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Physical Parameter Based Model for Characteristic Impedance of SWCNT Interconnects and its Performance Analysis

Nisha Kuruvilla[1*], Kollarama Subramanyam [2] and J.P. Raina[3]

[1,2&3](Center of Nanotechnology, VIT University, Vellor, Tamilnadu, India)

[1*] (Electronics and Communication Department, College of Engineering, Chengannur, Kerala, India)

([*] E-mail of the corresponding author: nisha@ceconline.edu)

Abstract

Single walled carbon nanotubes (SWCNTs) have been identified as a possible replacement for copper interconnects due to their magnificent electrical and material properties. A series of performance predictions of these interconnects have been done in the last decade. Even then none of the literatures have been provided compact expression for characteristic impedance (Z_o) in terms of physical parameters of SWCNT interconnects. A simplified representation of characteristic impedance and the analyze the transient behavior under different mismatch conditions will enable the chip designer to optimize the performance of total circuitry. These studies give an overview of safe amount of load mismatch that can be tolerated by different lengths of interconnects without causing any signal reliability issues.

Keywords: SWCNTs, CNT Interconnects, characteristic impedance, transient response, frequency response, load mismatch

1. Introduction

Carbon nanotube (CNT) was an allotrope of carbon discovered by Iijima (Iijima S, 1991) . Since then, CNTs have been proposed as a leading contender for continued improvement in speed and enabling improvement in downward scaling of I.C. (G. D. Mildred, S.Dresselhaus, 2001). Interconnects made of traditional interconnecting materials are considered as the main hurdle for that giga-scale integration because of the RC delay that is added to the critical paths, the dissipation, noise and cross-talk and the vulnerability to electro migration. Carbon nanotubes can potentially address these challenges if they are optimally utilized (Ali Javey, Jing Kong, 2009).

Several attempts have been made by many, to study the performance of SWCNTs in interconnect applications (O. Jamal and A. Naeemi, 2011) (A. Nieuwoudt and Y. Massoud, 2006) (Arijit Raychowdhury and Kaushik Roy, 2006) (Azad Naeemi and James D. Meindl, 2009) (A. Naeemi, R. Sarvari, and J. D. Meindl, 2005) (P.J. Burke, 2002) (F. Kreupl, A. P. Graham, M. Liebau, G. S. Duesberg, R. Seid and E. Unger, 2004) (HongLi, Chuan Xu, Navin Srivastava and Kaustav Banerjee, 2009). Most of these studies got initiated after the proposed RF equivalent model for SWCNT interconnects by (P.J. Burke , 2002) . This is the basic electrical model which has been used in most of the performance analysis of SWCNT structures. As the inherent quantum resistance of an individual CNT interconnect is high, a proposal for using them in bundle got attention (Navin Srivastava and Kaustav Banerjee, 2005). A model for tightly packed SWCNT bundles was proposed by (Kaustav Banerjee and Navin Srivastava, 2006). In that work they compared the performance of SWCNTs against copper. A review of comparative studies between SWCNT, MWCNT and 1D- graphene sheets with respect to copper has been done by (HongLi, Chuan Xu, Navin Srivastava and Kaustav Banerjee, 2009). Mean while series of performance predictions of SWCNT interconnects from various perspectives were carried out by (A. Nieuwoudt and Y. Massoud, 2006) (Yehia Massoud, Arthur Nieuwoudt, 2006). In their work they evaluated the effect of variations in multiple process parameters on latency of bundled carbon nanotube interconnects. A real life possible implementations of carbon nanotubes in interconnect applications was demonstrated by (F. Kreupl, A.P. Graham , G.S. Duesberg , W. Steinhogl, M. Liebau, E. Unger and W. Honlein, 2002). The maximum supporting bandwidths of various lengths of CNT interconnects both in SWCNT and bundled SWCNT with perfect contacts and without any repeaters under various loading conditions were analyzed by (Nisha Kuruvilla, J. P. Raina, 2009). A work on the analysis of realistic carbon nanotubes (in both SWCNT and bundled SWCNT) on chip interconnects by considering the process variations in the contact resistance under various loading is reported by (Nisha Kuruvilla, J. P. Raina, 2008). The performance and reliability analysis of bundled CNTs due to process variations were also evaluated by (Nisha Kuruvilla, J.P. Raina, A.G.John and A. Athulya, 2010).

