A Comparative Study of EMI Shielding Efficiency of Metal and Single Walled Carbon Nanotubes

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Approval

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A thesis report submitted to East West University as a partial fulfillment for the M.S. in Telecommunications Engineering (MTE).

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Declaration

This is to certify that, this report prepared by me under the project work (TE-598). It has not been submitted elsewhere for the requirement of any degree or any diploma or any other purpose except publication.

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Abstract

Assembling of a large number of high frequency electronic devices in a congested area has gradually been increased. This creates electromagnetic interference (EMI) which causes malfunctioned or abnormal operation of the devices. For this reason more and more effective EMI shielding is required among the devices. Moreover, to minimize the health hazards from the electromagnetic radiation from high frequency devices like cell phones, proper effective shielding should be used for those devices. Nowadays metal is the mostly used EMI shielding material. Metal based shielding materials have heavy weight. They also suffer from mechanical corrosion and erosion. Due to lower thermal conductivity, they cannot be used in a hot environment, where rapid heat dissipation is necessary. The aim of this thesis is to compare the EMI shielding efficiency of Metal with that of Single Walled Carbon Nanotubes (SWCNT). For that purpose we derived the analytical expressions for the shielding efficiency of any materials. From the results obtained in this work, it is found that SWCNT offers better EMI shielding efficiency than that of metal (copper and stainless steel). Compared with metal, SWCNT offers much less weight, higher thermal conductivity and mechanically hard. Therefore, SWCNT can be the best option as an EMI shielding materials instead of Metal.

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Chapter 1

Introduction

In recent years, the progress of technology and increment in the amount of information are remarkable and high-speed communication is indispensable. To realize high-speed communication, the higher frequency range from the microwave to the millimeter wave is expected. Many electronic instruments with the higher frequency, such as satellite communication, automobile collision prevention radar, accident surveillance of a railroad, and millimeter wave wireless local area network (LAN) and so on, have been developed and applied [1,2]. The electromagnetic waves produced from some electronic instruments have an adverse effect on the performance to other equipment's. This is called as electromagnetic interference (EMI). EMI may cause malfunctin to medical apparatus, industry robots or even cause har to human body and become one of public muisances. Therefore, in order to alleviate these troubles the development of EMI sheilding materials for microwave and millimeter waver are receiving increaseing attention briskly [3].

EMI shielding refers to the reflection and/or absorption of electromagnetic radiation by a material, which thereby acts as a shield against the penetration of the radiation through the shield. As electromagnetic radiation, particularly that at high frequencies (e.g. radio waves, such as those emanating from cellular phones) tend to interfere with electronics (e.g. computers), EMI shielding of both electronics and radiation source is needed and is increasingly required by governments around the world. The importance of EMI shielding relates to the high demand of today's society on the reliability of electronics and the rapid growth of radio frequency radiation sources [4–12].

EMI shielding is to be distinguished from magnetic shielding, which refers to the shielding of magnetic fields at low frequencies (e.g. 60 Hz). Materials for EMI shielding are different from those for magnetic fielding.

The shielding can reduce the coupling of radio waves, electromagnetic fields and electrostatic fields. A conductive enclosure used to block electrostatic fields is also known as a Faraday cage. The amount of reduction depends very much upon the material used, its thickness, the size of the shielded volume and the frequency of the fields of interest and the size, shape and orientation of apertures in a shield to an incident electromagnetic field.

Typical materials used for electromagnetic shielding include sheet metal and metal foam. Any holes in the shield or mesh must be significantly smaller than the wavelength of the radiation that is being kept out, or the enclosure will not effectively approximate an unbroken conducting surface.

Another commonly used shielding is with electronic goods housed in plastic enclosure is to coat the inside of the enclosure with a metallic ink or similar material. The ink consists of a carrier material loaded with a suitable metal, typically copper or nickel, in the form of very small particulates. It is sprayed on to the enclosure and, once dry, produces a continuous conductive layer of metal, which can be electrically connected to the chassis ground of the equipment, thus providing effective shielding.

EMI shielding enclosures filter a range of frequencies for specific conditions. Copper is used for EMI shielding because it reflects and also absorbs EM waves. Properly designed and constructed copper EMI shielding enclosures satisfy most EMI shielding needs, from computer and electrical switching rooms to hospital Computed Axial Tomography (CAT or CT)-scan and Magnetic Resonance Imaging (MRI) facilities.

A device is considered electromagnetically compatible with its surrounding if it does not interfere with other devices or itself, and it does not affected by emissions from other devices [13–15]. Therefore, a good shielding material should prevent both incoming and outgoing electromagnetic interference (EMI). EMI shielding effectiveness (SE) is expressed in decibel (dB).

Metal coated or metal plated polymers are the most widely used materials for EMI shielding [16–18]. Conventional CPCs made of stainless steel fibers, carbon fibers and nickel coated carbon fibers have also been used as EMI shielding enclosures but to a lesser extent [19, 20] because of the high concentration of filler required to achieve an adequate level of shielding.

Shielding effectiveness is the ratio of impinging energy to the residual energy. When an electromagnetic wave pass through a shield, absorption and reflection takes place. Residual energy is part of the remainng energy that is neither reflected nor absorbed by the shield but it is emerged out from the shield [21]. Shielding efficiency depends on the thickness and conductivity mainly. To increase efficiency it need to increase the thickness and/or increase the conductivity where weight of the shield also increases with thickness. Current world is becaming lighter and smaller. So, decreasing weight, size and increasing efficiency is the main challange.

In our study we consider Single Wall Carbon Nanotube (SWCNT) as EMI shield. Due to their very light weight, outstanding electrical conductivity, temperature stability, structural integrity, outstanding mechanical properties SWCNT are attractive to satisfy electromagnetic compatibility requirements [22]. Using SWCNT as shield we found significant amount of efficiency compared to mostly used shield Copper and Stainless Steel. For the same thickness of shield we found more shielding efficiency with SWCNT than copper and Stainless Steel. So, we can get same shielding efficiency with less thickness and with very light weight.

References:

[1] Hatakeyama K, Togawa H. Simplified measurement method of electromagnetic wave shielding and absorbing characteristics in mm-wave. IEICE Trans B-Π 1998;J81-B-Π:651-656.

[2] Harada Y. Research and development of frequency resources in MPT. J IEICE 1995;78:741-744.

[3] Chun-Sheng Zhang, Qing-Qing Ni*, Shao-Yun Fu, and Ken Kurashiki. Electromagnetic Interference Shielding Effect of Nanocomposites with Carbon Nanotube and Shape Memory Polymer.

[4] Bjorklof D. EMC fundamentals. Part Six: EMI filters and transient. Compliance Engineer 1998;15(5):10.

[5] Brewer R, Fenical G. Shielding: The hole problem. Evaluation Engineer 1998;37(7):S4–S10.

[6] O'Shea P. How to meet the shielding needs of a 500-MHz PC. Evaluation Engineer 1998;37(6):40, 43, 45–46.

[7] Devender, Ramasamy SR. Review of EMI shielding and suppression materials. Proc. Int. Conf. Electromagnetic Interference and Compatibility 1997. IEEE, Piscataway (New Jersey, USA): IEEE 1997;459–466.

[8] Geddes B. Putting a lid on EMI/RFI. Control (Chicago, Ill) 1996;9(10):4.

[9] Hempelmann S. Surface engineering for EMI compliance. Process and practical examples. Galvanotechnik 1997;88(2):418–24.

[10] Kimmel WD, Gerke DD. Controlling EMI with cable shields. Medical Device & Diagnostic Industry 1995;17(7):112–5.

[11] Markstein HW. Effective shielding defeats EMI. Electronic Packaging & Production 1995;35(2):4.

[12] McRae KA. Electromagnetic shielding in today's environment. National Conf. Publication – Institution of Engineers, Australian, Vol. 2, No. 94/ 11, IE Aust, Crows Nest, NSW, Aust. 1994;495–498.

[13] Paul CR. Introduction to electromagnetic compatibility. 2nd ed. Hoboken, New Jersey: John Wiley and Sons Inc.; 2006.

[14] Markham D. Shielding: quantifying the shielding requirements for portable electronic design and providing new solutions by using a combination of materials and design. Mater Des 2000;21(1):45–50.

[15] Chung DDL. Electromagnetic interference shielding effectiveness of carbon materials. Carbon 2001;39(2):279–85.

[16] Schlechter M. EMI/RFI: materials and technology [cited 2007 August 20]. Available from: <www.bccresearch.com>.

[17] Jiang G, Gilbert M, Hitt DJ, Wilcox GD, Balasubramanian K. Preparation of nickel coated mica as a conductive filler. Compos Part A 2002;33(5):745–51.

[18] Murthy M. Permanent EMI shielding of plastics using copper fibers annual technical conference – ANTEC. San Francisco, CA, USA: Society of Plastics Engineers; 1994.

[19] Chung DDL. Electrical applications of carbon materials. J Mater Sci 2004;39(8):2645–61.

[20] Amarasekera J. Conductive plastics for electrical and electronic applications. Reinf Plast 2005;49(8):38–41.

[21] S. Geetha, K. K. Satheesh Kumar, Chepuri R. K. Rao, M. Vijayan, D. C. Trivedi. EMI Shielding: Methods and Materials-A Review. Wiley InterScience. DOI 10.1002/app.29812.

