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A Simulation Tool for the Evaluation of the Performances of A Nanointerconnect Based on SWCNT

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Abstract. A simple approach based on the commercial package PSIM® is used for simulating the behaviour of a principle InterConnect (IC) based on a Single Wall Carbon NanoTube(SWCNT) modelled by an equivalent Transmission Line (TL). The simulator is also employed for computing all the per unit length parameters of the TL in terms of the geometrical, physical and thermal dependencies of the considered structure. An equivalent two port circuit is developed that can be used both for time and frequency domain analysis of the nano-ICs, including also the interesting feature of the evaluation of the performances ranges occurring in presence of characteristic parameter variations.

Key words: nanointerconnect, Carbon Nano Tubes, circuital simulation.

1. Introduction

The continuous miniaturization and the increase of the working frequencies and power density of future nano electronics integrated circuits drive towards innovative realizations for on chip interconnections and vias. The actual technology based on copper will no longer satisfy future requirements in terms of electrical and electromagnetic performances [1]. In fact, it has been shown that at very low cross section the resistance of copper, due to grain boundary scattering, surface scattering and the presence of the very resistive diffusion barrier layer may be affected by steep increase, thus hindering the interconnect speed and reliability [2]. In particular, the waveform of the output voltage V_2 would be characterized by a reduced amplitude and by an unacceptable time delay with respect to the input V_1.

For these reasons, Carbon NanoTubes (CNTs) have been proposed for the realization of future interconnects in gigascale systems [3–7]. They are rolled up sheets of graphene exhibiting a mean-free path for the electrons of the order of the micrometers, hence much larger than that of copper and characterized by high current carrying capability and remarkable thermal and mechanical stability. The CNT may be single-walled (SWCNTs, i.e. only one shell) or multi-walled (MWCNTs i.e. nested tubes). While SWCNTs can be either metallic or semiconducting, MWCNTs behave always as metallic conductors.

Research efforts are therefore aimed at building up a CNTs-based interconnect technology, acting on both the capability of producing CNTs with controlled physical and geometrical characteristics and on the development of reliable simulation models for the analysis and design of the devices (see for example [8] and references therein). Along this stream reliable simulation tools, able to take into account the influence on electromagnetic performances due to the variations of the physical characteristics, are very important [9–11]. Several approaches have been developed in order to analyse the behaviour of CNT-based nano-IC and evaluate some relevant electromagnetic performances [12–15].

In this paper a simple but widely adopted approach employing an equivalent Transmission Line (TL) is used for simulating the behaviour of a principle nano-interconnect in which the conductor is formed by a SWCNT. Although such a configuration is someway not viable in real applications, it allows to develop a simulation tool characterized by some interesting features. The variability of some important geometric and physical properties of the device is taken into account by efficiently evaluating the nonlinear expressions linking such variable characteristics to the per unit length parameters of the TL, through a peculiar feature of the adopted commercial simulation package PSIM® [16]. The proposed simulation tool can be used for computing some interesting performances of the nano-IC both in time and frequency domain. Hence, and this represents a distinctive aspect of this paper, the simulator is used for a twofold aim: the evaluation of the TL parameters and the study of the time evolution of the CNT-based IC when such parameters are assumed as variable.

The paper is organized as follows. Firstly the characteristic parameters of the TL model and their relationships with the geometric and physical and properties of the CNT structure are considered. Successively the results of the numerical simulations are discussed and finally some conclusion and perspectives for future work are presented.

2. Nano-IC and its circuit model

The schematic set-up of a nano-IC and its made-up implementation through a SWCNT are shown in Fig. 1. In Fig. 1b the relevant geometric and physical parameters considered as variable due to the technological production processes are also indicated. They are the radius of the SWCNT, a, the length of the nano-IC, L, the distance between the centre of the SWCNT and the ground, d. The variable physical properties are the electron mean free path in the SWCNT, l_{mfp} and the relative permittivity of the surrounding medium ε_r.

The associated TL circuit modelling the behaviour of the nano-IC is shown in Fig. 2. The considered TL is formed by N cells simulating an IC section of length dx: the resistance, inductance and capacitance (R', L', C') of each cell are obtained from the corresponding per unit length (p.u.l.) parameters which, in turn, depend on the geometric and physical properties of the CNT-based structure [11–12].

In particular, the p.u.l. damping resistance R', the total p.u.l. inductance L' and capacitance C' of the nano-TL, which will be discussed later in more detail, are given respectively by:

$$R' = \begin{cases} \dfrac{h}{4 \cdot e^2} \cdot \dfrac{L}{l_{mfp}} & \text{with} \quad L > l_{mfp} \\ \dfrac{h}{4 \cdot e^2} & \text{with} \quad L \leq l_{mfp} \end{cases}, \tag{1}$$

