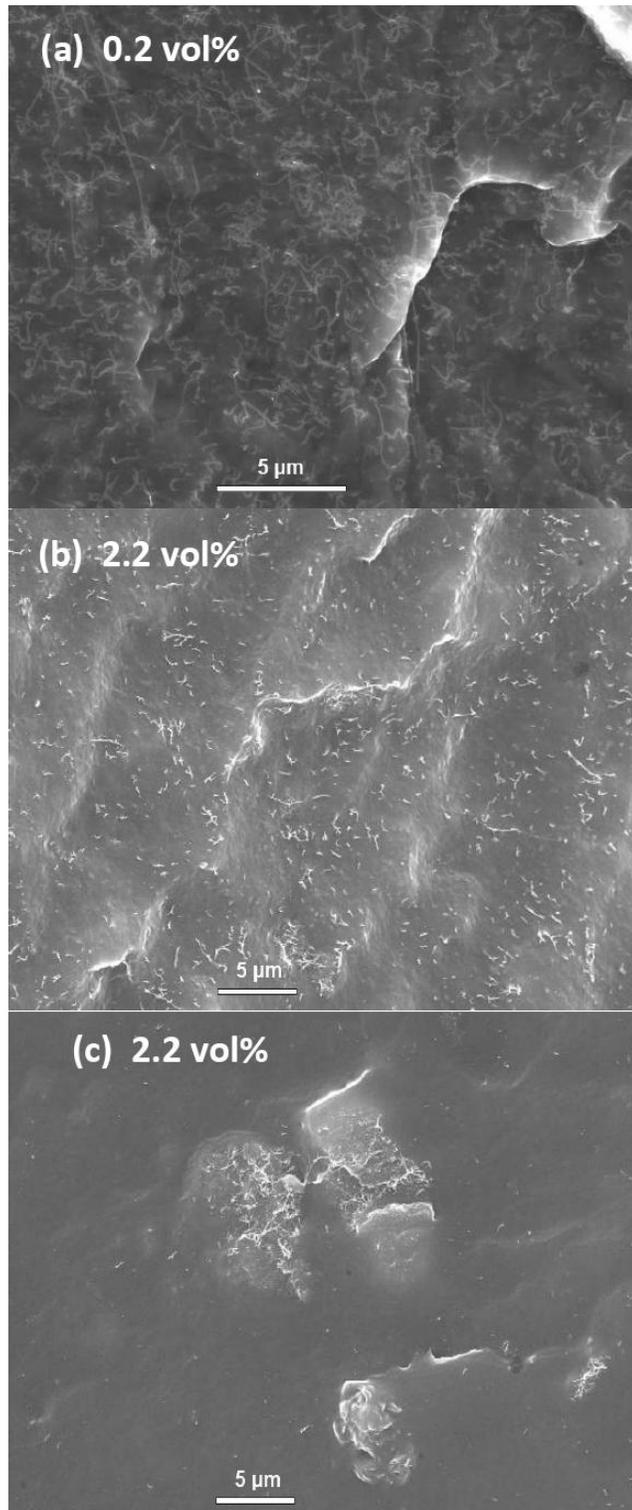


Fig.2. Uniform dispersion of functionalized SWNTs in the RET polymer is indicated, through Scanning Electron Microscope (SEM) micrographs, at both (a) 0.2 volume % and (b) 2.2 volume % filling fractions of the SWNTs. On the other hand, (c) non-functionalized SWNTs dispersed into the RET matrix exhibit clumping.

However, if the defects are considered to be randomly dispersed, isotropic bonding of the CNTs with the polymer matrix is implied yielding uniform dispersion and mixing. While different strategies have been used for homogeneous dispersion[16, 17], it has been generally observed that covalent