[22] http://www.iws.fraunhofer.de/content/dam/iws/en/documents/publications/product_sheets/500-3_swcnt_en.pdf

Chapter 2

Modeling

2.1 Introduction

The proliferation of electronic devices in the world has caused **electromagnetic interference** (EMI) and **radio frequency interference** (RFI) to become important concerns. Although all electronics emit magnetic and electrical energy, if this energy unintentionally interacts with another device and causes it to malfunction, then it is considered interference. Most EMI is caused by frequencies that fall between 1 kilohertz and 10 gigahertz, and this range is known as the RFI band, which includes radio and audio frequencies. Common sources of interference include radios, televisions, motors, appliances, radar transmitters, static electricity, and lightning. Devices that are susceptible to interference, such as computers, microprocessors, broadcasting receivers, measuring instruments, and navigation systems, must often be shielded to protect them from the effects of EMI.

2.2 EMI Shielding Effectiveness Tests

Determining the level of attenuation for an EMI shield can be complex, and the methods used to retrieve the results often vary according to the particular shielding application. Some of the more common techniques for testing shielding strength include [1]:

2.2.1 Open Field Test

The open field test is designed to simulate the normal usage conditions for an electronic device as closely as possible. Antennae are placed at varying distances from the device in an area with no metallic materials other than the testing equipment. This usually occurs in an open site to allow for free space measurements of radiated field strength and conductive emissions. The results are recorded by a noise level meter, which detects the level of EMI produced. The open field test is best suited for finished electronic products.

2.2.2 Coaxial Transmission Line Test

This testing method measures plane-wave field electromagnetic wave radiation to determine the shielding effectiveness of a planar material, and it is commonly employed for comparative testing. A reference testing device is positioned in a specialized holding unit and the voltage it receives at multiple frequencies is recorded. The first subject is then replaced by a load device, which undergoes the same series of tests. A comparison between the reference and the load devices establishes the ratio between power received with and without a shielding material.

2.2.3 Shielded Box Test

The shielded box technique employs a sealed box with a cut-out portion. A conductively coated shielding unit is placed over the box's opening, and all transmitted and received emissions are measured. The electromagnetic signals from both inside and outside the box are recorded and compared, with the ratio between the signals representing shielding effectiveness. This method is often ineffective for frequencies exceeding 500 megahertz.

2.2.4 Shielded Room Test

In some situations, it may be impossible to significantly reduce the amount of ambient noise in an area and a shielded room technique may be needed. The method usually involves at least two shielded rooms with a wall between them, through which sensors can be run. The testing device and testing equipment are placed in one room, and sensor arrays in the other. Shielding leads are often included to reduce the potential for measuring errors caused by external signals. The shield room process is well-suited for evaluating a device's susceptibility [2.3].

The American Society for Testing and Materials, ASTM D4935-99, has adopted coaxial transmission line technique [4] as recognized standard method for measurement of the shielding effectiveness of planar specimens.

2.3 Modeling of EMI Shielding Effectiveness

Three mechanisms have been reported to be involved in EMI shielding, namely: reflection, absorption and multiple-reflection.

The primary mechanism of EMI shielding is usually reflection. For reflection of the radiation by the shield, the shield must have mobile charge carriers (electrons or holes) which interact with the electromagnetic fields in the radiation. As a result, the shield tends to be electrically conducting, although a high conductivity is not required. For example, a volume resistivity of the order of 1 V cm is typically sufficient. However, electrical conductivity is not the scientific criterion for shielding, as conduction requires connectivity in the conduction path (percolation in case of a composite material containing a conductive filler), whereas shielding does not. Although shielding does not require connectivity, it is enhanced by connectivity. Metals are by far the most common materials for EMI shielding. They function mainly by reflection due to the free electrons in them. Metal sheets are bulky, so metal coatings made by electroplating, electroless plating or vacuum deposition are commonly used for shielding [5–21]. The coating may be on bulk materials, fibers or particles. Coatings tend to suffer from their poor wear or scratch resistance.

A secondary mechanism of EMI shielding is usually absorption. For significant absorption of the radiation by the shield, the shield should have electric and/or magnetic dipoles which interact with the electromagnetic fields in the radiation. The electric dipoles may be provided by $BaTiO_3$ or other materials having a high value of the dielectric constant. The magnetic dipoles may be provided by Fe_3O_4 or other materials having a high value of the magnetic permeability [5], which may be enhanced by reducing the number of magnetic domain walls through the use of a multilayer of magnetic films [17,18].

The absorption loss is a function of the product $\sigma_r\mu_r$, whereas the reflection loss is a function of the ratio $\sigma_r\mu_r$, where σ_r is the electrical conductivity relative to the conductive material and μ_r is the relative magnetic permeability. Silver, Copper, Gold, Stainless steel and Aluminum are excellent for reflection due to their high conductivity. Superpermalloy and mumetal are excellent for absorption, due to their high magnetic permeability. The reflection loss decreases with increasing frequency, whereas the absorption loss increases with increasing frequency.

Other than reflection and absorption, a mechanism of shielding is multiple reflections, which refer to the reflections at various surfaces or interfaces in the shield. This mechanism requires the presence of a large surface area or interface area in the shield. An example of a shield with a large surface area is a porous or foam material. An example of a shield with a large interface area is a composite material containing a filler which has a large surface area. The loss due to multiple reflections can be neglected when the distance between the reflecting surfaces or interfaces is large compared to the skin depth, $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$. Typically, multiple-reflection decreases the overall shielding if the shield is thinner than the skin depth and can be ignored if the shield is thicker than the skin depth [19].

The losses, whether due to reflection, absorption or multiple reflections, are commonly expressed in dB. The sum of all the losses is the shielding effectiveness (in dB). The absorption loss is proportional to the thickness of the shield [20].

2.4 Modeling of EMI Shielding Effectiveness (Calculation)

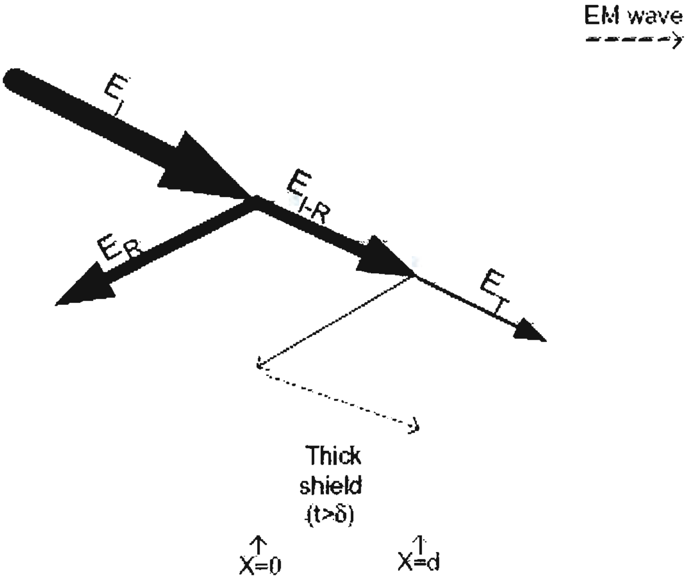

Fig. 1 - Schematic showing shielding in conductive plate.

EMI SE is the logarithm of the ratio of the transmitted power when there is no shield (P_I) to the power when there is a shield (P_T), Eqn. (2.1).

$$SE = 10\log(P_I/P_T) \tag{2.1}$$

When an electromagnetic plane wave (E_I) strikes a monolithic conductive material having different intrinsic impedance than the domain in which the EM plane wave was propagating, two waves will be created at the external surface: a reflected wave (E_R) and a transmitted wave (E_{I-R}), as shown in Fig. 1. The amplitude of the E_R and E_{I-R} waves depend on the intrinsic impedance of the shielding material (η_s) and the EM incident wave propagating domain (η_o). As the transmitted wave from the external surface (E_{I-R}) travels in the conductive shield, the strength (amplitude) of the wave exponentially decreases due to absorption. The absorbed energy will be dissipated as heat.

Once the wave reaches the second surface of the sheet(x = d), a portion of the wave will be transmitted from the sheet and a portion will be reflected into the sheet (note that this first reflection from the internal surface is part of the reflection mechanism). If the shield is thicker than the skin depth, the reflected wave from the internal surface will be absorbed by the conductive material, and thus multiple-reflection can be ignored. However, if the shield is thinner than the skin depth, the influence of multiple-reflection will be significant in decreasing overall EMI shielding. Eqn. (2.2)–(2.5) were developed to quantify the contribution of reflection, absorption and multiple-reflection to the overall EMI SE of conductive monolithic materials, $\eta_s \ll \eta_o^2$ [26-29].

Total EMI shielding is the sum of shielding due to reflection, absorption and multiple reflections. So we can write the expression as

$$SE_T = SE_R + SE_A + SE_{MR} \qquad (2.2)$$

$$\text{Shielding by reflection} = SE_R = 20 \log \frac{\eta_o}{4\eta_s} \qquad (2.3)$$

$$\text{Shielding by absorption} = SE_A = 20 \log e^{d/\delta} \qquad (2.4)$$

$$\text{Shielding by multiple-reflection} = SE_{MR} = 20 \log (1 - e^{-2d/\delta}) \qquad (2.5)$$

$$\text{Where } \eta = \frac{|E|}{|H|} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \qquad (2.6)$$

Where ω is the angular frequency of the radiation, μ is the magnetic permeability, σ is the electrical conductivity and ε is the permittivity of the medium. Note that the amount of energy absorbed increases with increase in the shield thickness and decrease in skin depth. Skin depth decreases within crease in shield conductivity, magnetic permeability and EM wave frequency.