All these works agree with the fact that CNTs are capable of carrying signals of Tetra Hertz frequencies. Impedance mismatch and the effect on transient behavior have not been analyzed and this can introduce serious signal integrity problem specifically in CNT interconnects (Debaprasad Das and Hafzur Rahaman, 2011) (Manoj Kumar Majumder, Nisarg D. Pandya, B. K. Kaushik, and S. K. Manhas, 2012). For high-speed interconnect design; signal integrity has become a critical issue and needs selection of proper termination and consequently appropriate circuit design. None of the reported works cited have critically evaluated the amount of mismatch that can be tolerated when there is load mismatch. Also there is no literature available with compact relations for extracting Z_o as a function of physical parameters such as length, diameter and frequency of operation. This work is aimed to fill this gap.

Section 2 gives the overview of the compact modeled expression for characteristic impedance and its verification. In section 3 the variation of characteristic impedance along with variations in length and frequency has been analyzed. Section 4 and 5 discuses the variation of transient response and frequency response under load mismatch conditions. The section 6 discusses the conclusions drawn.

2. Compact model for characteristic impedance

A simplified compact expression for characteristic impedance is derived in terms physical parameters such as length, diameter and frequency. The electrical phenomenological model of SWCNT in Figure 1(a), is used for the modeling Z_0. The L-section equivalent circuit composed of various resistive, inductive and capacitive effects which are discussed below.

The resistance of CNT consists of contact resistance, quantum resistance and scattering resistance. Quantum resistance of CNT, which arises due to the flow of electrons in the conducting channel, is given by

$$R_Q = \frac{h}{2e^2N}\ \Omega \qquad (1)$$

Where R_Q= 12.9kΩ, N represents the number of conducting channels in the CNT and in bundle form. The ballistic nature of the CNT generally depends on whether the length of the nanotube is less or greater than its Mean Free Path (MFP) (λ). Scattering of electrons occurs for length more than the MFP of CNT. Note that scattering also occurs for lengths less than MFP. This scattering resistance is given by (Kaustav Banerjee and Navin Srivastava, 2006).

$$R_S = \frac{h}{2e^2N}\frac{l}{\lambda}\ \Omega \qquad (2)$$

where l and λ are length and MFP of CNT respectively. The work done by (X. J. Zhou, J. Y. Park, S. M. Huang, J. Liu, and P. L. McEuen, 2005) revealed that MFP depends on diameter as given in eq.(3).

$$\lambda = \frac{D\,v_F}{\alpha T} \qquad (3)$$

where D is the diameter, v_F is the Fermi velocity, α is the coefficient of scattering rate and T is the temperature. The work done in (Azad Naeemi and James D Meindl , 2007) (A. Naeemi and J. D. Meindl, 2007) indicate that for an SWCNT of diameter 1nm, MFP is 1μm. Hence throughout this work λ is approximated as 1000D. With the advancements in fabrication technology, perfect metal CNT contacts can be possible (M. Nihei et. al. , 2005). Hence in this work contact resistance is ignored.

Inductance of the nanotube consists of kinetic inductance (L_K) and magnetic inductance (L_M). The kinetic inductance per unit length of the nanotube is given by

$$L_k = \frac{h}{2e^2v_F} \approx 16\ \text{nH}/\mu\text{m} \qquad (4)$$

The magnetic inductance of SWCNT is given in (5) which can be ignored from the equivalent inductance calculations since it is a weak function of ratio between the nanotube diameter and the distance (t) to the "ground plane".(P.J. Burke, 2002), (Hong Li et. al., 2008)

$$L_M = \frac{\mu}{2\pi}\cosh^{-1}\left(\frac{2t}{D}\right) \qquad (5)$$

The capacitance of the nanotube consists of quantum capacitance (C_Q) and electrostatic capacitance (C_E) (P.J. Burke, 2002). The quantum capacitance per unit length of the nanotube is given by

$$C_Q = \frac{2e^2}{hv_F} \qquad \ldots\ \ldots(6)$$

While the electrostatic capacitance per unit length of CNT is given by

$$C_E = \frac{2\pi\varepsilon}{\cosh^{-1}\left(\frac{2t}{D}\right)} \quad \text{...} \quad (7)$$

The characteristic impedance of typical RLC network shown in Figure 1(a) is

$$Z = \sqrt{\frac{L}{C} - \frac{jR}{\omega C}} \quad (8)$$

The physical parameter based model for characteristic impedance can be derived by solving equation (8) using equations (1-7). Two separate models characteristics models for Z_0 and Z_0' were derived for interconnect length less than mean free path ($l \leq \lambda$) and also for interconnect lengths greater than mean free path ($l > \lambda$), as scattering of electrons occurs beyond MFP.