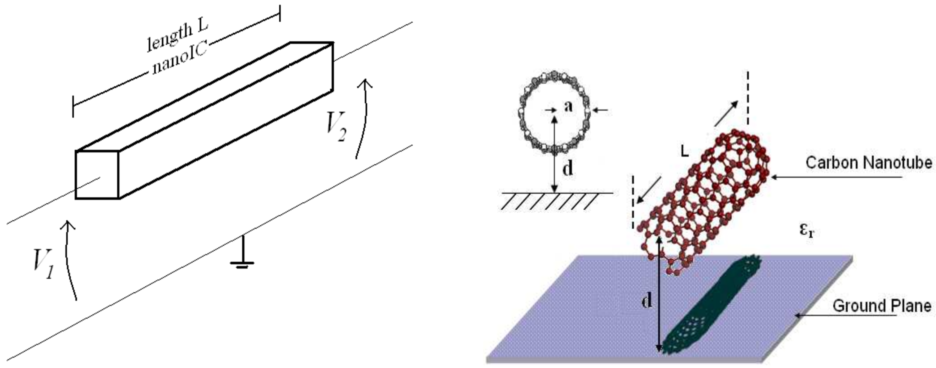
$$L' = L'_m + \frac{L'_K}{4} = \frac{\mu_0}{2\pi} \ln \frac{2d}{a} + \frac{1}{4} \cdot \frac{h}{2 \cdot e^2 \cdot \upsilon_F}, \tag{2}$$

$$C' = \frac{4C'_q \cdot C'_e}{4C'_q + C'_e} = \frac{4 \cdot \dfrac{2 \cdot e^2}{h \cdot \upsilon_F} \cdot \dfrac{2\pi\varepsilon}{\ln\left[\dfrac{d}{a} + \sqrt{\left(\dfrac{d}{a}\right)^2 - 1}\right]}}{4 \cdot \dfrac{2 \cdot e^2}{h \cdot \upsilon_F} + \dfrac{2\pi\varepsilon}{\ln\left[\dfrac{d}{a} + \sqrt{\left(\dfrac{d}{a}\right)^2 - 1}\right]}}. \tag{3}$$

In these expressions L'_m and C'_e are the p.u.l. effective magnetic inductance and electrostatic capacitance of the structure, L'_k and C'_q are the so-called p.u.l. kinetic inductance and quantum capacitance, h is the Planck constant, e is the electron charge, $\upsilon_F = 8 \cdot 10^5$ m/s is the Fermi velocity, μ_0 the magnetic permeability of the air and $\varepsilon = \varepsilon_0 \varepsilon_r$ is the dielectric constant of the medium. L'_k and C'_q are linked to the nature of quantum wire of a CNT.

In particular, L'_k takes into account that the kinetic energy of electrons can be substantially larger than that stored in the magnetic field, whereas C'_q describes the fact that to add electric charge to a quantum wire, one must add electrons to available states above the Fermi level [8].

Although *ad hoc* simulation environments [12–15] have been developed in order to analyze the behaviour of CNT-based nano-IC, once the considered circuits are reduced to a TL model, even commercially available software packages as PSIM®, PSPICE, etc. can be profitably used. In particular, in this paper PSIM is adopted since it allows an efficient way to implement the relationships between circuit parameters and geometric characteristics of the device and physical properties of the CNTs. In fact, such relationships can be represented in the PSIM simulator by means of the two port component depicted in Fig. 3 where the p.u.l. TL parameters, as indicated by the (1)–(3), are considered as function of the considered geometric and physical properties $f_i = f_i\left(d, a, l_{mfp}, \varepsilon_r, L\right)$ with $i \in \{R', L', C'\}$.



a) b)

Fig. 1. Schematic set-up of the nano-IC, a) and the possible realization through a SWCNT, b). In b) some relevant geometric and physical parameters are also evidenced: the radius of the SWCNT, a, the length of the nano-IC, L, the distance between the centre of the SWCNT and the ground, d, and the relative permittivity of the surrounding medium ε_r.

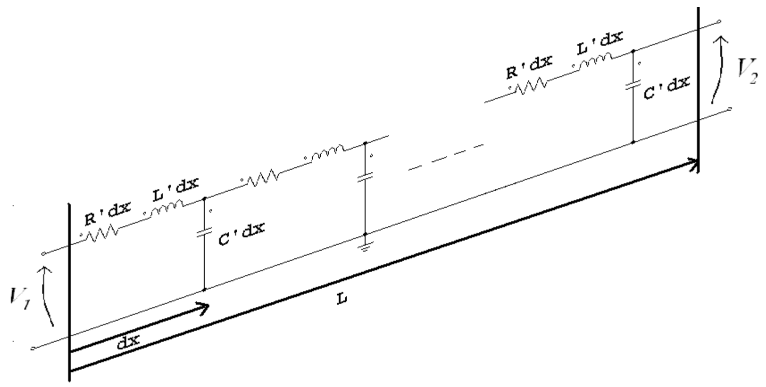


Fig. 2. Transmission Line modelling the SWCNT-based nanointerconnect.

The end user of the proposed simulation tool can indeed perform numerical experiments of a SWCNT-based nano-IC by a two steps procedure: the circuital computation of the p.u.l. parameters and the adoption of such values for the lumped parameters in the circuit of Fig. 3. First of all the blocks linking in a circuital way the physical and geometric properties to the p.u.l. parameters are constructed. Each input and the corresponding outputs are indicated by means of a label and considered as a voltage, whereas every constant appearing in the expression is treated as a DC voltage source.

In the following the different blocks associated to the TL parameters are described.

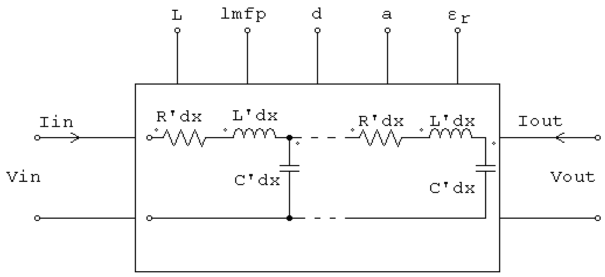


Fig. 3. Equivalent two-port modelling the TL.