To elaborate the influence of different process variables on the EMI shielding by reflection and absorption, Eqn. (2.3) and (2.4) were re-written in terms of f, μ, and σ. For electromagnetic plane wave in space or vacuum $\sigma = 0$, therefore, Eqn. (2.6) reduces to $\eta_o = \sqrt{\mu/\varepsilon}$. For conductive materials, $\sigma >> \omega\varepsilon$ therefore, Eqn. (2.6) simplifies to $\eta_s = \sqrt{j\omega\mu/\sigma} = \sqrt{2\pi f\mu/\sigma}$, f is the frequency of the EM wave. Now SE_R becomes as from Eqn.(2.2) is :

$$SE_R = 20 \log \frac{\eta_o}{4\eta_s} = 20 \log \eta_o - 20 \log 4\, \eta_s$$

$$= 20 \log 377 - 20 \log 4 - 20 \log \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \qquad \text{[putting } \eta_o \text{ and } \eta_s \text{ value]}$$

$$= 51.53 - 12.04 - 20 \log \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}$$

$$= 39.5 - 20 \log \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}$$

$$= 39.5 - 10 \log \frac{j\omega\mu}{\sigma + j\omega\epsilon}$$

For a conductor used below optical frequencies defined by $\sigma >> \omega\epsilon$, so the Eqn. can be written as:

$$= 39.5 - 10 \log \frac{\omega\mu}{\sigma}$$

$$SE_R = 39.5 + 10 \log \frac{\sigma}{2\pi f\mu} \qquad [\,\omega = 2\pi f\,] \qquad (2.7)$$

And from Eqn. (2.4) Shielding by absorption (SE_A) becomes:

$$SE_A = 20 \log e^{d/\delta}$$

$$= (\tfrac{d}{\delta})\, 20 \log (e)$$

$$= (\tfrac{d}{\delta})\, 20 \times 0.4343$$

$$SE_A = 8.7\frac{d}{\delta} = 8.7d\sqrt{\pi f\mu\sigma} \qquad [\text{ putting skin depth, } \delta = \frac{1}{\sqrt{\pi f\mu\sigma}}\,] \qquad (2.8)$$

2.5 Quantum skin depth and its effect in EMI

The resistance and inductance of interconnects are strongly depend on the frequency due to skin effect and/or proximity effect. At high frequency, the resistance of a metal wire increases significantly while inductance decreases with the frequency. But for CNT, the resistance almost unchanged, implying a negligible skin effect. The reduced skin effect of CNT bundle can be attributed to the presence of large kinetic inductance. Due to the existence of kinetic inductance ($= \tau/\sigma_0$), the resistivity of CNT bundle becomes complex. Here momentum is :

$$\tau = \lambda/2v_F$$

Based on this complex conductivity, one can derive the equivalent skin depth of a CNT bundle as below form [30]. That is also known as quantum skin depth.

$$\delta_q = \sqrt{\frac{2}{\omega\mu\sigma_0}} \cdot \sqrt{[\,(\omega\tau)^2 + 1\,] \,.\, [\sqrt{[(\omega\tau)^2 + 1}\; - \;\omega\tau\,]}$$

$$\delta_q = \sqrt{\frac{1}{\pi f\mu\sigma_0}} \cdot \sqrt{[\,(2\pi f\tau)^2 + 1\,] \,.\, [\sqrt{[(2\pi f\tau)^2 + 1}\; - \;2\pi f\tau\,]}$$

As SWCNT has greater conductivity considering this we found from Eqn. (8) is:

$$SE_{A\text{-quantum}} = SE_A \cdot \frac{1}{\sqrt{[\,(\omega\tau)^2+1\,]\,.\,[\sqrt{[(\omega\tau)^2+1} - \omega\tau\,]}} \qquad \text{[considering } \delta_q \text{ value]}$$

$$= 8.7d\sqrt{\pi f \mu\sigma} \cdot \frac{1}{\sqrt{[\,(2\pi f\tau)^2+1\,]\,.\,[\sqrt{[(2\pi f\tau)^2+1} - 2\pi f\tau\,]}}$$

$$SE_{A\text{-quantum}} = \frac{8.7d\sqrt{\pi f \mu\sigma}}{\sqrt{[\,(2\pi f\tau)^2+1\,]\,.\,[\sqrt{[(2\pi f\tau)^2+1} - 2\pi f\tau\,]}} \tag{2.9}$$

Where, $\omega = 2\pi f$ and $\tau = \frac{\lambda}{2v_F}$

And τ = Momentum relaxation time [s]

λ = Mean Free path of CNT [m]

v_F = Velocity [m/s]

Eqn. (2.5) shows that multiple-reflection is a negative term. Therefore, multiple-reflection in thin shields reduces the overall SE. This might be the case of CNTs. In the X-band frequency range, the skin depth of CNT is in the range of 14.3–17.8 *μm*, assuming that CNT electrical conductivity is greater than (>) 1×10^5 S/m. This thickness is much larger than the diameter of CNTs (≈1–50 *nm*). According to Eqn. (2.5), multiple-reflection between internal surfaces of carbon plate 20 nm in thickness and 1×10^5S/cm in electrical conductivity is -47 dB. Thus, multiple- reflection within CNT internal surfaces is expected to significantly decrease the overall EMI SE if there is multiple reflection within the CNT internal surfaces (because of the small size of CNTs compared to the wave length of the EM radiation in X-band frequency range, EM might not be re-reflected between the CNT internal surfaces) [26]. So, we can neglect multiple-reflection here.

So we can summarize the EMI SE as

From eqn. (2.7)

Shielding by reflection, SE_R $= 39.5 + 10\log\frac{\sigma}{2\pi f\mu}$

From eqn. (2.8)

Shielding by absorption, SE_A $= 8.7d\sqrt{\pi f \mu\sigma}$

From eqn. (2.9),

Shielding by absorption for SWCNT, $SE_{A\text{-quantum}} = \dfrac{8.7d\sqrt{\pi f \mu \sigma}}{\sqrt{[\,(\omega\tau)^2+1\,]\,.\,[\sqrt{[(\omega\tau)^2+1} - \omega\tau\,]}}$

[considering quantum skin depth]

2.6 Total Shielding Efficiency

From eqn. (2.2) is

$$SE_T = SE_R + SE_A + SE_{MR}$$

Considering negligible SE_{MR} as per our above study,

$$SE_T = SE_R + SE_A$$

Putting values from eqn. (2.7) and eqn. (2.8)

$$SE_T = 39.5 + 10 \log \frac{\sigma}{2\pi f\mu} + 8.7d\sqrt{\pi f \mu \sigma} \tag{2.10}$$

Considering quantum skin depth, as per our above study,

$$SE_T = 39.5 + 10 \log \frac{\sigma}{2\pi f\mu} + \frac{8.7d\sqrt{\pi f \mu \sigma}}{\sqrt{[\,(\omega\tau)^2+1\,]\,.\,[\sqrt{[(\omega\tau)^2+1} - \omega\tau\,]}} \tag{2.11}$$

[21] Grimes CA. EMI shielding characteristics of permalloy multilayer thin films. In: IEEE Aerospace Applications Conf. Proc., IEEE, Computer Society Press Los Alamitos, California, USA: IEEE, 1994, pp. 211–21.

[22] Biter WJ, Jamnicky PJ, Coburn W. In: 7th International SAMPE Electronics Conference, Shielding improvement by use of thin multilayer films, vol. 7, Covina, California, USA: SAMPE, 1994, pp. 234–42.

[23] Mohammed H. Al-Saleh, Uttandaraman Sundararaj* Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G6, Electromagnetic interference shielding mechanisms of CNT/polymer composites, CARBON 47 (2009), p. 1738 –1746

[24] D.D.L. Chung*, Composite Materials Research Laboratory, State University of New York at Buffalo, Buffalo, NY 14260-4400, USA, Received 23 March 2000; accepted 22 July 2000, Electromagnetic interference shielding effectiveness of carbon materials, Carbon 39 (2001) pp. 279–285

[25] Paul CR. Introduction to electromagnetic compatibility. 2nded. Hoboken, New Jersey: John Wiley and Sons Inc.; 2006.

[26] Kaiser KL. Electromagnetic shielding. Boca Raton, FL:CRC Press; 2006. p. 1-52.

[27] Schulz RB, Plantz VC, Brush DR. Shielding theory and practice. Electromagnetic compatibility. IEEE Trans 1988;30(3):187–201.

[28] Neelakanta PS. Handbook of electromagnetic materials: monolithic and composite versions and their applications. CRC Press Inc.; 1995. p. 447–90.

[29] Hong Li, Chuan Xu ; Srivastava, N. ; Banerjee, K. Carbon Nanomaterials for Next-Generation Interconnects and Passives: Physics, Status, and Prospects. Electron Devices, IEEE Transactions on (Volume:56 , Issue: 9) Sept. 2009, p. 1799 - 1821

[30] Mohammed H. Al-Saleh, Uttandaraman Sundararaj* Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G6, Electromagnetic interference shielding mechanisms of CNT/polymer composites, CARBON 47 (2009), p. 1738 –1746

Chapter3

Result and Discussion

3.1 Introduction

The SE describes the ability to prevent the transmission of electromagnetic waves from the outside to the inside or vice versa.

The main factors which determine the shielding effect are the capability of shielding materials (the conductivity and the permeability), the thickness and the frequency of the incident wave. If we know all these factors, the material's shielding effects can be calculated by our previous study.