$$|Z_0| = \frac{1}{10^{-3}}\left[\sqrt{\left(1 + 1.8\ln\frac{2t}{D}\right)\sqrt{100 + \frac{65 \times 10^{12}}{\omega^2 l^2}}}\right] \quad \text{for } l < \lambda \quad (9)$$

$$|Z_0'| = \frac{1}{10^{-3}}\sqrt{\left[\left(1 + 1.8\ln\frac{2t}{D}\right)\sqrt{100 + \frac{65\times10^6}{\omega^2}\left(\frac{1000}{l} + \frac{1}{D}\right)^2}\right]} \quad \text{for } l > \lambda \quad (10)$$

This model can be extended to SWCNT bundles by estimating R, L and C of bundle interconnects in terms of number of CNTs in a bundle (n_{CNT}) (Navin Srivastava and Kaustav Banerjee, 2005).

For SWCNT bundle Z_0 and Z_0' and are given by

$$|Z_0| = \sqrt{\frac{4\times10^{-3} l}{n_{CNT} * m}\sqrt{1 + \left(\frac{65\times10^{10}}{\omega^2 l^2}\right)}} \quad \text{for } l<\lambda \quad (11)$$

$$|Z_0'| = \sqrt{\frac{4\times10^{-3} l}{n_{CNT} * m}\sqrt{1 + \frac{65\times10^4}{\omega^2}\left(\frac{1000}{l} + \frac{1}{D}\right)^2}} \quad \text{for } l>\lambda \quad (12)$$

Where 'm' is given by

$$m = \frac{C_Q C_E}{C_Q + C_E} \quad (13)$$

$$C_E^{bundle} = 2C_{En} + \frac{n_W - 2}{2} C_{Ef} + \frac{3(n_H - 2)}{5} C_{En} \quad (14)$$

$$C_Q^{CNT} = C_Q^{CNT}.n_{CNT} \quad , \; C_{En} = \frac{2\pi\epsilon}{\ln\left(\frac{w}{D}\right)} \quad , \; C_{Ef} = \frac{2\pi\epsilon}{\ln\left(\frac{2w}{D}\right)} \quad (15)$$

where 'w' is the width of the interconnect bundle and D is the diameter of the CNT

2.1 SPICE verification of characteristic impedance

This work proposes two sets of equations for characteristic impedance of SWCNT and SWCNT bundle. Each set of equations calculate characteristic impedance for length less than MFP and greater than MFP for both interconnect geometries. The authenticity of these equations is validated against real life scenario of RLC circuit simulation using SPICE.

For SPICE simulation, symmetrical circuit is considered. Usually symmetrical sections can be of either T or π type. These are built of unsymmetrical L-sections, connected together in one fashion for T-network and oppositely for π network. For symmetrical networks image impedances at input and output are equal and this image impedance is called as characteristic impedance Z_0. Hence for any symmetrical network, Z_0 is calculated using eq. (16).

$$|Z_0| = \sqrt{Z_{OC} Z_{SC}} \qquad (16)$$

Hence the characteristic impedance can be obtained from the open circuited and short circuited impedance from any of the ports of the symmetrical T-network.

In order to estimate the Z_0 of CNT interconnects, the proposed electrical equivalent model of unsymmetrical L-section is transformed into symmetrical T-section (Debaprasad Das and Hafzur Rahaman, 2011) as shown in Figure 1 (b).

The symmetrical network shown in Figure 1(b) can be represented either as Lumped or distributed network. The magnitude of Z_0 is calculated from simulation using eq. (18), both from the lumped as well as distributed network models of CNTs. In both scenarios the obtained Z_0 is found to be in agreement with impedance obtained from eq. (9)-(12). Figure 2 gives the comparison of impedance obtained from compact expression against SPICE simulation of SWCNT interconnects of length 1μm (<MFP) and a diameter of 1nm. The compact expression is in agreement with simulated values up to 1THz. Beyond 1THz, the impedance obtained from SPICE simulation starts increasing as Z_{OC} increases at high frequency due to inductive reactance. Similarly for an interconnect length of 10μm (l >MFP) impedance vs frequency graphs is shown in Figure 3.

