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Performance assessment of optimized carbon-nanotube-based wireless on-chip communication

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ABSTRACT

We use 3D FEM simulation to study electrically-short carbon-nanotube-based antennas and their application to wireless on-chip communication. We first expose our model for single-wall carbon nanotubes and our simulation technique. This is then used to study extensively the various parameters involved in the design of a planar dipole antenna made of carbon nanotubes aligned over a quartz substrate. From this study, an appropriate design is selected and studied in an antenna-to-antenna transmission link.

Keywords: carbon nanotubes, antenna, plasmonics, full-wave, finite element method

1. INTRODUCTION

Since the advent of modern computing, the quest for reduced dimensions in electronics has led us to probe ever smaller scales. In recent years, as the physical limits of conventional fabrication techniques are becoming more and more stringent, possible next generation techniques have attracted much attention.

Nanotubes, nanowires and more recently graphene are of particular interest owing to their inherent nanometric scale and extraordinary physical properties. They have been explored as possible replacement of Si in transistors and have recently demonstrated performances surpassing state-of-the-art technology^{1,2}.

However most of the focus has been put on the development of devices, often overlooking the problem of their integration with micro and macro-world technologies. Lithography contacting of these nanodevices is difficult to scale and decreases the achievable density. Furthermore ohmic contact to nano-objects is still, to-date, difficult to achieve and displays high variability.

Wireless communication with these devices could be an alternative. Indeed single-wall carbon nanotubes (SWCNTs) have been foreseen as interesting candidates for antenna applications. They are predicted^{3,4} to display a high kinetic inductance, leading to slow propagation of electromagnetic waves along their axis. The existence of the kinetic inductance has been verified experimentally⁵. Since a reduced propagation velocity implies a shorter wavelength at a given frequency, this would allow the design of resonant antennas much smaller than with usual materials – about fifty-fold in the case of a single-SWCNTs dipole⁶. Bundled CNTs may however be necessary to overcome certain experimental challenges such as high contact resistance at CNT-metal junctions⁷, poor efficiency of single-tube devices or to match the impedance of the antenna with that of the fabricated device. The antenna link would then act as an impedance transformer.

Additionally, owing to their reduced size and high operating frequency range, CNT-based nano-antennas seem an ideal candidate for wireless chip-to-chip and on-chip communications – an emerging interconnect concept⁸. We thus develop the tools necessary to the systematic design of such devices. SWCNTs are modeled by a material with complex EM properties⁹ derived from models available in literature^{3,4} and using published values for the phenomenological constants. This is implemented in two different frequency-domain 3D electromagnetic solvers relying on the finite-elements method. Our modeling approach was validated by direct comparison with published theoretical and experimental results^{6,10}. We then study bundles of CNTs in a planar dipole configuration to shed light on the specific

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considerations and trade-offs between size reduction, impedance matching, and operating frequency. Based on this study, we simulate an optimized CNT-dipole-based transmission link.

2. METHODOLOGY

2.1 Model

We use an effective medium approach to model aligned SWCNTs in 3D full-wave simulation suites. The properties of this medium are derived from a published Drude model^{3,6} for the surface conductivity of SWCNTs taken as hollow tubes. The derivation technique is exposed in⁹.

The model is applicable to SWCNTs of radius smaller than 3.39nm, and typically up to tens of terahertz in frequency. To justify the effective medium approach, the CNTs should be closely packed with respect to the wavelength under consideration.