Resistance R′

The per unit length resistance R' is a function of the length of the interconnection L and the electron mean free path, $R' = f_{R'}(l_{mfp}, L)$. In particular, if the length of the CNT is not greater than the mean free path l_{mfp} i.e. 1 μm, "ballistic transport" occurs and the resistance assumes a constant value ∼ 6.45 kΩ.

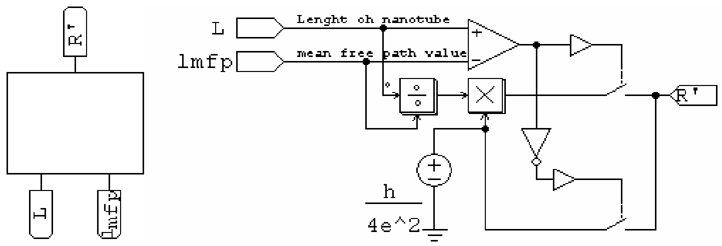


Fig. 4. PSIM® sub-circuit which models the resistance in the TL adopted for the simulation of the nano-IC.

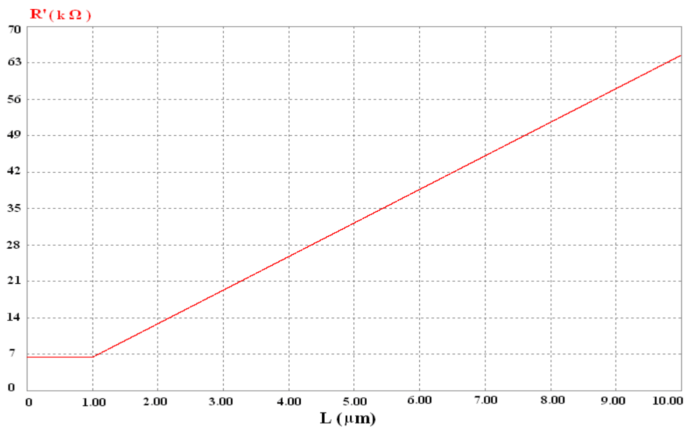


Fig. 5. Resistance vs. length of the CNT in the nano-IC.

The circuital block corresponding to the resistance expression (1) is shown in Fig. 4. A control circuit performs the choice associated to the considered mean free path l_{mfp} by opening/closing the switch that enables the correct value. The plot of the resistance as a function of the length of the nanotube, going from local (0.1 µm) to intermediate (10 µm) nano-IC, is shown in Fig. 5.

Inductance L′

The total inductance is the sum of magnetic (L'_m) and the kinetic (L'_K) components. The PSIM® circuit implementation of this component is shown in Fig. 6. It can be noted that only the magnetic term $L'_m = \frac{\mu_0}{2\pi} \ln \frac{2d}{a}$ is linked to the geometric dimensions of the device (the CNT radius and its distance from the return plane) whereas the kinetic term $L'_K = \frac{h}{2 \cdot e^2 \cdot v_F}$ is constant. The factor 1/4 takes into account the number of conducting channels in a metallic CNT. For metallic CNTs, v_F is 8×10^5 ms^{-1} and hence the kinetic inductance per conduction channel is $L'_K = 8$ nH µm^{-1}. It can be easily verified that the magnetic contribution becomes appreciable with respect to the kinetic term only for very long (global) nano-IC.

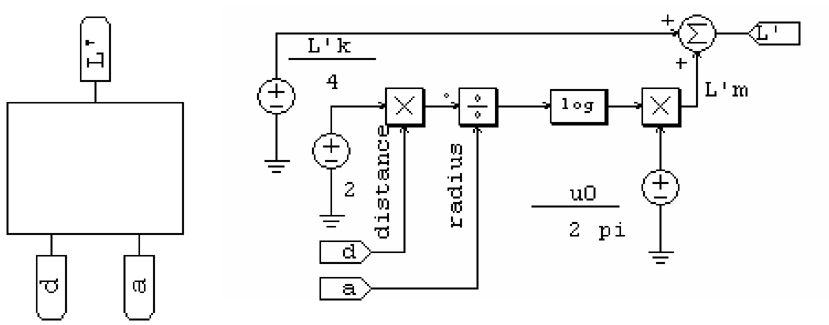


Fig. 6. PSIM® sub-circuit which models the inductance in the TL adopted for the simulation of the nano-IC.

Capacitance C′

The p.u.l. capacitance C', as depicted in Fig. 7, is the sum of the quantum term and the electrostatic one which is a function of the geometric dimensions (the CNT radius and its distance from the return plane) and the physical property (the dielectric permittivity of the medium) $C' = f_{c'}(d, a, \varepsilon_r)$. In the expression of the quantum capacitance C'_q the term 4 takes into account the four conductive channels that are present in a SWCNT. The Analytical expression of the electrostatic capacitance C'_e, between a wire and a ground plane, can be simplified when $d/a \gg 1$, giving:

$$C'_e = \frac{2\pi\varepsilon}{\ln\left[\frac{d}{a} + \sqrt{\left(\frac{d}{a}\right)^2 - 1}\right]} \cong \frac{2\pi\varepsilon}{\ln\frac{2d}{a}}$$

The equivalent electrical circuit implemented in PSIM also allows the evaluation of this simplified expression.