3.2 Calculation

From our previous study in chapter 2, we found total sheilding from Eqn. (2.11) is

$$SE_T = SE_R + SE_A \tag{3.1}$$

$$SE_T = 39.5 + 10 \log \frac{\sigma}{2\pi f\mu} + 8.7d\sqrt{\pi f\mu\sigma} \tag{3.2}$$

where, $SE_R = 39.5 + 10 \log \frac{\sigma}{2\pi f\mu}$ and $SE_A = 8.7d\sqrt{\pi f\mu\sigma}$

For SWCNT we got shielding by absorption considering quantum skin depth from Eqn. (2.11). Than the total shielding efficiency of SWCNT became

$$SE_{T\text{-quantum}} = 39.5 + 10 \log \frac{\sigma}{2\pi f\mu} + \frac{8.7d\sqrt{\pi f\mu\sigma}}{\sqrt{[(2\pi f\tau)^2+1]\,.\,[\sqrt{[(2\pi f\tau)^2+1} - 2\pi f\tau]}} \tag{3.3}$$

where, $$SE_{A\text{-quantum}} = \frac{8.7d\sqrt{\pi f\mu\sigma}}{\sqrt{[(2\pi f\tau)^2+1]\,.\,[\sqrt{[(2\pi f\tau)^2+1} - 2\pi f\tau]}}$$

Here,

σ = conductivity of shield

ω = angular frequency of the radiation = $2\pi f$

μ = shield's magnetic permeability = $\mu_0\mu_r$

μ_0 = $4\pi \times 10^{-7} H/m$

μ_r = shield's relative magnetic permeability

f = frequency of the EM wave [Hz]

δ = skin depth = $1/\sqrt{\pi f \mu \sigma}$

d = shield's thickness [m]

τ = Momentum relaxation time [s]

3.3 Magnetic permeability of shielding materials

The magnetic permeability, $\mu = \mu_0\mu_r$, where μ_0 is the absolute permeability of free space ($4\pi\times10^{-7}$H/m). Since SWCNT, Copper, and Stainless Steel is considered as a non-magnetic substance [1], therefore, in our calculation we consider $\mu_r = 1$.

3.4 Conductivity of shielding Materials

According to the Eqn (3.2), the conductivity of the shielding materials significantly contributes to the total shielding efficiency. The conductivity is diameter dependent. In our calculation we have taken the average diameter of SWCNT as 1.5nm. The resistivity of SWCNT having diameter of 1.5nm is 1.1μΩ.cm [2]. Therefore, the conductivity is 9.09×10^7 S/m. The conductivities of copper and stainless steel are 5.813×10^7 S/m and 1.1×10^6 S/m respectively [3].

3.5 Results and Discussions

In this work, we have investigated the shielding efficiency of SWCNT, copper and stainless steel for a frequency range of 1 GHz to 20 GHz. The thickness of the shielding materials was taken from5nm to 5mm.

3.5.1 Skin depth (δ):

The classical skin depth can be expressed as:

$$\delta_c = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{3.4}$$

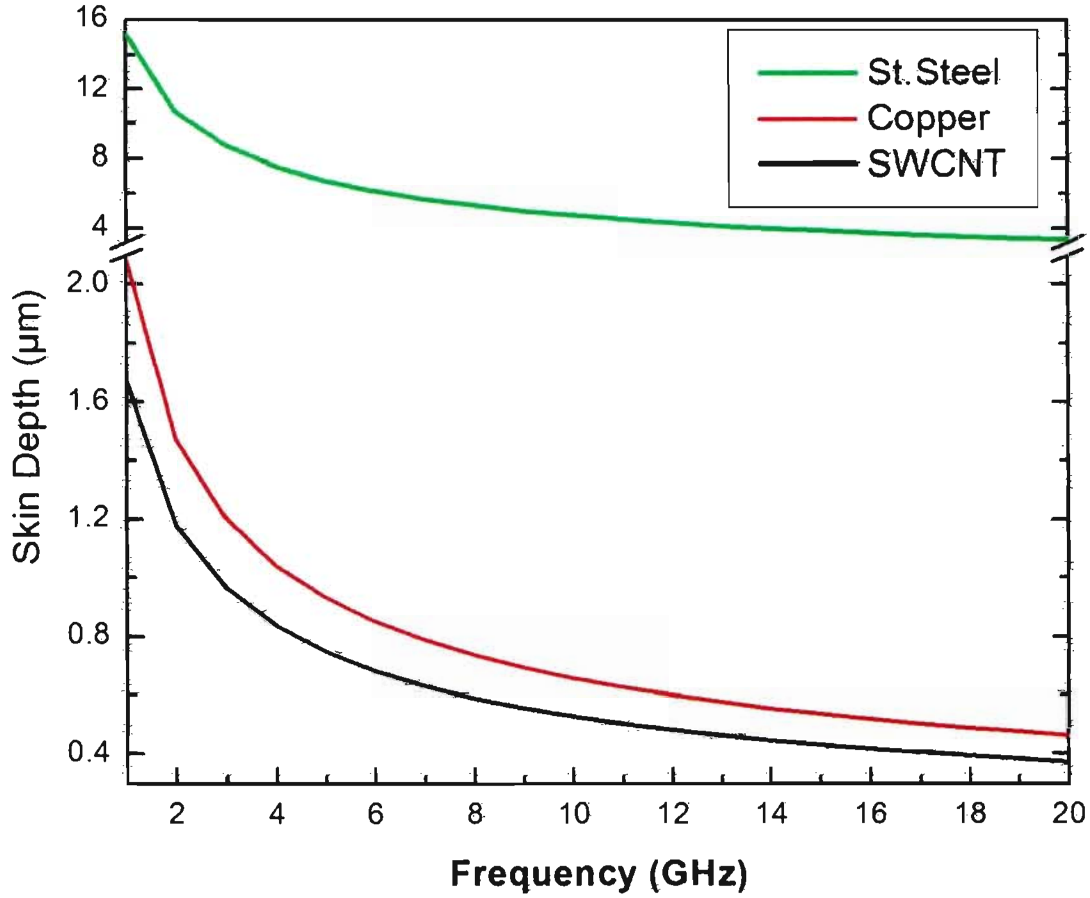

Fig 3.1 Skin depth comparison with Frequency for SWCNT (classical), Copper and stainless Steel

Using Eqn 3.4 the skin depth has been calculated for SWCNT, copper and stainless steel. Figure 3.1 shows the evolution of skin depth with frequency. From the figure it found that SWCNT has the lowest skin depth. And St. Steel has the highest Skin depth.

3.5.2 Comparison between quantum skin depth and classical skin depth:

Considering the quantum effect, the skin depth for a SWCNT bundle can be written as:

$$\delta_q = \sqrt{\frac{1}{\pi f \mu \sigma_0}} \cdot \sqrt{[\,(2\pi f\tau)^2 + 1\,]\,.\,[\sqrt{[(2\pi f\tau)^2 + 1} \;-\; 2\pi f\tau\,]} \tag{3.5}$$

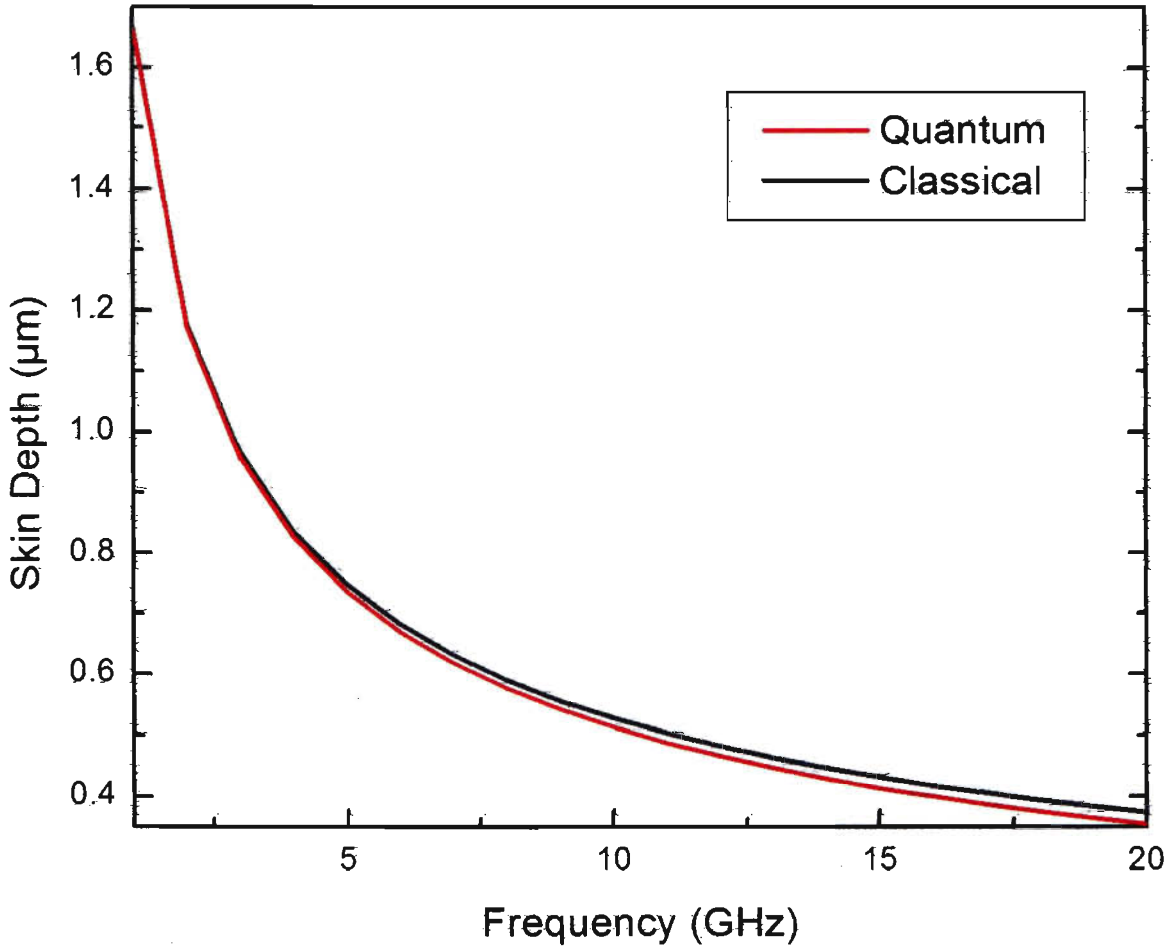

Fig 3.2 Comparison between quantum skin depth and classical skin depth for SWCNT

Figure 3.2 shows the evolution of skin depth with frequency of SWCNT for classical quantum effects. From this figure, it is noticed that the quantum skin depth is lower than that of classical skin depth which will result better EMI shielding. But the difference between them is very smaller which will not cause any significant improvement.