The resulting uniaxial bulk conductivity used for SWCNT arrays embedded in a perfect dielectric is:

$$\sigma_{Axial} = \frac{8e^2 v_F}{h(\nu + j\omega)} * D_{NT} \quad (1)$$

where ω is the angular frequency, $e \approx 1.602 \cdot 10^{-19}C$ is the elementary charge, $h \approx 6.626 \cdot 10^{-34} J.s$ is the Plank constant, $\nu = \tau^{-1}$ is the relaxation frequency and v_F is the Fermi velocity in CNTs. The latter is given by $v_F = 3\gamma_0 b / 2\hbar$ with $b=0.142nm$ and γ_0 the overlap integral. Both $\gamma_0 \approx 2.5-3.1$ eV¹¹ and $\tau \approx 3 \cdot 10^{-12}s$ (low frequencies) – $10^{-13}s$ (IR below optical transitions)¹² are phenomenological constants^{13,14} that may vary depending on the frequency band. Unless stated otherwise, we take $\gamma_0 = 3$ eV, leading to $v_F = 9.71 \cdot 10^5$ m/s, and $\tau = 3 \cdot 10^{-12}s$ – as chosen in⁶. This makes comparing numerical results more relevant and straightforward.

This may also be written in the form

$$\sigma_{Axial} = \sigma_{lin,0} D_{NT} \zeta(u) \quad (2)$$

Where

$$\sigma_{lin,0} = \frac{8e^2 v_F}{h\nu} \quad (3)$$

is the DC linear conductivity over a single SWCNT and

$$\zeta(u) \equiv \frac{1 - ju}{1 + u^2} \quad (4)$$

$$u \equiv \frac{\omega}{\nu} = \frac{f}{F_\nu} \quad (5)$$

The function $\zeta(u)$ governing the variations of the frequency dependent bulk is the usual line shape of a Drude model. For $u < 1 \Leftrightarrow f < F_\nu \approx 53GHz$, damping prevails and therefore it will not be possible to design plasmon resonant antennas below this frequency.

2.2 Implementation

This anisotropic material is implemented in HFSS, as described in⁹. Let us write $\varepsilon = \varepsilon' + j\varepsilon''$ and $\sigma = \sigma' + j\sigma''$ the anisotropic (matrices) bulk permittivity and conductivity respectively in the equivalent bulk material. In HFSS, for a given material, the bulk conductivity σ can be defined as anisotropic and frequency dependent but it may not be given complex values. Nonetheless the permittivity and conductivity are linked by the following relation:

$$\varepsilon = \varepsilon' + j\varepsilon'' = K\varepsilon_0 - j\frac{\sigma}{\omega} \quad (6)$$

Therefore we can derive and use as equivalent definition the real part of the relative permittivity ε'_r paired to the real part of the conductivity σ' .

3. PARAMETRIC STUDY

3.1 Design and experimental tangibility

The planar dipole antenna design simply consists of two identic strips of metal aligned longitudinally on the surface of a substrate and separated by a gap, as shown on Figure 1. An EM field is then applied in the gap. We adapt this simple structure to make a CNT-based electrically-short antenna. The two strips of metal are replaced with aligned SWCNTs of uniform length and cut in their middle to constitute the two arms.

This design is compatible with CNTs grown horizontally on a substrate, in particular CNTs grown on quartz by catalytic chemical vapor deposition (CVD). Indeed reported CNT lengths by this technique can go up to millimeters while densities range from 0.1 to 50 CNTs/ μm . This is well suited to tailor a strip of aligned CNTs to the desired characteristics (number of CNTs and physical dimensions) for our application as shown in the following study. The foregoing fabrication process employs conventional techniques such as photolithography and RIE. Using standard photolithography you can achieve a resolution of 2 μm and hence, using the appropriate CNT density, control the number of CNTs with a precision ranging from 1 to 100 CNTs – as a trade-off to antenna width.

CVD growth of such CNTs is in progress at CINTRA. We produce high-purity SWCNTs on quartz. A metal-CNT fabrication process has also been established – a fabricated characterization structure is shown Figure 1.

Figure 1. Left: Planar dipole on quartz substrate with lumped port. Right: SEM image of a gap structure made of gold patterned over SWCNTs grown on quartz, as realized by the authors.