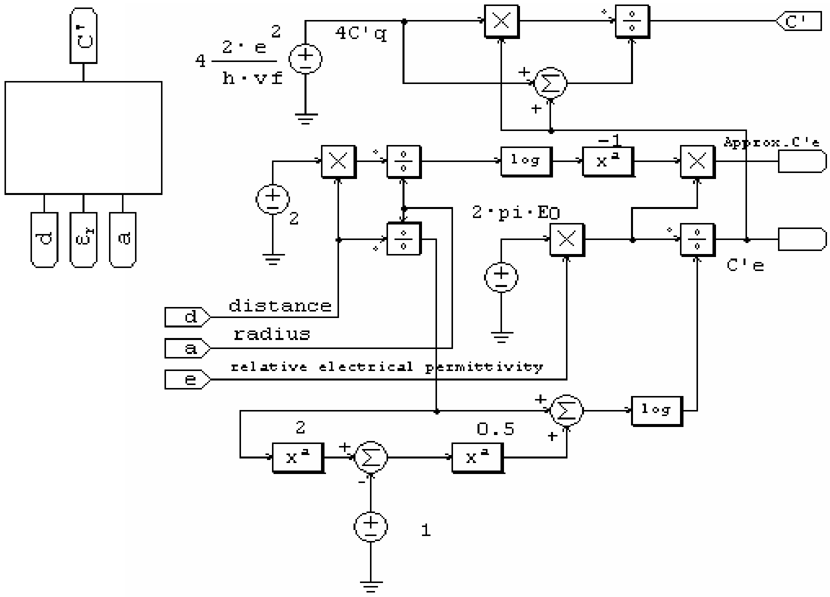


Fig. 7. PSIM® sub-circuit which models the capacitance in the TL adopted for the simulation of the nano-IC.

3. Results

The circuit depicted in Fig. 8a comprising a driver and a load with their parasitic parameters is adopted for performing the numerical simulation of the considered nano-IC. The associated circuit adopted in the PSIM simulation for computing both time and frequency domain performances is depicted in Fig. 8b. Since none of the parameters assumed as variable in the nano-IC structure is time dependent, the simulation of the proposed “sub-circuits” for R', L' and C' instantaneously furnishes the values that must be adopted in the two-port network in Fig. 8b.

In particular, a drive resistance R_{dr} of 96 Ω, an input capacitance C_{in} equal to the parasitic capacitance C_{par} of 64 fF and a load with a capacitance C_{load} of 91 fF have been considered. Moreover, in this scheme also the CNT/metal contact resistance, R_{cont} equal to 61 Ω has been assumed [8].

The nano TL line is approximated by $N = 5$ cells of length $\delta x = L/N$. Local interconnects with a variable length $L \in \{0.1, 1, 10\}$ µm, a SWCNT of radius $a \in \{0.5, 1, 1.5\}$ nm, at 100 nm of distance by the perfectly conducting ground plane, with a mean free path of 1 µm and a low-permittivity medium with a $\varepsilon_r = 1.5$, have been assumed.

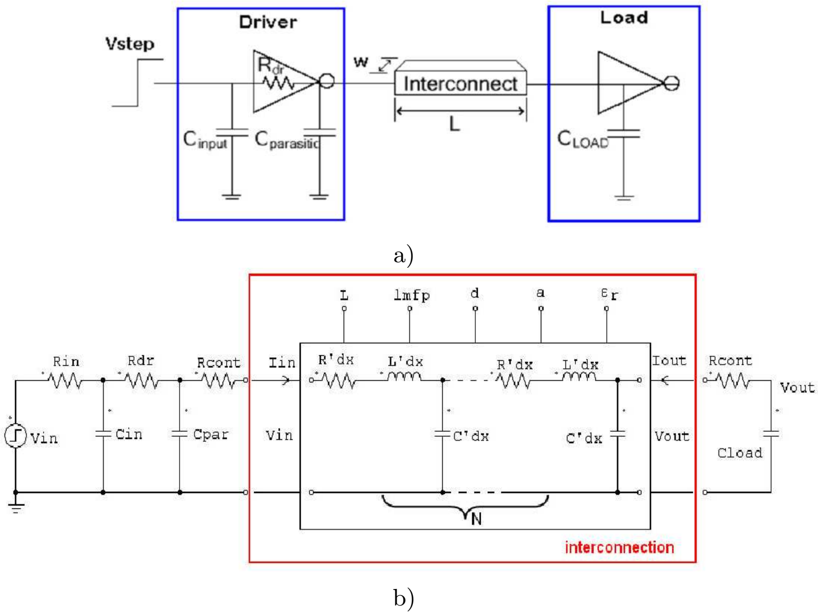


Fig. 8. Circuit considered in the simulation comprising a driver and a load with parasitic parameters, a) and its representation in PSIM, b).

The p.u.l. TL parameters computed by performing the simulation of the three sub-circuits relevant to R', L', C' for different values of the geometric dimensions and physical properties are reported in Tables 1–3.

The time response to an ideal voltage step is considered and the obtained results for different values of the CNT radius and for different lengths of the nano-IC are reported in Fig. 9. In particular the interconnect show a quasi-RC behaviour for all set of parameters. By increasing the length going from local to intermediate nano-IC, a higher value of the delay becomes visible. In fact, as highlighted by the measurements shown in the inset on the same figures, the output voltage reaches approximately 50% of its steady state value in a time equal to 0.104 ns and 0.141 ns for a nano-IC-length of 0.1 µm and 10 µm, respectively. The small influence of the considered factors on the performance of the nano-IC can be justified by observing the values of R', L', C' reported in Tables 1–3, where only a change on the third/fourth significant digit, induced by the variations of geometrical and physical parameters, is appreciable. In Fig. 10 the 50% time delay is reported as a function of the nano-IC length. A linear increase can be appreciated for lengths greater than 1 µm, corresponding to the assumed mean free path in the CNT. When the nano-IC is shorter than this value, ballistic conduction take place in the CNT and the delay is almost independent of the length.