In case of compact bundled SWCNT interconnect, verification of computed expressions for Z_0 are given in eq.(11)-(12) and was done against various technology nodes such as 28nm, 22nm and 18nm. For each technology node, bundle height to width ratio is fixed as 1:2 (ITRS, 2007 edition Interconnects (2008 Update Interconnects)). The number of CNTs in a bundle was calculated based on the work given in (Navin Srivastava and Kaustav Banerjee, 2005). Figure 4 gives the comparison of compact expression against SPICE simulation. In this case length of interconnect is fixed as 1μm. These results indicate that the proposed compact expressions will help us to directly calculate impedance of a nanotube structures in very simple wave using only the physical information such as length, diameter of the tube and frequency of the interest. The characteristic impedance of the modeled expressions are verified against the published results (P.J. Burke, 2002) and impedance obtained from the simulation of equivalent circuit model of CNT interconnects using SPICE tool and it is shown in the Table 1.

3. Variation of characteristic impedance as a function of length and frequency

This work also evaluated the variation of characteristic impedance as a function of length and frequency. In this analysis CNTs of diameter 1nm is considered to start with. The 3D plot given in Figure 5 consolidates variation of characteristic impedance of SWCNT as a function of frequency and length. Figure 6 consolidates variation of characteristic impedance of bundled SWCNT as a function of frequency and length. The SWCNT bundle structure considers for this consolidation are compatible with 18nm technological node (ie. height: width = 36nm:18nm)

4. Transient response of SWCNT interconnects under load mismatches

The equivalent circuit in Figure 1(a) is terminated at both input and output with Z_0 calculated from eq. (9)-(12) to observe the transient response of the nanotube. Transient behaviors of signals through SWCNT interconnect under matched and mismatched conditions are given in Figure 7. The magnitude of critical mismatch variation in the impedance is given in Table 2.

Input impedance is matched with the impedance of the nanotube as transmission line and the output impedance is varied. When the output impedance is matched to the impedance of the nanotube, there is no ringing in the transient response output. Ringing occurs when there is mismatch between output impedance and impedance of the nanotube as transmission line. Nanotube interconnect in circuit configuration will function without introducing signal integrity issues, if the overshoot or undershoot due to ringing is less than 30% of the settled value. The critical mismatching condition is thus estimated from the impedance at which the overshoot crosses 30% of the settled value is tabulated for different lengths of interconnects in Table 2. It can be observed that the critical mismatching impedance of SWCNT is same for any length of interconnect. For SWCNT bundle, the critical mismatching impedance ranges from 0.35kΩ to 1.73kΩ.

5. Frequency response of SWCNT interconnects under load mismatches

The frequency response of SWCNT interconnects under load mismatches are as shown in Figure.8. From the transient response we have obtained the critical mismatch impedance up to which the circuit can withstand. From the frequency response we obtain the corresponding 3 dB frequency at critical mismatch impedance is tabulated and given in Table 3.

6. Conclusion

A Physical Parameter based expressions for calculation of characteristic impedance of SWCNT/bundled SWCNTs interconnects geometries are proposed as a function of physical parameters such as length, diameter and frequency and validated against SPICE simulated results and with other published results as indicated in Table 1 and Table 2. The variation of characteristic impedance as a function of frequency and length of interconnects is also predicted with this model. This will facilitate designers to fix appropriate loading impedance for CNT interconnects so that signal reflections and attenuations are bare minimum. This work also evaluates the range of frequencies that can be transmitted through these interconnects at different lengths under critical mismatch conditions.

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Nisha Kuruvilla:- She received her M.Tech (Electrical Engineering) degree with specialization in Microelectronics and VLSI from IIT, Kanpur and B.E (Electronics) from Dr. Babasaheb Ambedkar Marathwada University, Aurangabad. She is currently serving College of Engineering, Chengannur as Head of the Department (Electronics) and also peruse towards her doctoral degree under the guidance of Prof. (Dr.) J .P. Raina at Center of Nanotechnology, VIT Vellore. She is a recipient of 'Outstanding IEEE Student Branch Counselor International award' for the academic year 2005-2006.Her areas of interest Include Carbon nanotube Interconnects, interconnect optimization, low power VLSI and optical wireless. She has authored / co-authored around 15 technical papers in international journals/ conferences.