3.2 Motivation

We aim at integrating this antenna in systems which means meeting or formulating resonance frequency, bandwidth and feeding impedance requirements. For instance, to characterize the antenna experimentally with significant signal on a vector network analyzer, impedance matching to 50 Ω may be required. The techniques are usually narrow band and correspond to known impedance. A good prior knowledge of the antenna is thus necessary. It can only be achieved through careful theoretical investigation and characterization of the CNTs used for the antenna fabrication.

Many parameters influence the frequency response of this antenna. We divided them as CNT characteristics, antenna geometrical configuration and bundle parameters. Although a circuit interpretation¹⁵ can give some indications on their effect, the non-conventional scales and effects due to the SWCNTs can lead to misinterpretations. On the other hand, full-wave simulation with the technique exposed above provides a fast and intuitive tool guaranteeing to take all effects into account. It additionally allows for the study of the integration of the antenna with feeding structures, in arrays or, in the present case, in a transmission link as exposed Section 4.

A parametric study of the SWCNT on quartz antenna is thus carried out with EM simulation in HFSS using the SWCNT bulk model presented in Section 2.

3.3 CNT characteristics

As exposed in Section 2, the values γ_0 and τ used in the model are phenomenological constants that depend mainly on the SWCNTs quality and arrangement. In this subsection we will study their effect on the frequency response of a 4-micrometer-wide 160-micrometer-long planar dipole antenna made of two arms of 80 SWCNTs each separated by a 4-micrometer gap. The ranges of values chosen correspond to those found in literature.

Figure 2. Effect of γ_0 on the frequency response of a CNT-based antenna. Return loss plotted from 0 to 300GHz for $\gamma_0 = 2.5$, 2.7 and 3eV. The antenna arms are 78 μ m-long by 4 μ m-wide, made of 80 aligned CNTs each and separated by a 4 μ m gap fed with a 50- Ω lumped port.

On Figure 2, the return loss of the antenna is plotted against frequency for γ_0 varying in its experimental range. As one would expect, the effect of γ_0 is rather limited as its value only varies by $\pm 10\%$ and only the module of the conductivity is affected – linearly, leaving the relative weight of the imaginary and real part of the conductivity with frequency unchanged.

Figure 3. Effect of τ on the frequency response of a CNT-based antenna. Return loss plotted from 0 to 300GHz for $\tau = 0.10$ ps, 0.32ps, 1.0ps, 3.0ps and 3.2ps. The antenna configuration is identical.

On Figure 3 the return loss of the antenna is plotted against frequency for τ varying in its experimental range. Here, since the range covers an order of magnitude, τ is varied on a logarithmic scale and the effect is very pronounced. As expected, the antenna is over damped when its fundamental resonance frequency is below $F_v(\tau)$.

3.4 Antenna geometrical configuration

For the design and experimental realization of the antenna it is important to understand how topological variations affect its response. We use the same planar dipole antenna design described in 3.3 – 78 μ m-long 80-SWCNT arms – but we vary the arms width and the gap width to study their influence.

Figure 4. Effect of antenna width on the frequency response of a CNT-based antenna. Return loss plotted from 0 to 300GHz for $W_A = 1, 2, 4, 8, 16$ and 32μ m.

Figure 5. Effect of feeding port gap width on the frequency response of a CNT-based antenna. Return loss plotted from 0 to 300GHz for $W_{Gap} = 4, 16, 32, 64$ and 128μ m. The arms are kept 78 μ m-long each. When the gap is varied at constant dipole length, the frequency shifts upward, accounting for a shorter effective length due to the different propagation speeds.

Because various CNT densities may be achieved experimentally, it is important to consider the effect of density if a fixed number of SWCNTs were to be used. To address this, Figure 4 shows a logarithmic progression of width from 1 to 32 μ m. As long as the aspect ratio of the antenna arm remains high, the resonant frequency is unchanged. However, when the aspect ratio becomes lower than 10, the resonant frequency gradually shifts lower which can be interpreted as increased arm-to-arm capacitance. From 5 to 10 CNTs/ μ m up the effect is moderate.