Table 1. Computed p.u.l. values of the TL parameters for different values of the CNT radius (the assumed values of the other geometric and physical properties are $d = 100$ nm, $l_{mfp} = 1$ μm, $\varepsilon_r = 1.5$)

L [μm]	**a [nm]**	**R′ [kΩ]**	**L′ [mH/m]**	**C′ [pF/m]**
0.1	0.5	6.45	4.035	0.134
	1	6.45	4.035	0.151
	1.5	6.45	4.035	0.163
1	0.5	6.45	4.035	0.134
	1	6.45	4.035	0.151
	1.5	6.45	4.035	0.163
10	0.5	64.55	4.035	0.134
	1	64.55	4.035	0.151
	1.5	64.55	4.035	0.163

Table 2. Computed p.u.l. values of the TL parameters for different values of the distance from the ground plane (the assumed values of the other geometric and physical properties are $a = 1$ nm, $l_{mfp} = 1$ μm, $\varepsilon_r = 1.5$)

L [μm]	**d [nm]**	**R′ [kΩ]**	**L′ [mH/m]**	**C′ [pF/m]**
0.1	50	6.45	4.035	0.173
	100	6.45	4.035	0.151
	150	6.45	4.035	0.141
1	50	6.45	4.035	0.173
	100	6.45	4.035	0.151
	150	6.45	4.035	0.141
10	50	64.55	4.035	0.173
	100	64.55	4.035	0.151
	150	64.55	4.035	0.141

Table 3. Computed p.u.l. values of the TL parameters for different values of the medium permittivity (the assumed values of the other geometric and physical properties are $a = 1$ nm, $d = 100$ nm, $l_{mfp} = 1$ μm)

L [μm]	$\varepsilon_\mathbf{r}$	**R′ [kΩ]**	**L′ [mH/m]**	**C′ [pF/m]**
0.1	1.5	6.45	4.035	0.151
	3	6.45	4.035	0.291
	4.5	6.45	4.035	0.421
1	1.5	6.45	4.035	0.151
	3	6.45	4.035	0.291
	4.5	6.45	4.035	0.421
10	1.5	64.55	4.035	0.151
	3	64.55	4.035	0.291
	4.5	64.55	4.035	0.421

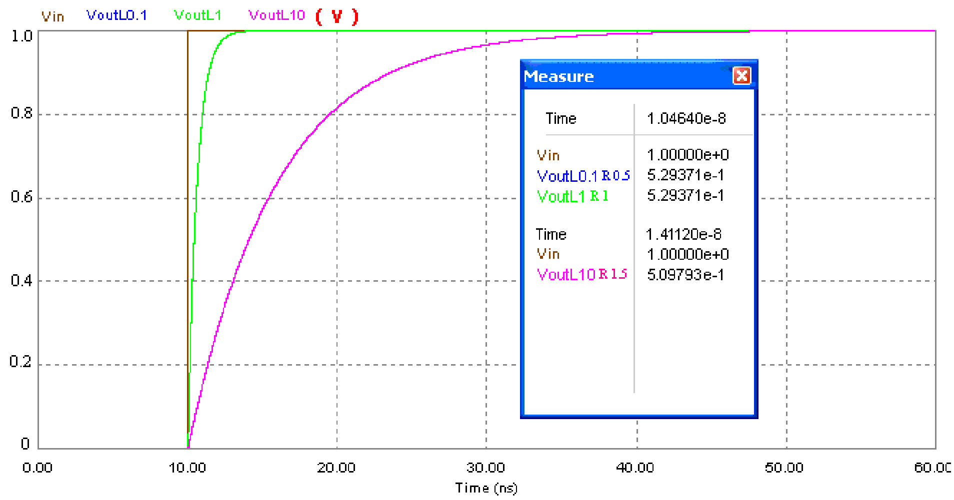


Fig. 9. Time behaviour of the input and output voltage for three different values of the CNT radius and for $L = 0.1, 1.0$ and 10 μm. The green curve refers to the response with $a = 1$ nm and $L = 1$ μm, whereas the magenta line concerns that one with $a = 1.5$ nm and $L = 10$ μm. The curve (blue colour) concerning the parameter set $a = 0.5$ and $L = 0.1$ μm is almost coincident with the green line.

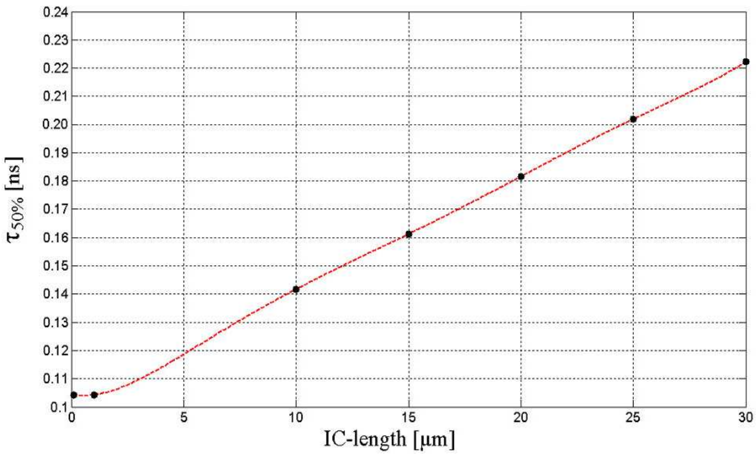


Fig. 10. 50% time delay in the output voltage vs. length of the nano-IC for $a = 1$ nm, $d = 100$ nm, $\varepsilon_r = 1.5$.