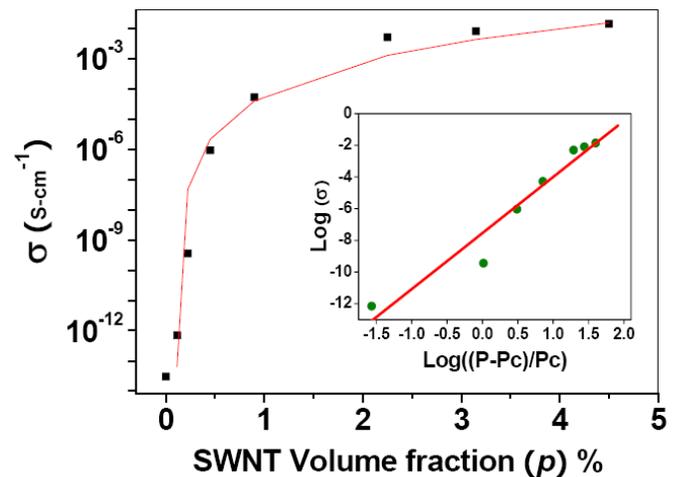


Fig.3. The electrical conductivity of the functionalized SWNT-RET composites follows a power law characteristic of percolation like behavior. The inset shows log-log plot of  $\sigma$  vs.  $(\rho - \rho_c)/\rho_c$ , exhibiting a threshold volume fraction,  $\rho_c \sim 0.11\%$  and a slope  $\sim 3.4$ .

stabilization [18] and intimate chemical reaction[14, 19] could be beneficial for enhanced electrical conductivity and electromagnetic shielding effectiveness. In line with the above reasoning, we have indeed observed a more uniform dispersion using functionalized SWNTs for both low (Fig. 2a) and high (Fig. 2b) CNT filling fractions, as observed through the Scanning Electron Microscopy (SEM: Phillips XL30) images of the fracture surfaces of the CNT/RET composite. The beneficial effects of our proposed functionalization scheme are also evident through a more homogeneous dispersion of the CNTs in the polymer matrix in comparison to the clumping observed (Fig. 2c) when un-functionalized CNTs are mixed into the polymer. (Note that more rigorous quantification of uniform dispersion is challenging due to the different length scales involved[20]). A thickness of  $\sim 2$  mm of the CNT-RET polymer composite was used for all measurements reported in this paper.

The composites were treated with oxygen plasma (Oxford Plasmalab 80 RIE) prior to electrical contacting of the surface. Subsequently, 50nm of gold were sputtered on for the contacts. The four-wire resistance method was used to measure the resistance (R) for composites with  $R < 1G \Omega$ , using the Keithley 487 picoammeter and the Keithley 2400 Sourcemeter. For such measurements, we used samples with rectangular cross-section (5 mm wide X 2 mm thick, typically). The outer current leads were separated by 25 mm while the inner voltage leads were separated by 15 mm. For higher resistance ( $> 1G \Omega$ ) composites, two point measurements using the Agilent B1500A semiconductor device analyzer, with triaxial probes were used.

We next monitored the SE of the synthesized composite in the microwave frequency range (8.2-12.4 GHz: X-band) using a two-port vector network analyzer (Agilent 5242A PNA-X). The X-band is used for both civil and military communications with applications as diverse as weather monitoring, vehicular detection and air traffic control and defense tracking[21]. The desired amount of conducting filler is generally dependent on

the required SE, where  $SE = 10 \log \frac{P_i}{P_t}$ , where  $P_i$  and  $P_t$  are the magnitudes of the incident and transmitted power densities and