Kollarama Subramanyam:- He received his M.Tech (Nanotechnology) degree with specialization in Nanoelectronics and Nanophotonics from VIT University, Vellore in 2012 and B.Tech degree (Electronics and Communications) from VIT University, Vellore in 2010. He is currently working on CNT based interconnects. His areas of interest include Carbon nanotube interconnects, graphene nano ribbon based transistors and heterostructure transistors. He authored / co-authored 2 technical papers in international conferences.

PROF. (DR.) J. P. RAINA:- Born 1937 in SGR (KMR), obtained M.Sc.(Physics) degree from M.S. University, Baroda, and subsequently obtained D.Sc. (Engg.) degree from UCL Belgium . Worked in CEERI , Pilani (Raj) in various capacities from 1961 to 1979. Joined I.I.T. Madras in 1979 as Professor and Head, T.V.Engg., Image Signal Processing, Photonics and Fiber Optics Communication, in the Elect. Engg. Deptt;. Retired from I.I.T. Madras in 1998 and from 1999 till 2004 was Managing Director of A.T.I.I.T. Chennai. Joined V.I.T. University as Dean School of Electrical Sciences in 2005. In 2008 took charge as Director of Center for Nanotechnology Research, were presently continuing. During the past 52 yrs of Teaching and Research experience handled large number of sponsored research projects from DRDO, ARDB, DOE and DST of Govt; of India. Handled number of International assignments, organized many International and National conferences, guided nearly 14 Ph.D. scholars and presently guiding 6 Ph.D. scholars at V.I.T. University. Published nearly 90 papers in International and National journals, Edited number of books and took 7 national patents. Received prestigious National Award from President of India's Gold Shield for Invention Promotion. Present interest in Nanotechnology, Nanophotonics /Plasmonics, Low Power Electronics, Image Signal Processing

Table 1 – Comparison of Characteristic Impedance values of SWCNT interconnect with a length of 1µm and CNT diameter of 1nm

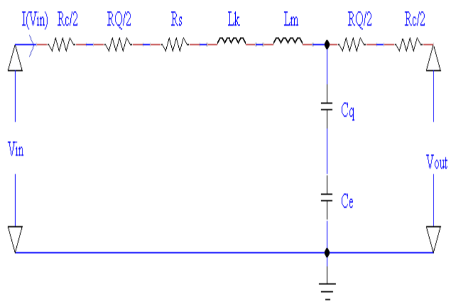
Frequency (Hz)	Impedance (in this paper) of SWCNT	Impedance (P.J. Burke, 2002)	Impedance (obtained from simulation)
10	1.23e+9	1.23e+9	1.23e+9
10^3	1.23e+8	1.23e+8	1.23e+8
10^6	3.88e+6	3.88e+6	3.89e+6
10^9	1.22e+5	1.22e+5	1.23e+5
10^{12}	10.8e+3	10.8e+3	6.71e+3
10^{13}	10.8e+3	10.8e+3	1.25e+5

Table 2. Critical Mismatch Impedance for different length of single SWCNT and Bundle SWCNT

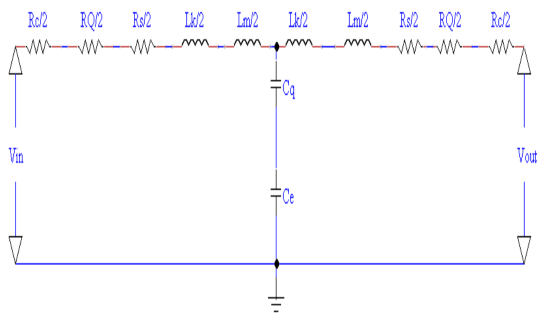
Type of the Interconnect	Length of interconnect (nm)	Critical mismatching impedance (Ω)
SWCNT	1	3.5e+4
	10	3.5e+4
	100	3.5e+4
	1000	3.5e+4
	10000	3.5e+4
SWCNT Bundle (18nm Technology node)	1	1.7e+3
	10	350
	100	350
	1000	350
	10000	500

Table 3. Comparison of 3 dB frequencies of single SWCNT and SWCNT bundle

Type of the Interconnect	Length of interconnect (nm)	3 dB frequency (Hz) at critical mismatch
SWCNT	1	6.52e+14
	10	6.52e+13
	100	6.52e+12
	1000	6.52e+11
	10000	6.52e+10
SWCNT Bundle (18nm Technology node)	1	1.06e+16
	10	9.82e+14
	100	9.82e+13
	1000	9.82e+12
	10000	1.03e+12



(a)



(b)