3.5.3 Shielding by Reflection, SE_R:

This is the main mechanism of EMI shielding. And as per our previous study,

$$SE_R = 39.5 + 10 \log \frac{\sigma}{2\pi f \mu} \tag{3.6}$$

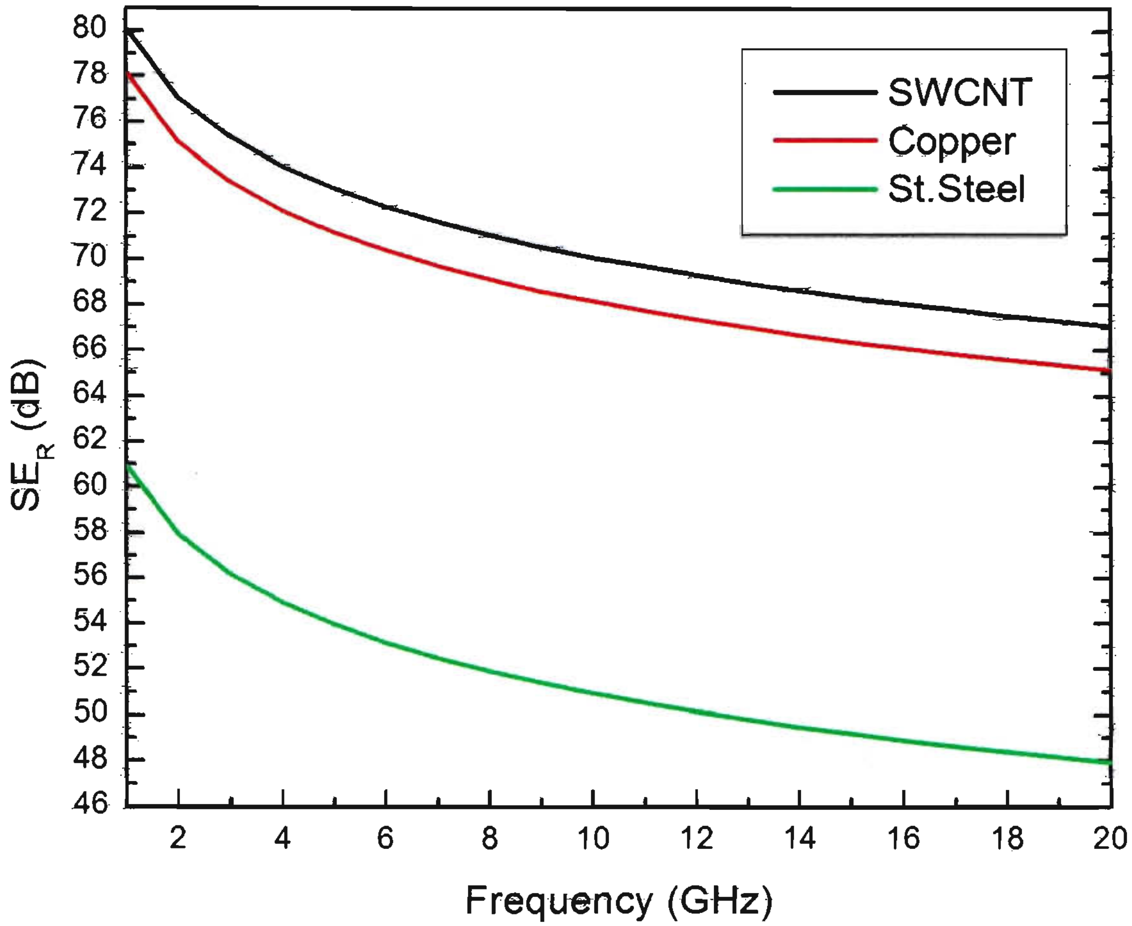

Fig 3.3 Shielding due to reflection comparison between SWCNT, Copper and St. Steel

The shielding efficiency due to reflection has been calculated. Figure 3.3 shows the effects of frequency on the shielding efficiency. It is evident from the figure that better shielding performance may be resulted by reflection with SWCNT over Copper and St. Steel. Currently copper is the best EMI shielding material. However SWCNT may replace copper as a shielding material having better performance.

3.5.4 Shielding by absorption

3.5.4.1 Classical absorption, SE_A

From our previous study,

$SE_A = 8.7d\sqrt{\pi f \mu \sigma}$ considering thickness $d = 5nm$ (3.7)

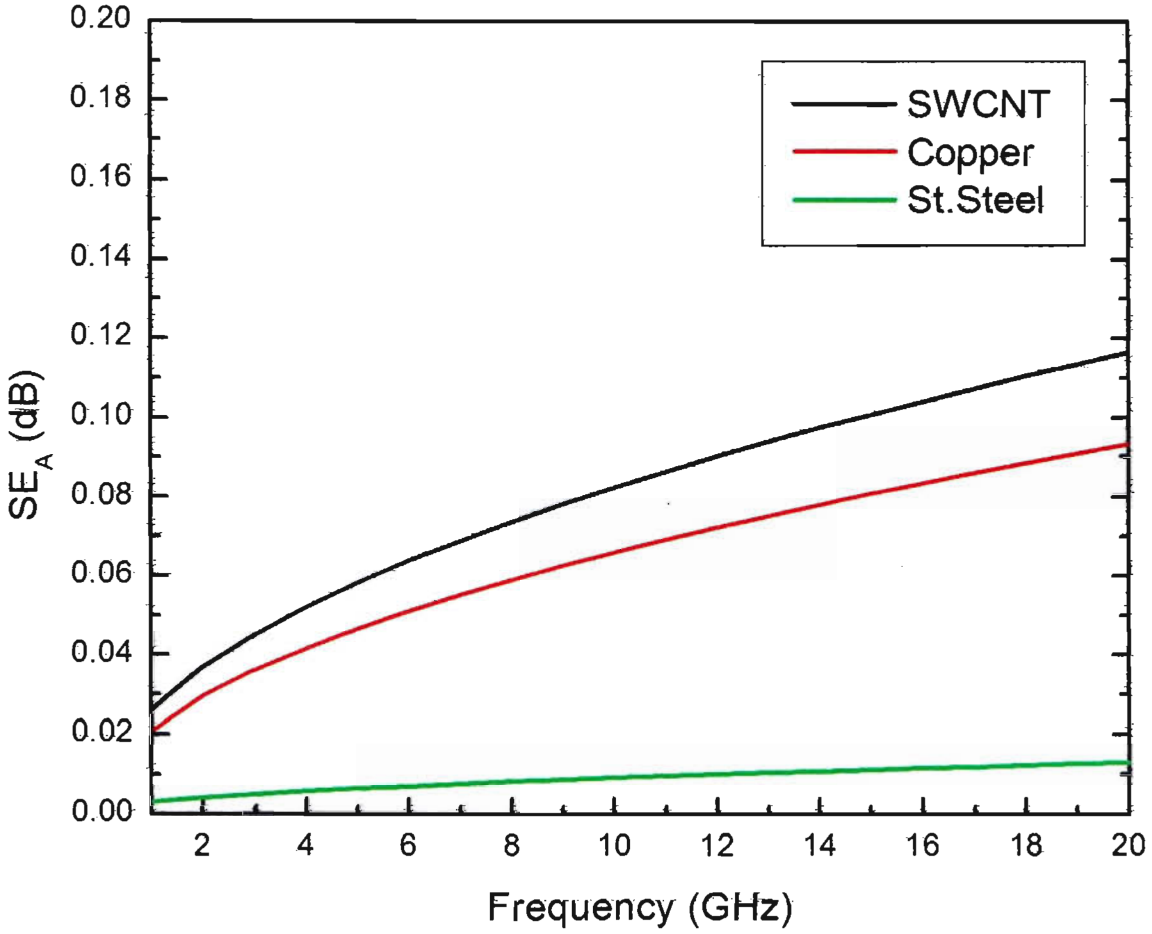

Fig 3.4 Shielding due to Absorption comparison between SWCNT (classical), Copper and Stainless Steel

Figure 3.4 shows the effects of frequency on the shielding efficiency due to absorption for SWCNT, copper and stainless steel. Shielding efficiency due to absorption is inversely proportional to the skin depth. In this figure we have calculated the shielding efficiency considering the classical skin depth. From this figure it is found that SWCNT offers better shielding efficiency due to absorption than that of copper and stainless steel.