As it concerns the analysis in frequency domain, the magnitude and phase spectra of the transfer function $V_{\text{out}}/V_{\text{in}}$ have been evaluated for different nano-IC lenghts and physical parameters, as shown by the Bode's diagrams presented in Figs. 11 and 12. The analysis of the plots puts in evidence that while the physical and geometric parameters do not play a dominant role in the frequency behavior, an increasing length of the nano-IC determines a decrease in cut-off frequency and consequently a performance degradation of the interconnection. This confirms that such the ideal structure, based on a SWCNT, is better suited for very short nano-IC with a length comparable to the mean free path of electrons (≤1 μm).

The fast and simple computation of the circuit response allows to easily perform the optimization of relevant quantities of the SWCNT-based interconnect in presence of different physical and geometric characteristics. A parameter sweep can be included in the procedure in order to make such a sensitivity analysis fully automatic.

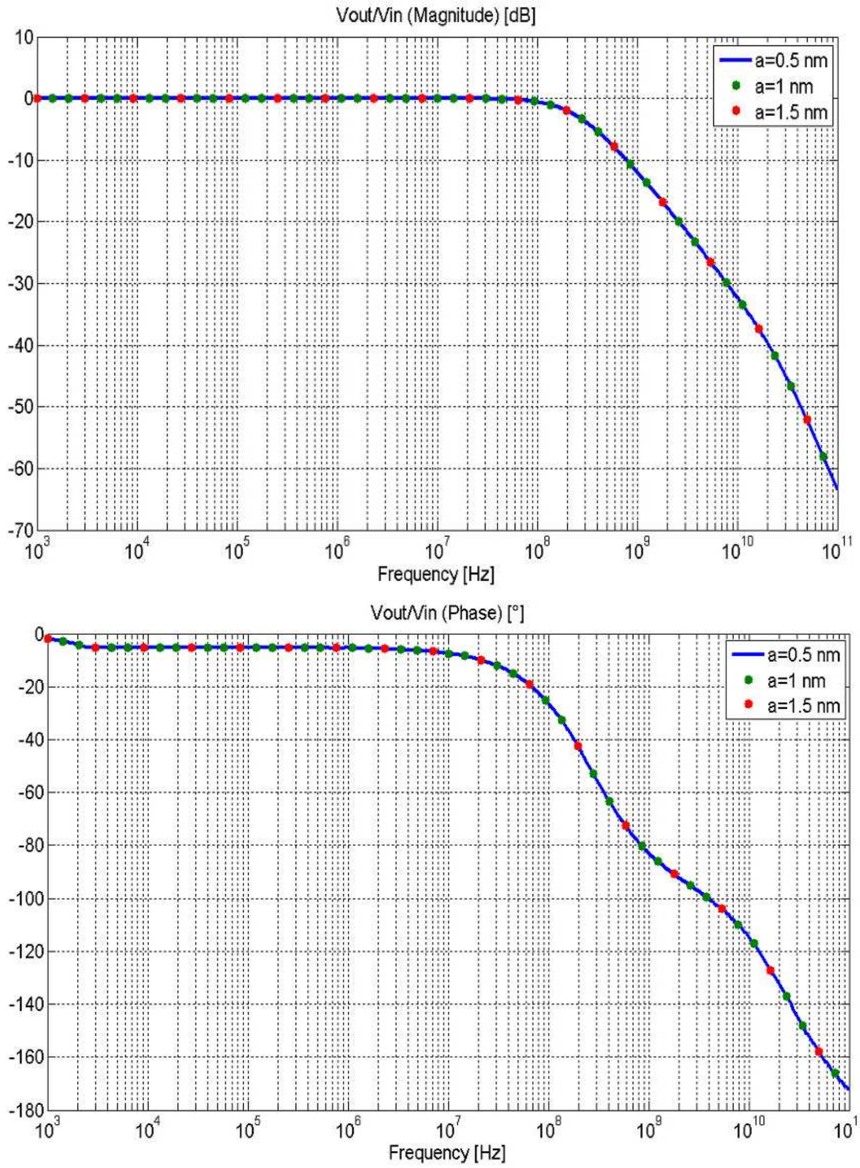
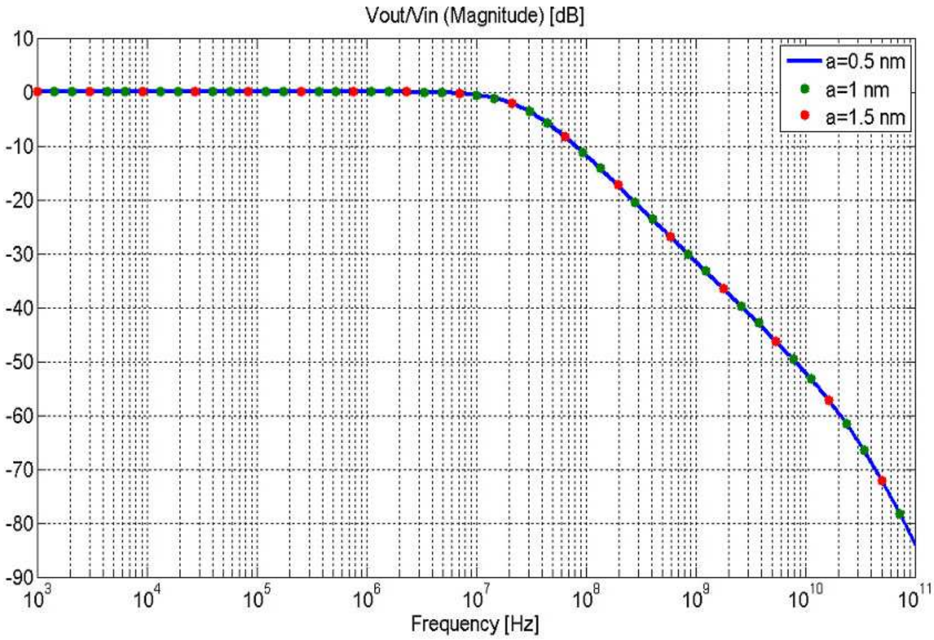


Fig. 11a. Bode's diagrams for a nano-IC with $a = 0.5, 1.0, 1.5$ nm; $L = 0.1$ μm.