Figure 1. (a) Equivalent circuit model of SWCNT interconnect (b) Equivalent Symmetrical T-section for Lumped SWCNT interconnect

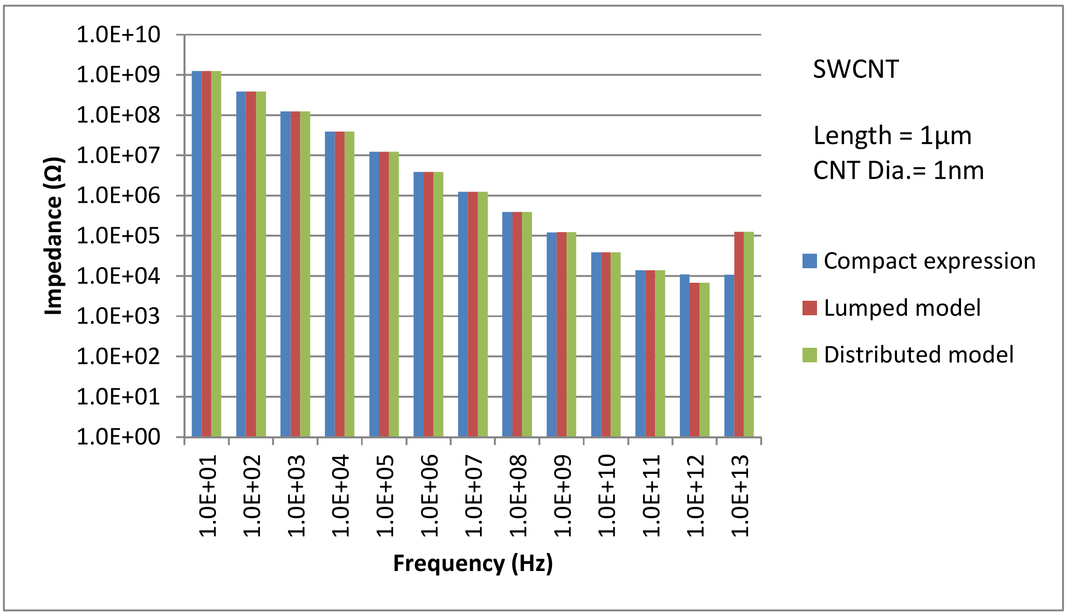


Figure 2. SPICE simulation of SWCNT interconnects for impedance of (i) Lumped Model, (ii) Distributed model compared with impedance calculated from compact expression.

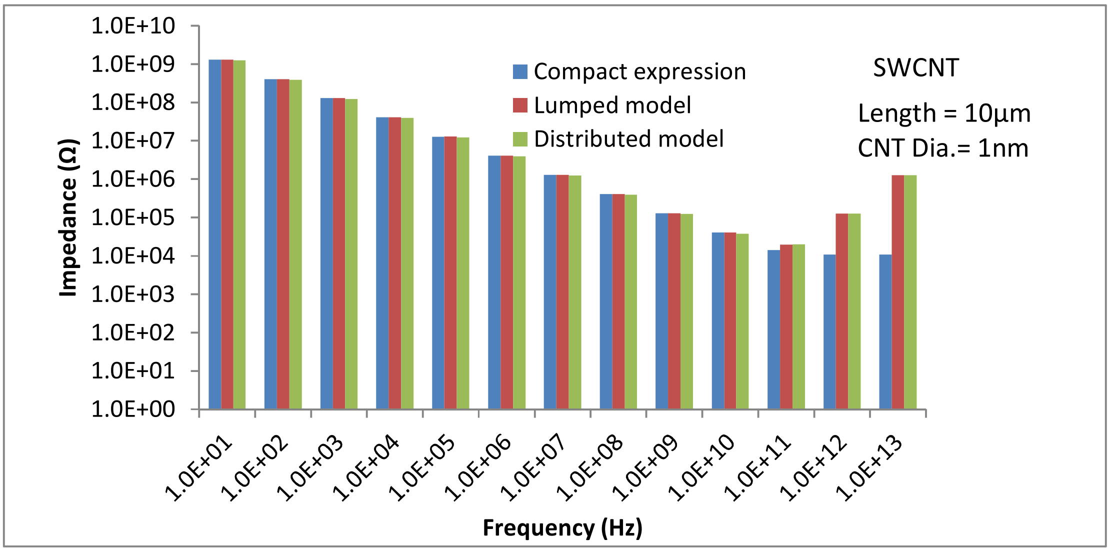


Figure 3. SPICE simulation of SWCNT interconnects for impedance of (i) Lumped Model, (ii) Distributed model compared with impedance calculated from compact expression.