3.5.4.2 Shielding by absorption due to quantum effect, $SE_{A\text{-quantum}}$

From our previous study, For SWCNT there is a quantum effect so,

$$SE_{A\text{-quantum}} = \frac{8.7d\sqrt{\pi f \mu \sigma}}{\sqrt{[(2\pi f \tau)^2+1] \, . \, [\sqrt{[(2\pi f \tau)^2+1}-2\pi f \tau]}} \qquad \text{thickness } d = 5nm \qquad (3.8)$$

And for other materials SE_A remain same as quantum effect is not applicable for copper and Stainless Steel that is Eqn 3.6

$$SE_A = 8.7d\sqrt{\pi f\mu\sigma}$$

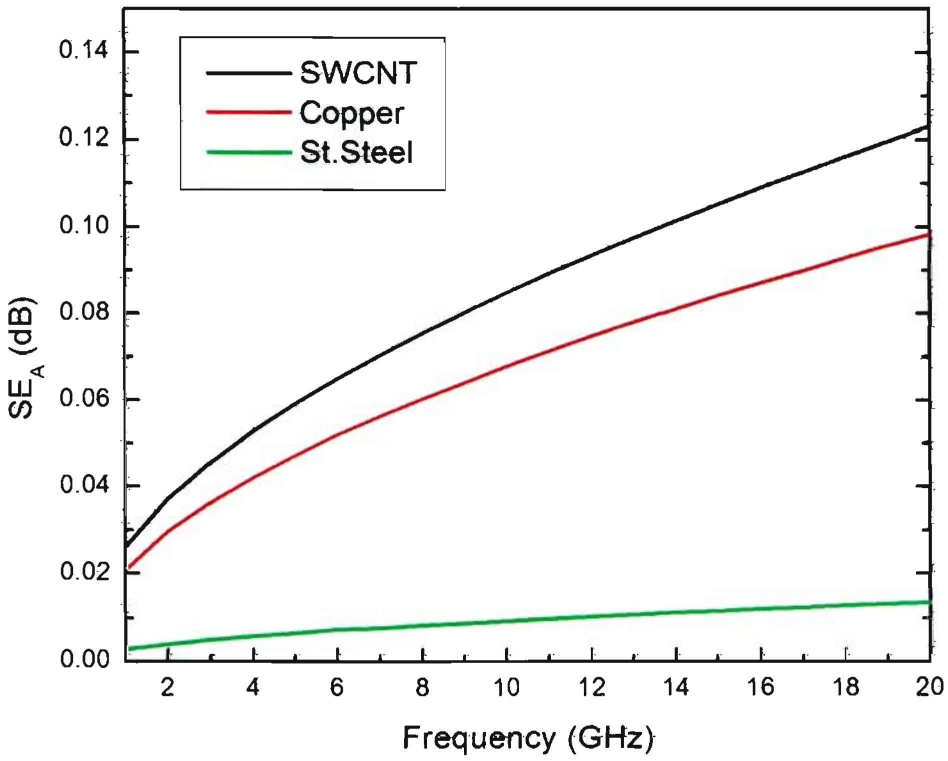

Fig 3.5 Shielding due to Absorption comparison between SWCNT (quantum), Copper and St. Steel

Figure 3.5 shows effects of frequency on the EMI shielding due to absorption taking the quantum skin depth for SWCNT. The effects of quantum skin depth and classical skin depth has no significant effect on shielding efficiency.

3.5.5 Total Shielding Efficiency

The total shielding efficiency is the sum of shielding efficiency due to absorption and reflection. Therefore total shielding efficiency (SE_T) can be expressed as:

$$SE_T = SE_R + SE_A \qquad (3.9)$$

or $SE_T = SE_R + SE_{A\text{-}new}$ (for SWCNT) (3.10)

As SE_A and $SE_{A\text{-}quantum}$ are nearly same so here we considering only classical skin depth and classical $SE_{A\text{-}quantum}$ for SWCNT.

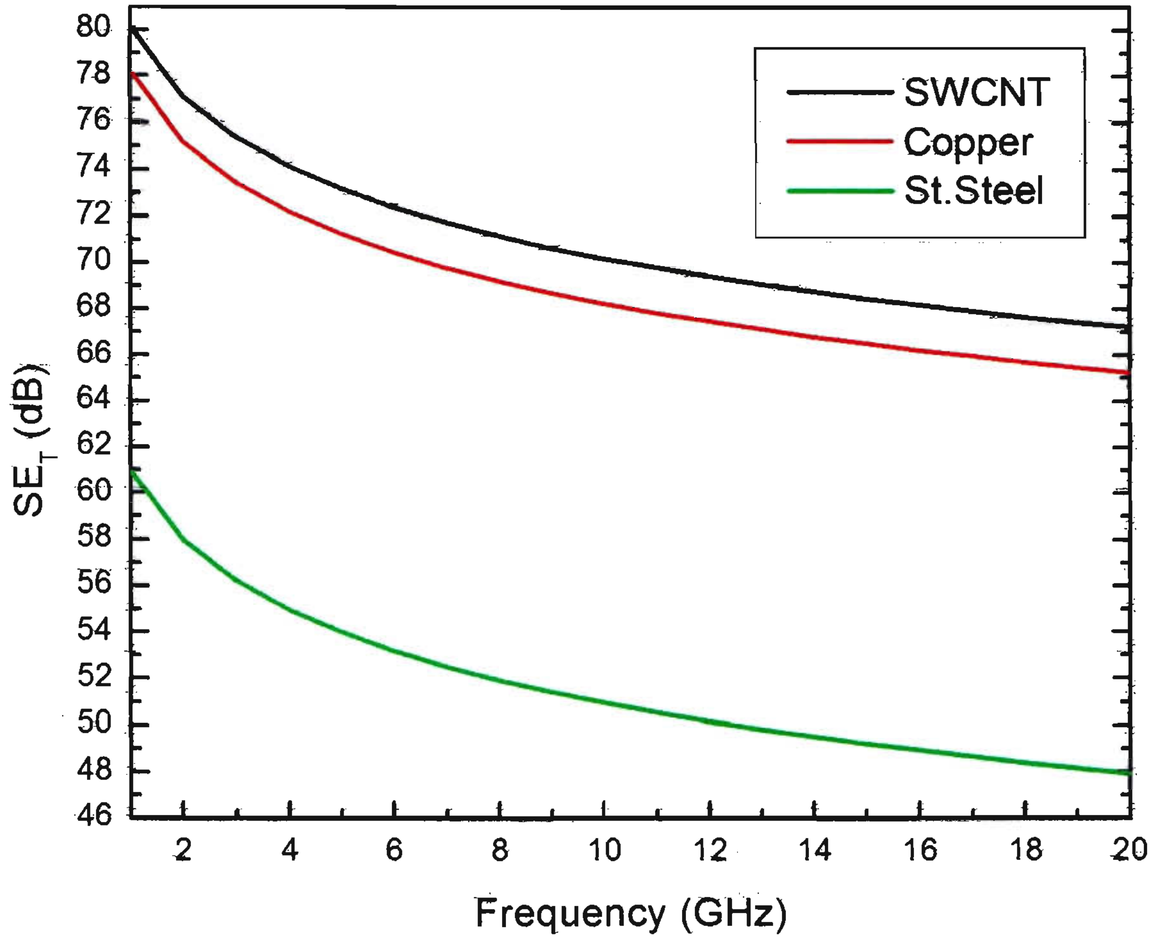

Fig: 3.6: Total shielding efficiency of SWCNT, Copper and St. Steel for a thickness of 5nm

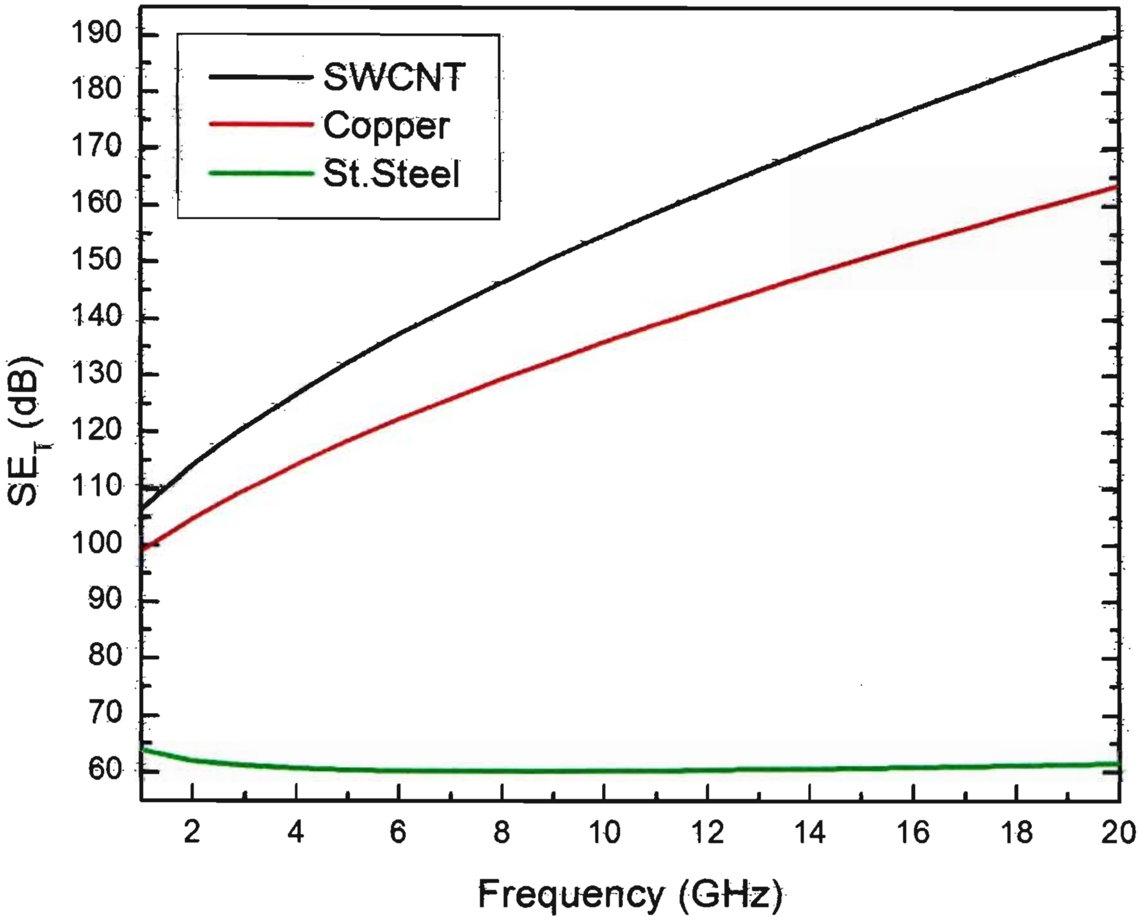

Fig 3.7 Total shielding efficiency of SWCNT, Copper and St. Steel for a thickness of 5μm