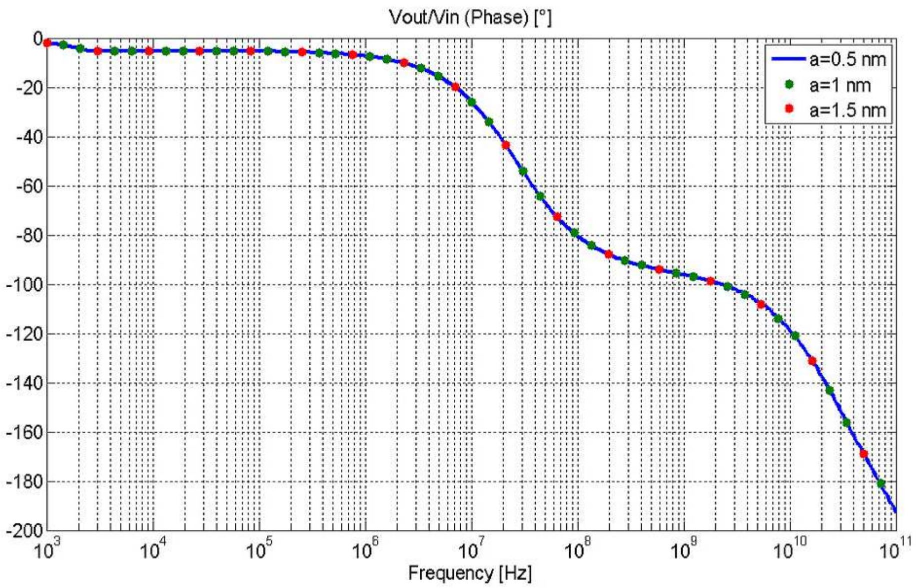
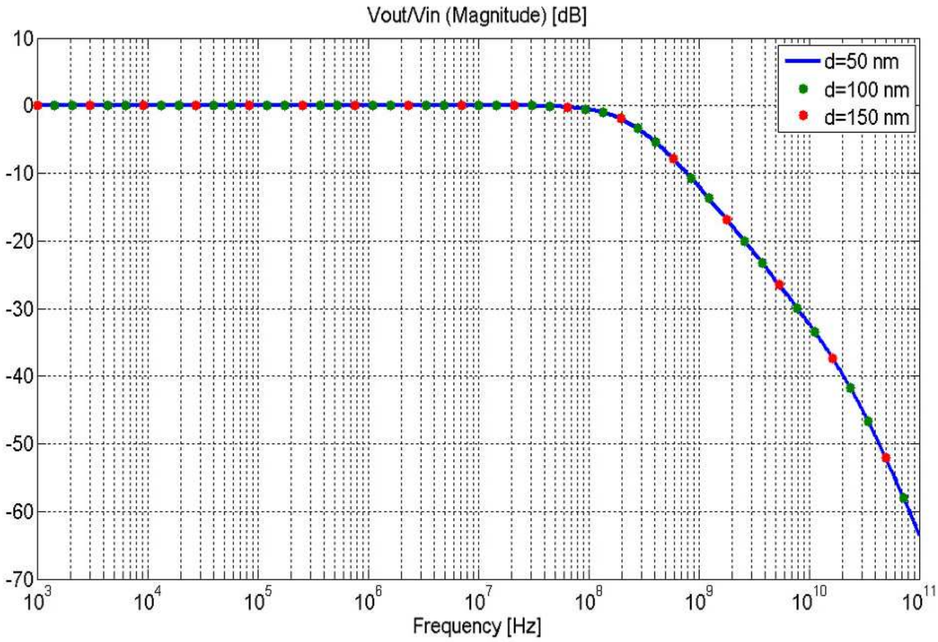


Fig. 11b. Bode's diagrams for a nano-IC with $a = 0.5, 1.0, 1.5$ nm; $L = 10$ μm. The three curves concerning the different values of the parameter a are almost coincident.