Figure 4. Impedance calculated from compact expression compared with corresponding impedance obtained from SPICE simulation of lumped model at different technology nodes of SWCNT bundle.

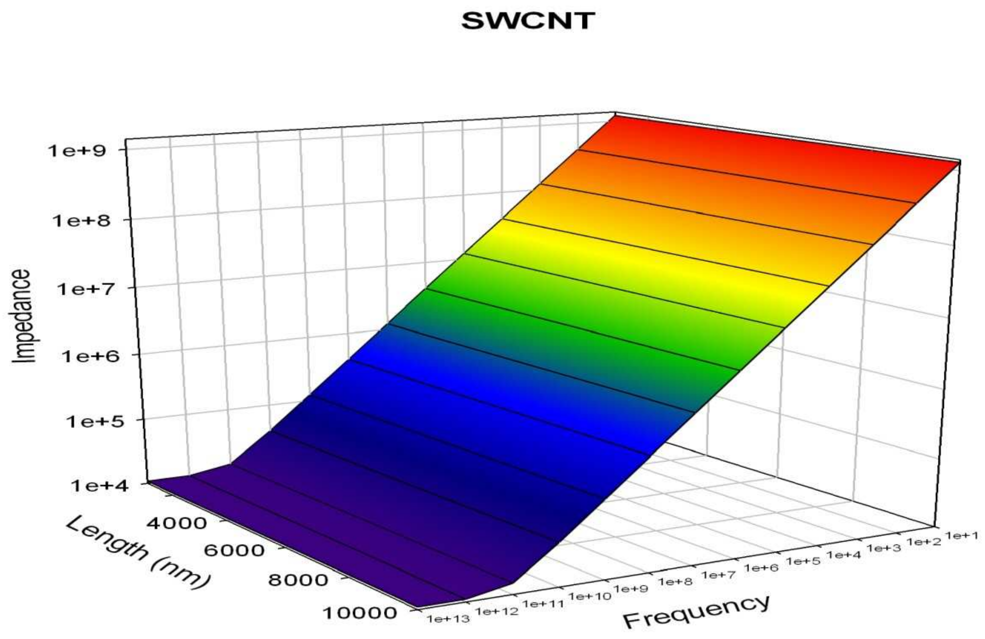


Figure 5. A 3D plot of Impedance as a function of Length and Frequency for single SWCNT interconnect. Diameter of the nanotube is 1nm. Diameter of the SWCNT is 1nm

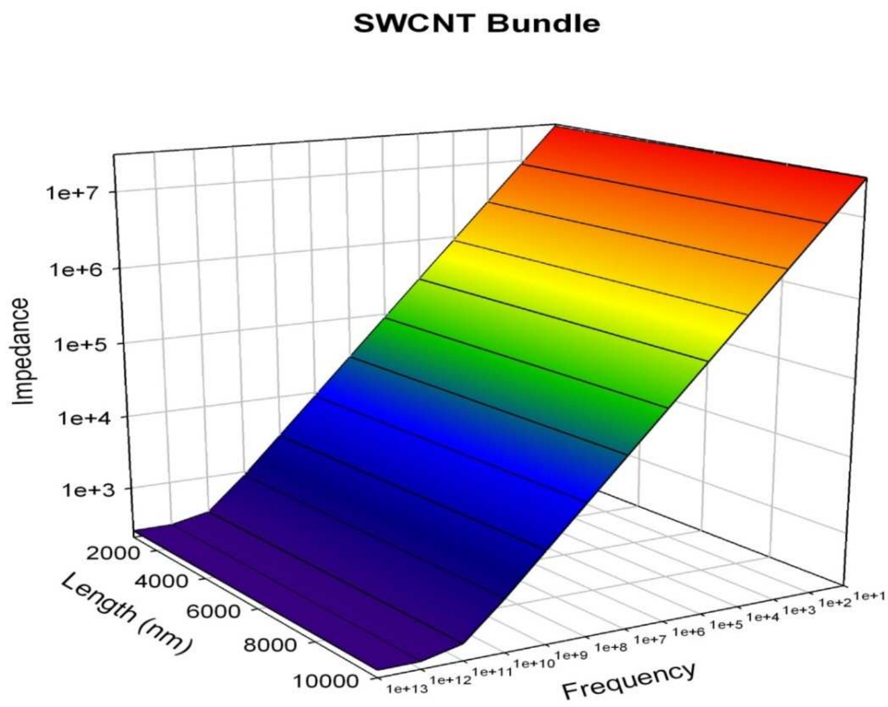


Figure 6. A 3D plot of Impedance as a function of Length and Frequency for SWCNT Bundle interconnects. Diameter of the nanotube is 1nm for 18nm technological node