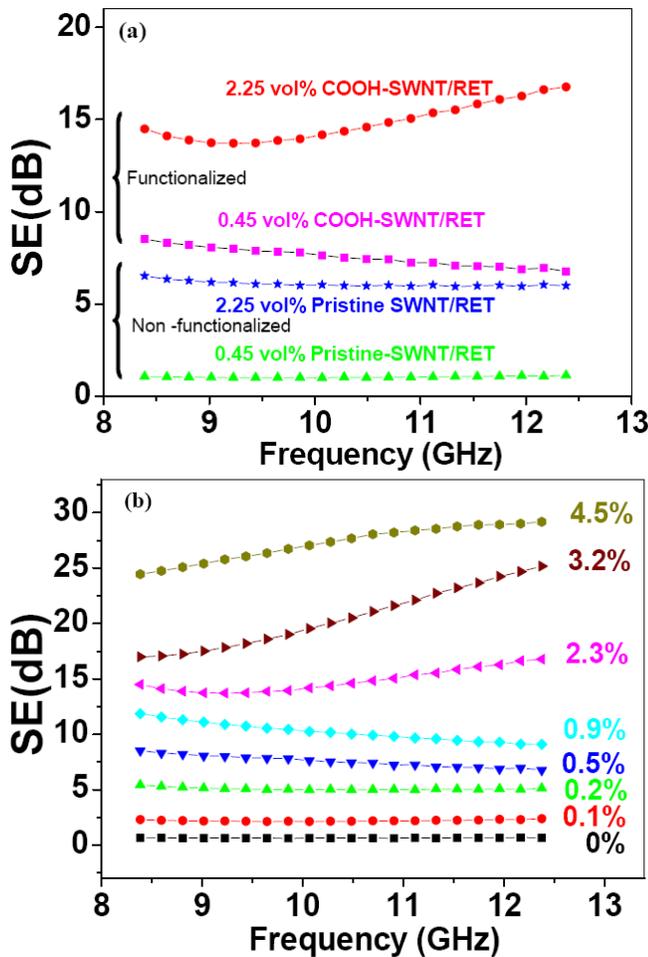


Fig.4. (a) An enhanced shielding effectiveness (SE) has been observed for the chemical functional group reaction enhanced SWNT-RET polymer composites(COOH-SWNT/RET) compared to non-functionalized SWNT-RET composites (Pristine SWNT/RET), (b) The SE increases with increased filling fraction (depicted in %) of the SWNTs

were measured through the network analyzer. The initial calibration was performed using the TRL (Thru-Reflect-Line) method [22] which is an improvement over the traditional OSL (Open-Short-Load) type calibration techniques. Using the TRL method, the “Thru” measurement was first performed by connecting the two 15 cm waveguide sections directly and measures the total loss and phase delay of the setup, in the absence of the sample. For the “Reflect” calibration, an aluminum short/load was placed between the waveguide sections, while the “Line” calibration was done through the insertion of a quarter-wave section of waveguide (WR-90). The latter measurements accurately delineate the plane of the DUT (device under test) through a consideration of the reflections and other losses prevalent in the test setup including the cabling, waveguide segments, and transitions, in the absence of a sample. The scattering parameters obtained from the calibration were then used for the baseline.

The CNT-polymer composite was pressed into a sample holder of size 0.9” X 0.4” - standard size for the X-band frequency range. The composite loaded holder was inserted between two 15 cm lengths of WR-90 X-band waveguide to

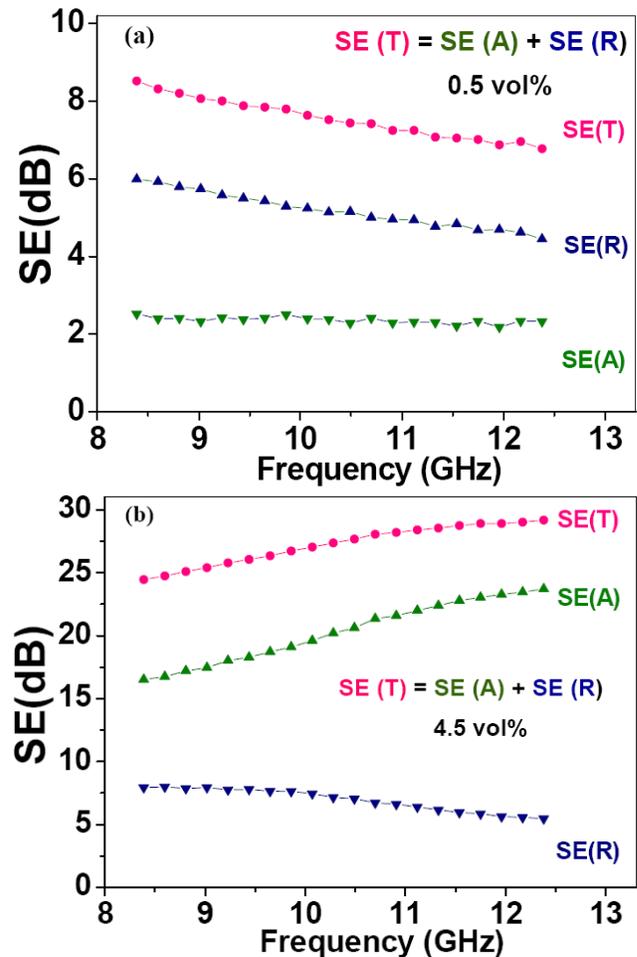


Fig.5. The total shielding efficiency, SE (Tot), can be decomposed into contributions from reflection, SE (R) and absorption, SE (A) through a consideration of the frequency dependence. (a) Reflective losses dominate the total SE for low (e.g., ~ 0.5 volume %) nanotube filling fractions, while (b) the absorption is more important at larger (e.g., ~ 4.5 volume %) fractions.

mitigate the near-field effects of the coax to waveguide transitions. It should be noted that while the measured SE, in our experiment, is not identical to the plane wave, free space SE due to the confinement and wave polarization effects[23], it can be shown that the difference is negligible[8, 10].