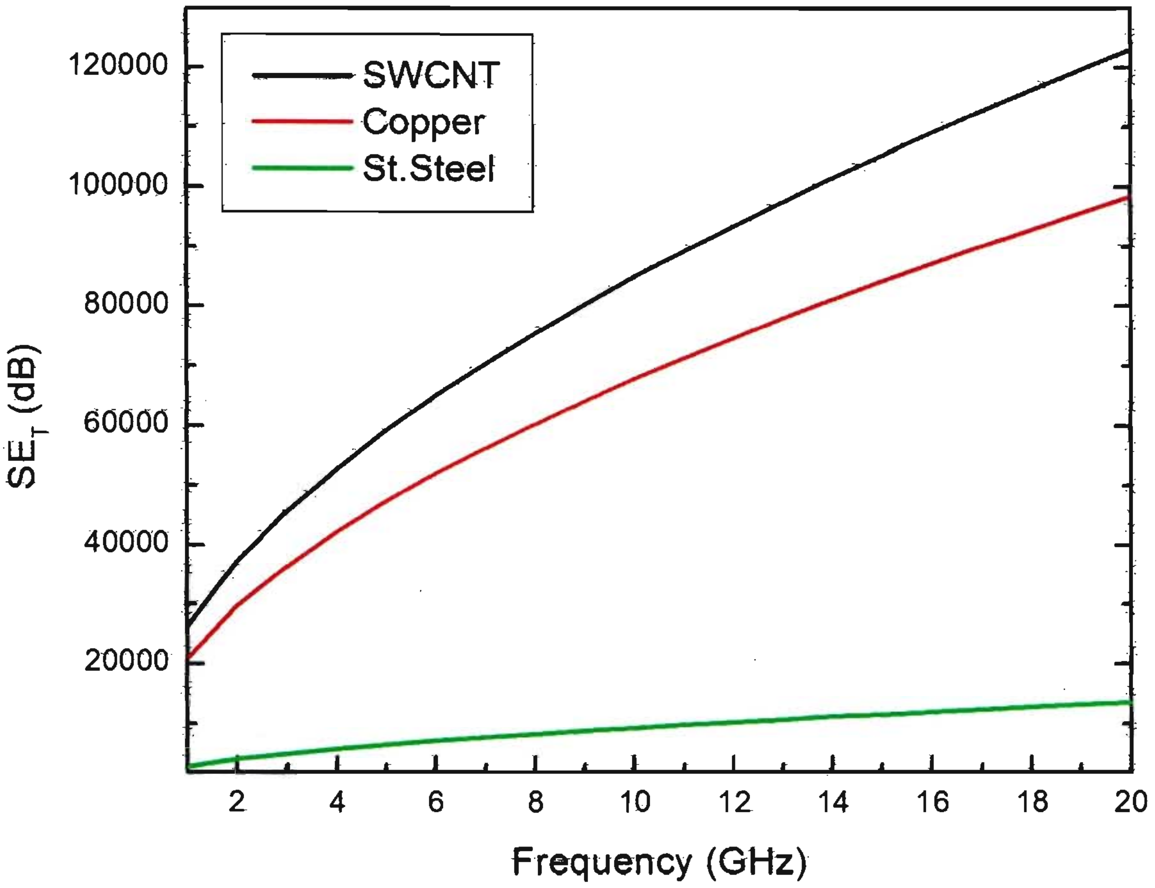

Fig 3.8 Total shielding efficiency of SWCNT, Copper and St. Steel for a thickness of 5 mm.

The total shielding efficiency is the sum of shielding efficiency due to reflection and absorption. From figures 3.3, 3.4 and 3.5, it is clear that shielding due reflection is the dominant mechanism of shielding than that of shielding due to absorption. The effects of frequency on the total shielding efficiency are shown in figure 3.6, 3.7, 3.8 for shielding thickness of 5nm, 5um and 5mm respectively. It is evident from these figures that in each case, SWCNT offers better EMI shielding efficiency than that of Copper and St. Steel.

3.5.6: Total Shielding Efficiency of SWCNT for different thickness

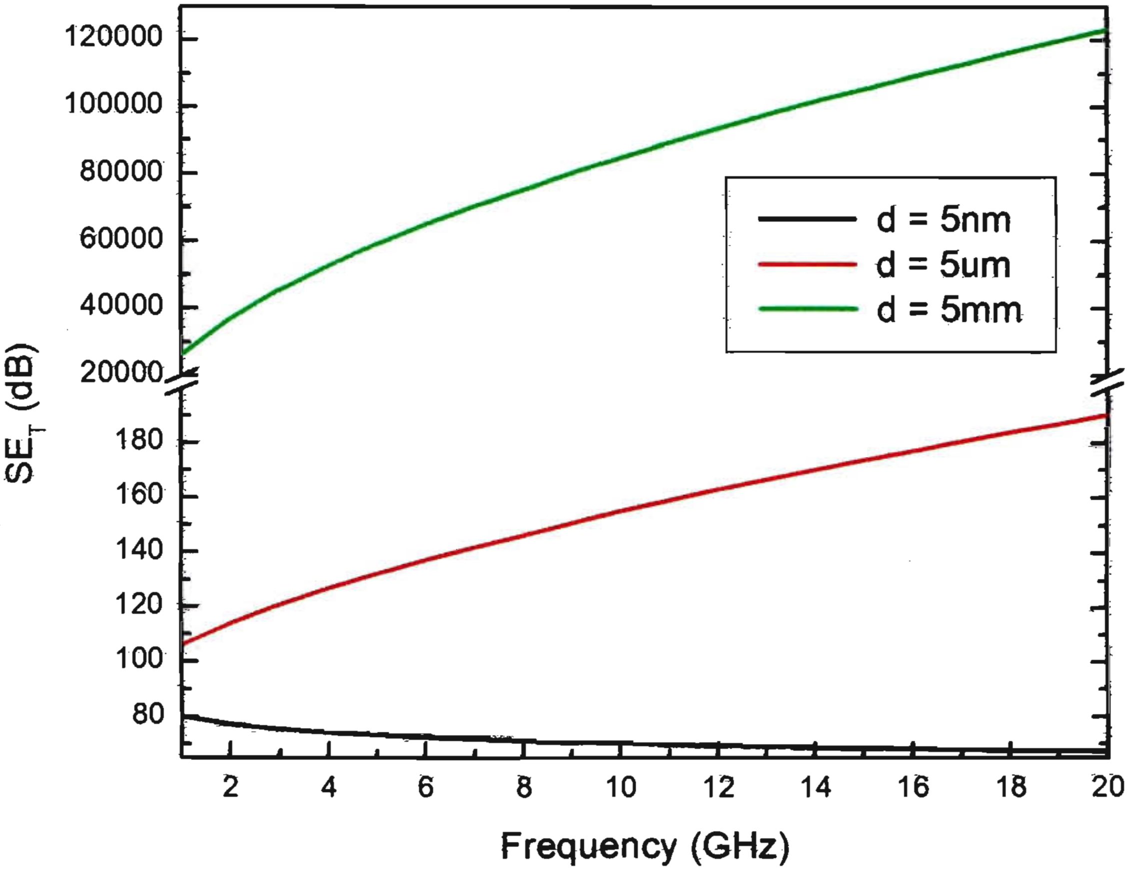

Fig 3.9 Dependence of total shielding efficiency of SWCNT on frequency and thickness