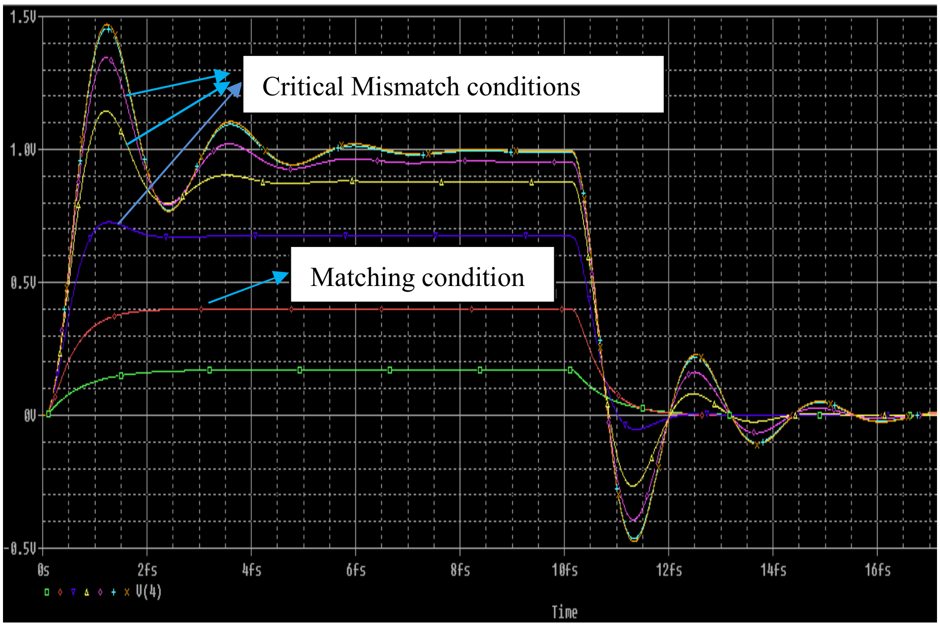


Figure 7. Transient behavior of SWNT interconnects for Matching and Mismatching conditions.

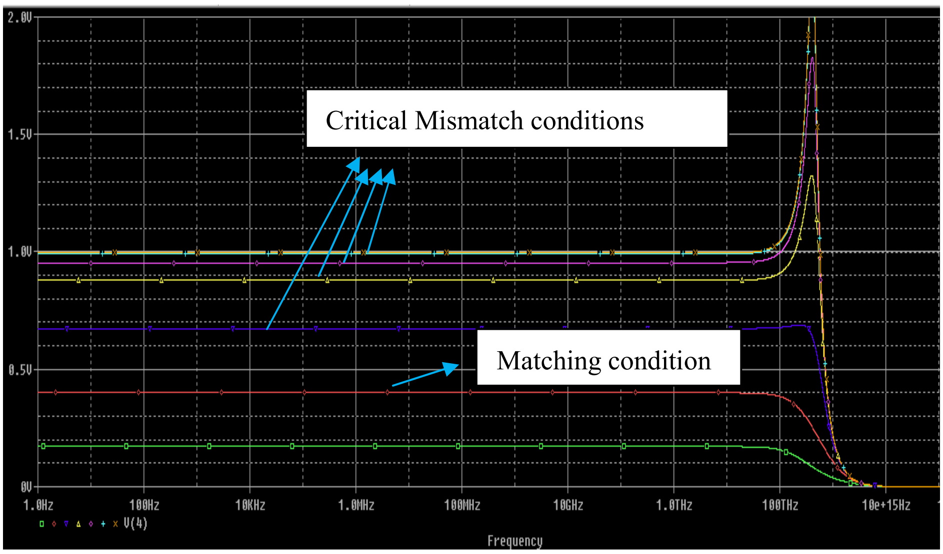


Figure 8. Frequency Response of SWCNT for Matching and Mismatching conditions.