### III. RESULTS AND DISCUSSION

We observed through DC electrical conductivity ( $\sigma$ ) measurements on the SWNT-RET composite electrical percolation like behavior (Figure 3), which could be fit to a power law of the form:  $\sigma \sim \sigma_0(p - p_c)^\beta$ , where  $p_c$  is the percolation threshold volume fraction ( $p$ ) and  $\beta$  a critical exponent.  $\sigma_0$  is a constant for a particular filler-polymer combination. The obtained values of  $p_c$  (~0.11%) and  $\beta$  (~3.4) from the best fit of the conductivity data to the log-log plots of the power laws in the inset to Fig. 3 are appropriate for a thick film resistor configuration with elongated fibers[24]. It should be noted that at higher frequencies, capacitive coupling,

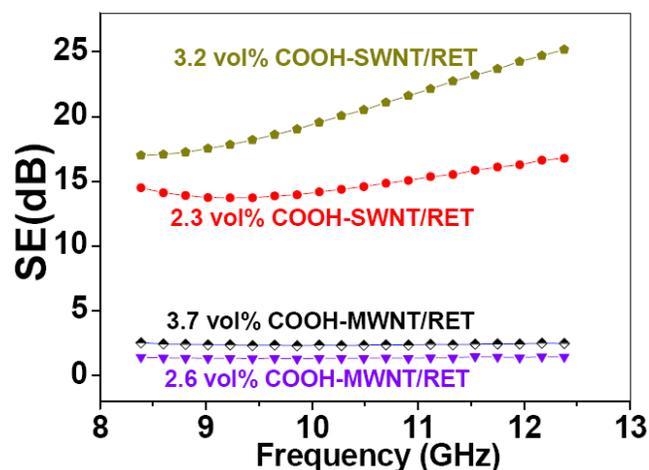


Fig.6. The SE is generally larger for the SWNT based composites compared to the MWNT based composites and is indicative of the influence of the aspect ratio (SWNT ~ 880, MWNT ~ 30) in determining the percolation and the SE.

in addition to continuous electrical paths between the CNTs can contribute significantly to the electrical conductivity [25].

We noticed that an order of magnitude higher SE was obtained for the COOH- functionalized CNTs compared to a dispersion of non-functionalized SWNTs in the RET polymer matrix (Fig. 4a). Such an effect is presumably due to the effect of uniform dispersion resulting in homogeneous connectivity of the SWNT fillers. As expected, the SE increases with increasing amount of SWNT filler (Fig. 4b).

Probing into the dependence of the SE vs. frequency, we notice (e.g., Fig. 4), that at low (/high) CNT filling fractions the SE decreases (/increases) with frequency while exhibiting a minimum at intermediate filling fractions (e.g., ~ 2.3 volume % - Figure 4b). One can understand such variations by considering the total effective shielding effectiveness,  $SE(Tot)$ , of the composite as the sum of the contributions due to both the reflective (R) and the absorptive (A) components, through  $SE(Tot) = SE(R) + SE(A)$ , where  $SE(R) = -10 \log(1-R)$  and  $SE(A) = -10 \log\left[\frac{T}{1-R}\right]$  [21, 26]. The R, A, and the T