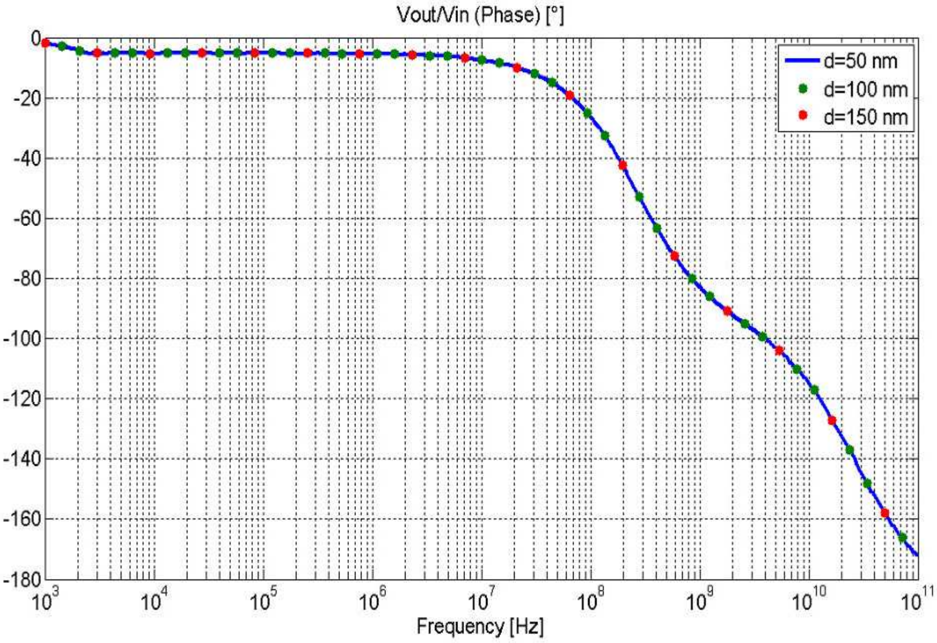


Fig. 12a. Bode's diagram for a nano-IC with $d = 50, 100, 150$ nm; $L = 0.1$ μm.

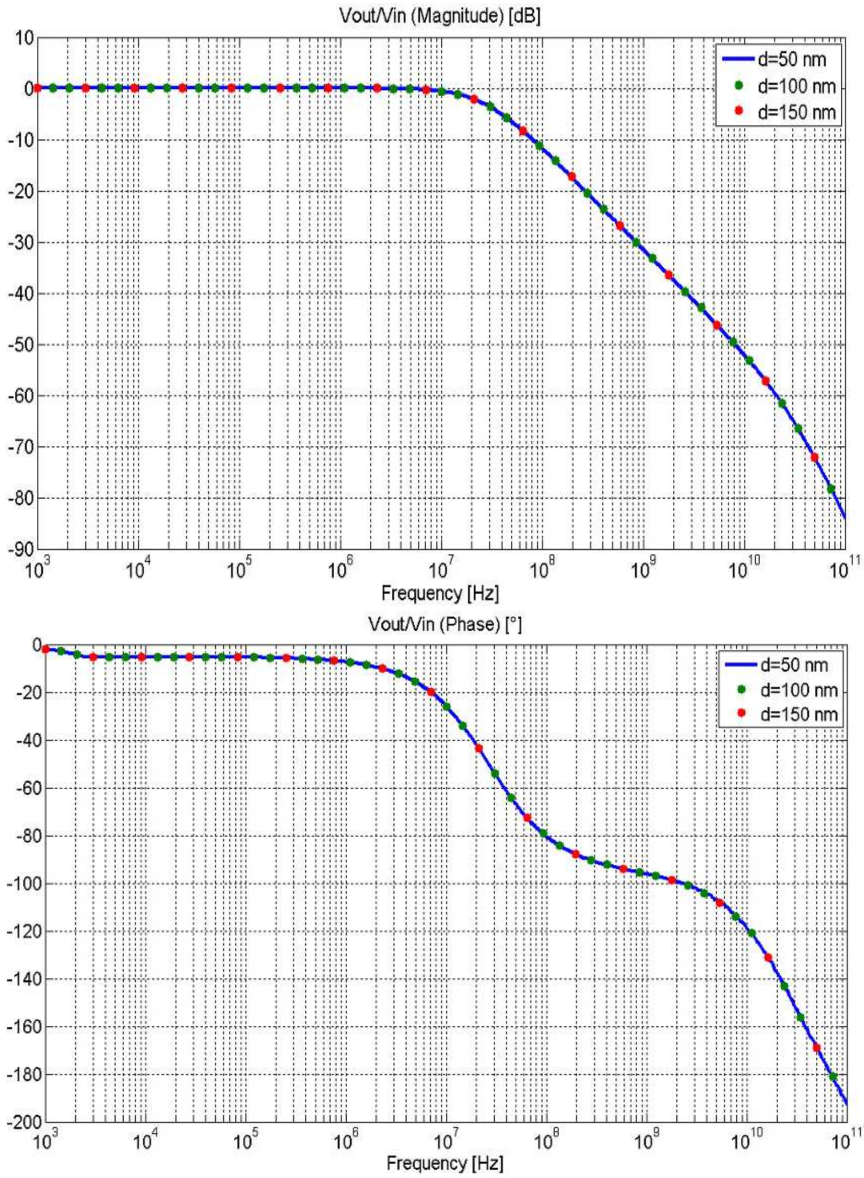


Fig. 12b. Bode's diagram for a nano-IC with $d = 50, 100, 150$ nm; $L = 10$ μm. The three curves concerning the different values of the parameter d are almost coincident.

4. Conclusions

The calculation of the p.u.l. parameters of an equivalent TL simulating a SWCNT-based nano-IC is carried out in PSIM® by implementing blocks in which the mathematical functions, relating the physical and geometric properties to the circuital parameters, are easily and rapidly evaluated. By using the same software package, such blocks can be easily integrated in a circuit comprising also the nano-IC driver and the load in order to perform both time and frequency domain analysis. In both analysis the performances are mainly influenced by the length of the nano-IC, whereas a substantial independence is observed for the CNT radius, distance from the ground plane and relative permittivity of the surrounding medium. The easy availability of the circuit response for different configuration/materials of the nano-IC can be exploited in order to perform the nano-IC design and optimization. Further efforts are now underway in order to consider also nano-IC based on bundles of SWCNT or Multi Wall CNT.

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