3.5.7: Total Shielding Efficiency of Copper for different thickness

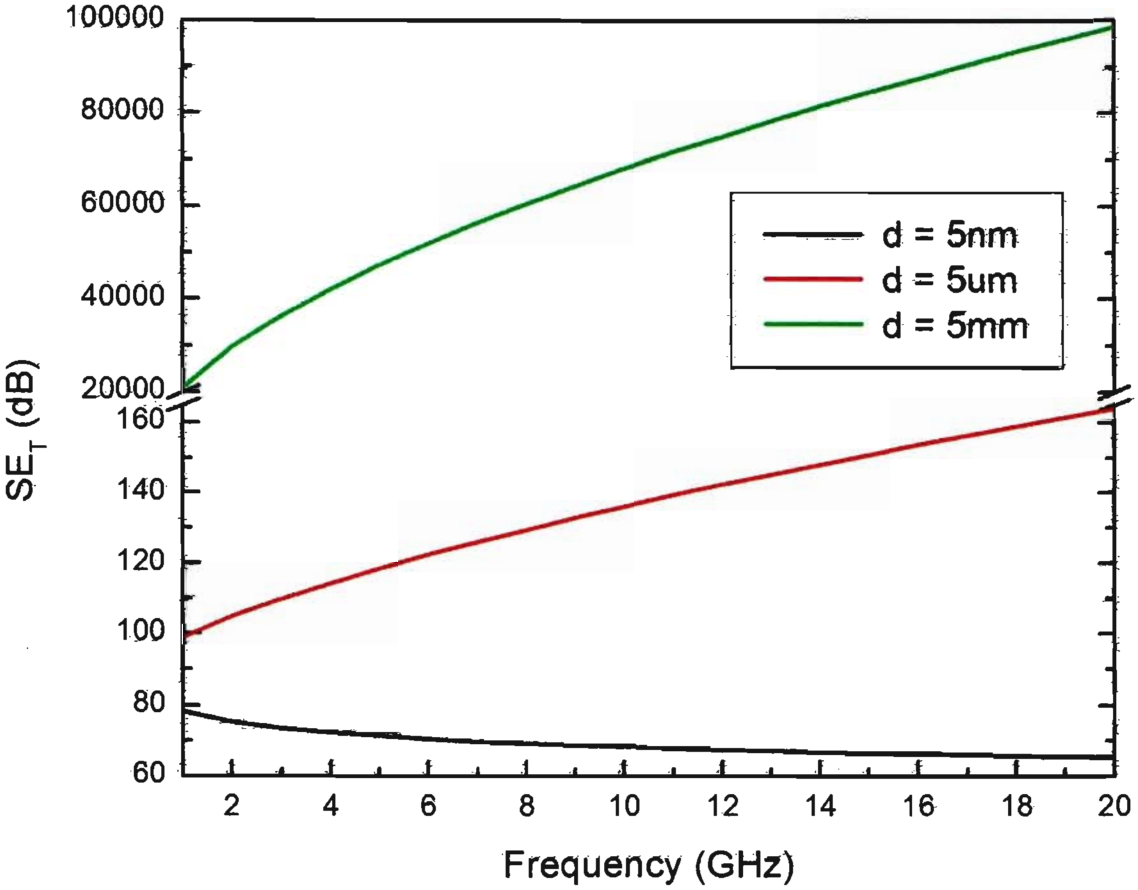

Fig 3.10 Dependence of total shielding efficiency of copper on frequency and thickness

3.5.8: Total Shielding Efficiency of Stainless Steel for different thickness

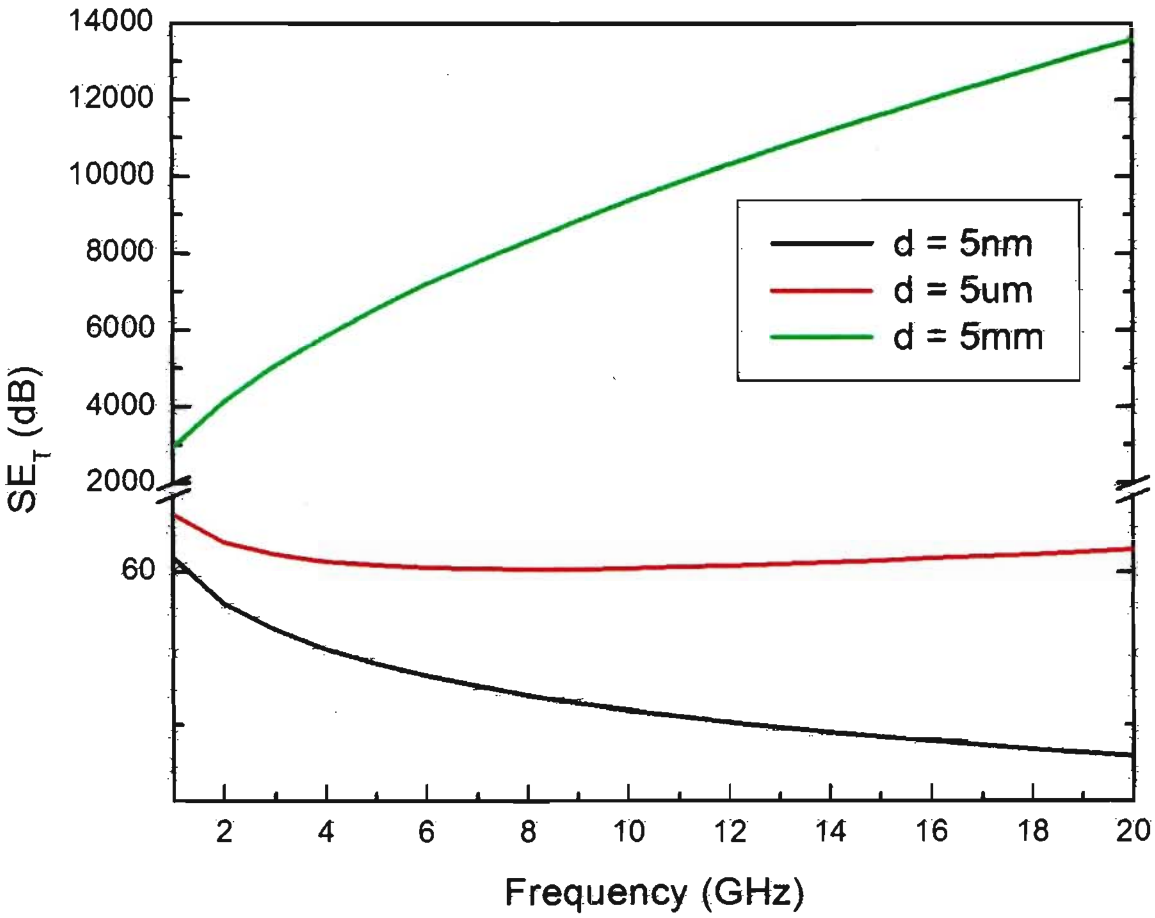

Fig 3.11 Dependence of total shielding efficiency of stainless steel on frequency and thickness

Also we have calculated shielding efficiency for different shielding thickness of SWCNTs. Figure 3.9 shows the effects of frequency on the shielding efficiency. It is noticed that total EMI shielding efficiency is decreasing with frequency when thickness of the shielding is below 5nm. However, it is increasing with frequency when thickness is over micrometer range. Again for Copper in figure 3.10 we found the same result like SWCNT. But for St. Steel in figure 3.11 it started changing its behavior from the micrometer range of thickness.

3.6 Advantage of SWCNT as EMI shield over mostly used shield:

From the previous discussion it is evident that SWCNT offers better EMI shielding efficiency than that of copper and stainless steel which are mostly used as EMI shielding material nowadays. SWCNT can be used as a better shield than Copper and St. Steel for below reasons:

- SWCNTs have much higher thermal conductivity than copper and St. Steel. Thus in a hot environment SWCNT may be used in place of metal.
- Conductive composites limitations as EMI shield: carbon/graphite suffers from brittleness, aluminum based has low impact resistance, and stainless steel has high density. The metal shield is susceptible for corrosion, which leads to Rusty Bolt Effect of nonlinearity to cause intermodulation problem especially in sea environment. The use of two different metals for shield and gasket causes galvanic corrosion which leads to nonlinearity and decrease in SE of the metallic shields [4].
- Conducting polymers is also good EMI shield but their thermal conductivity is poor compared with that of SWCNT.
- SWCNT is very light weight.

Transparent & flexible
EMI shielding

However, SWCNT is expensive compared with other EMI shielding materials.

References:

[1] Chun-Sheng Zhang, Qing-Qing Ni*, Shao-Yun Fu, and Ken Kurashiki. Electromagnetic Interference Shielding Effect of Nanocomposites with Carbon Nanotube and Shape Memory Polymer.

[2] Chris Rutherglen and Peter Burke*. Nanoelectromagnetics: Circuit and Electromagnetic Properties of Carbon Nanotubes. Volume 5, Issue 8, pages 884–906, April 20, 2009

[3] David M. Pozar, Microwave Engineering, 3rd Edn, *Wiley & Sons*, Singapore2009, p 687.

[4] Niranjanappa, A. C.; Biliya, R.; Trivedi, D.C. Seminar on State of the Art in EMI-EMC and Future Trens; India, 1996

Chapter 4

Conclusion

In this work, based on the literature, I have derived the expressions for the shielding efficiency of any material. After wards, I have calculated the shielding efficiency for SWCNT, copper and stainless steel. Metal based shielding materials suffer from heavy weigh, corrosion and difficulty in tuning their shielding efficiencies. Synthetic metal is good EMI shield due to their light weight, noncorrosive nature and commercial viability, but they have very poor heat dissipating capacity due to small thermal conductivity. That's why SWCNT can be the best alternative and most attractive as EMI shield due to their very light weight, high current density, high thermal conductivity (higher than copper), and mechanical stability. It is found that the shielding due to reflection is the dominant mechanism than shielding due to absorption. Also the total shielding efficiency is a strong function of frequency and thickness of the shielding material. It is also observed that the total shielding efficiency increases at higher frequencies with larger thickness; however, the total shielding efficiency decreases at higher frequencies at smaller thickness. For any thickness and frequency, the total shielding efficiency of SWCNT outperforms that of copper and stainless steel.