(transmission) were then obtained through the determination of the S-parameters using the vector network analyzer, where  $T = |S_{21}|^2$ ,  $R = |S_{11}|^2$ , and  $A = 1 - |S_{11}|^2 - |S_{21}|^2$ . It was assumed that the effect of multiple reflections on the SE is negligible for our considered composite thickness [4, 7]. It was then seen that the  $SE(R) > SE(A)$  for low volume % nanotube filling fractions – Fig. 5a, while  $SE(A) > SE(R)$  for higher filling fractions – Fig. 5b. It could be inferred that the cross-over from reflection dominated shielding to absorption dominated shielding occurs ~ 2.3 volume % (as seen in Fig. 4b). A preliminary explanation, and fit to experiment, where SE (R) decreases with frequency ( $f$ ) while SE (A) increases with  $f$  was obtained through examining the form of R which varies as ~

$$\log_{10}\left(\frac{\sigma}{f}\right)$$

through its dependence on the reflection loss and A, which is thickness ( $t$ ) dependent, and varies as  $t\sqrt{f\sigma}$  [27]. Simulations and experiments are in progress to explore such phenomena in more detail.

Interestingly, the SE is also much larger, almost by a factor of 100, for functionalized SWNTs compared to functionalized MWNT – RET composites (Fig. 6). We have noted previously (Section II) that the aspect ratio of the MWNTs are smaller than the SWNTs, which implies (from Fig. 1a) reduced percolation and lower SE. We have experimentally observed that several variables such as (1) the aspect ratio of the CNTs, (2) DC and AC electrical conductivity of SWNTs/MWNTs, and (3) the thickness of the composite, in addition to (4) frequency, can be used as knobs to determine practical applicability of the CNT-RET polymer. One example, as we have shown, is the way in which nanotube type and/or concentration modulates the reflective or absorptive components of EMI shielding.

#### IV. CONCLUSIONS

Our study has provided an example of a nanotube (SWNT/MWNT)-polymer (e.g., RET) system which utilizes functional group interactions for achieving uniform dispersion with low electrical percolation concentrations and enhanced microwave shielding effectiveness. Analysis of the total observed EMI shielding was used for investigating the mechanisms of absorption and reflection in the composite, where a cross-over from reflection dominated shielding to absorption dominated shielding was observed at a CNT volume fraction of ~ 2.3%. It was also concluded that SWNTs were much more effective compared to MWNTs. Preliminary experiments probing the mechanical characteristics of the proposed CNT-RET polymer composites have indicated increased tensile strength as a function of increasing volume fraction of the CNTs. In summary, our proposed scheme of using functionalized CNT-polymer composites together with our obtained results could be used as a basis for light-weight, high shielding efficiency materials for EMI applications.

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#### REFERENCES

- [1] O. Breuer, and U. Sundararaj, "Big returns from small fibers: A review of polymer/carbon nanotube composites," *Polymer Composites*, vol. 25, pp. 630-645, 2004.
- [2] H. W. Ott, *Noise reduction techniques in electronic systems*, New York: John Wiley & Sons, 1988.
- [3] Y. Wang, and X. Jing, "Intrinsically conducting polymers for electromagnetic interference shielding," *Polymers for Advanced Technologies*, vol. 16, pp. 344-351, 2005.
- [4] D. D. L. Chung, "Electromagnetic Interference Shielding Effectiveness of Carbon Materials," *Carbon*, vol. 39, pp. 279-285, 2001.
- [5] I. Balberg, C. H. Anderson, S. Alexander *et al.*, "Excluded volume and its relation to the onset of percolation," *Physical Review B*, vol. 30, pp. 3933-3943, 1984.
- [6] A. Celzard, E. McRae, C. Deleuze *et al.*, "Critical concentration in percolating systems containing a high-aspect ratio filler," *Physical Review B*, vol. 53, pp. 6209-6214, 1996.

- [7] N. Li, Y. Huang, F. Du *et al.*, "Electromagnetic Interference (EMI) Shielding of Single-Walled Carbon Nanotube Epoxy Composites," *Nanoletters*, vol. 6, pp. 1141-1145, 2006.
- [8] Y. Huang, N. Li, Y. Ma *et al.*, "The influence of single-walled carbon nanotube structure on the electromagnetic interference shielding efficiency of its epoxy composites," *Carbon*, vol. 45, pp. 1614-1621, 2007.
- [9] Z. Liu, G. Bai, Y. Huang *et al.*, "Reflection and absorption contributions to the electromagnetic interference shielding of single-walled carbon nanotube/polyurethane composites," *Carbon*, vol. 45, pp. 821-827, 2007.
- [10] N. C. Das, and S. Maiti, "Electromagnetic interference shielding of carbon nanotube/ethylene vinyl acetate composites," *Journal of Materials Science* vol. 43, pp. 1920-1925, 2008.
- [11] H. Xu, S. M. Anlage, L. Hu *et al.*, "Microwave shielding of transparent and conducting single-walled carbon nanotube films," *Applied Physics Letters*, vol. 90, pp. 183119, 2007.
- [12] D. Tasis, N. Tagmatarchis, A. Bianco *et al.*, "Chemistry of Carbon Nanotubes," *Chemical Reviews*, vol. 106, pp. 1105-1135, 2006.
- [13] S. Antonietti, S. Antonczak, and J. Golebiowski, "Acid-catalyzed oxidative ring-opening of epoxide by DMSO. Theoretical investigation of the effect of acid catalysts and substituents," *Theoretical Chemistry Accounts*, vol. 112, pp. 290-297, 2004.
- [14] E. Bekyarova, E. T. Thostenson, A. Yu *et al.*, "Functionalized single-walled carbon nanotubes for carbon fiber-epoxy composites," *Journal of Physical Chemistry C*, vol. 111, pp. 17865-17871, 2007.
- [15] J. A. Nichols, H. Saito, C. Deck *et al.*, "Artificial introduction of defects into vertically aligned multiwall carbon nanotube ensembles: Application to electrochemical sensors," *Journal of Applied Physics*, vol. 102, pp. 064306, 2007.
- [16] Y. Lin, M. J. Meziani, and Y.-P. Sun, "Functionalized carbon nanotubes for polymeric nanocomposites," *Journal of Materials Chemistry*, vol. 17, pp. 1143-1148, 2007.
- [17] R. Hagenmueller, J. E. Fischer, and K. I. Winey, "Single wall carbon nanotube/polyethylene nanocomposites: Nucleating and templating polyethylene crystallites," *Macromolecules*, vol. 39, pp. 2964-2971, 2006.
- [18] M. B. Bryning, M. F. Islam, J. M. Kikkawa *et al.*, "Very low conductivity threshold in bulk isotropic single-walled carbon nanotube-epoxy composites," *Advanced Materials*, vol. 17, pp. 1186-1191, 2005.
- [19] Z. Fan, G. Luo, Z. Zhang *et al.*, "Electromagnetic and microwave absorbing properties of multi-walled carbon nanotubes/polymer composites," *Materials Science & Engineering, B: Solid-State Materials for Advanced Technology*, vol. 132, pp. 85-89, 2006.
- [20] M. Moniruzzaman, and K. I. Winey, "Polymer nanocomposites containing carbon nanotubes," *Macromolecules*, vol. 39, pp. 5194-5205, 2006.
- [21] D. M. Pozar, *Microwave Engineering*, 2 ed., New York: John Wiley & Sons, Inc., 1998.
- [22] G. F. Engen, and C. A. Hoer, "'Thru-Reflect-Line' : An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer" *IEEE Transactions Microwave Theory and Techniques*, vol. MTT-27, pp. 987-993, 1979.
- [23] P. F. Wilson, M. T. Ma, and J. W. Adams, "Techniques for measuring the electromagnetic shielding effectiveness of materials. I. Far-field source simulation," *IEEE Transactions on Electromagnetic Compatibility*, vol. 30, pp. 239-250, 1988.
- [24] D. S. McLachlan, M. Blazkiewicz, and R. E. Newnham, "Electrical Resistivity of Composites," *Journal of the American Ceramic Society*, vol. 73, pp. 2187-2203, 2005.
- [25] A. Saïb, L. Bednarz, R. Daussin *et al.*, "Carbon nanotube composites for broadband microwave absorbing materials," *IEEE Transactions on Microwave Theory and Techniques*, vol. 54, pp. 2745-2754, 2006.
- [26] H. M. Kim, K. Kim, C. Y. Lee *et al.*, "Electrical conductivity and electromagnetic interference shielding of multiwalled carbon nanotube composites containing Fe catalyst," *Applied Physics Letters*, vol. 84, pp. 589-591, 2004.

- [27] D. L. Sengupta, and V. V. Liepa, *Applied Electromagnetics and Electromagnetic Compatibility*, New York: John Wiley & Sons, Inc., 2005.



interference (EMI) shielding material, microwave characterization of nanocomposites and nanopatterned surface.

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