Feeding the dipole with a realistic feed line may require widening its feed gap. Figure 5 demonstrates that, if the arm length remains constant, the former variation should not affect the antenna resonance much. It is so because most of the effective length seen by the EM wave is due to the CNT arms, which account for roughly 1 mm of propagation in free space at 70GHz. Hence spacing up to 100um has very little influence.

3.5 Bundle parameters and trade-offs

Finally we come to the main design parameters of these electrically-short antennas. The number of tubes in each arm (N_{CNT}) and their length (L_{CNT}) play a significant role in the antenna behavior^{16, 17, 15}. Figure 6 shows how, as the number of CNTs per arm is increased at constant dimensions of the antenna, the input impedance of the antenna is decreased, producing a better impedance match – as long as the impedance does not go below 50Ω. However the first resonance of the antenna is noticeably shifted to a higher range too. As CNTs are added in parallel in the same geometrical extent, the kinetic inductance decreases while the electrostatic capacitance is maintained. Hence the propagation speed along the CNT dipole increases.

Figure 6. Effect of N_{CNT} on the frequency response of a CNT-based antenna. Return loss plotted from 0 to 300GHz for N_{CNT} on a 2-logarithmic scale from 1 to 2048. The antenna is 80um-long in total by 4um-wide, made of aligned CNTs.

A number of simulations were run to cover comprehensively the possible designs. Figure 7 and Figure 8 summarize these many results in the manner exposed in^{15, 17}. They describe the performance of CNT based dipoles on quartz as a function of number of CNTs in each arm (x axis) and length of the CNTs (different curves). Figure 7 indicates the resonance frequency and return loss while Figure 8 gives the conjugate quantities; size reduction and power accepted at 50Ω. The configurations are only studied for resonance frequencies between 50 and 300 GHz which correspond to the range in which we could measure experimentally the antennas on VNA setups.

From this study we pick a design with relatively good performances. The design with 80um-long arms made of 256 CNTs each resonates at 240GHz with -4.4dB return loss. This makes it 4 times smaller than its metallic counterpart for a reasonable amount of power transferred to the antenna.

Figure 7. Resonance frequency and return loss for 50-Ω-fed planar SWCNT-based dipoles as a function of (N_{CNT} , L_{CNT})

Figure 8. Size reduction and input power accepted by 50-Ω-fed planar SWCNT-based dipoles as a function of (N_{CNT} , L_{CNT})

4. TRANSMISSION

In this section we study the feasibility and interest of a transmission link using CNT-based electrically-short dipoles.

4.1 Single SWCNT

The first configuration investigated is close-range THz communication based on two $2\mu\text{m}$ -long single-CNT dipoles. These are resonant at around 1.3THz – instead of $60\text{--}70\text{THz}$ if they were made out of copper. The CNT dipoles are placed in an air box, directly facing each other, as shown on Figure 9. Their spacing is varied on a logarithmic scale to estimate the efficiency with distance.

Figure 9. Two facing CNT dipoles in HFSS. The whole structure is contained in an air box. Additional “Russian doll” air boxes are used around the CNTs, where the mesh needs to be tighter, to help control the automatic meshing scales.

At $1\mu\text{m}$, the transmission from a 50-ohm port to a 50-ohm -port is -25dB at resonance (cf. Figure 10) instead of the average -80dB out of resonance. This validates the possibility of CNT-based short-dipole-antenna interconnects thanks to the plasmon resonance. The resulting transmission remains however very low. A few micrometers away from the transmitting antenna it becomes practically irrelevant.

This type of transmission is more adapted to link high-impedance nano-devices. In fact, if the ports are assigned 1150-ohm impedance instead, matched with the antenna input impedance, the return loss is then an excellent -20dB at resonance and thus the transmission at $1\mu\text{m}$ is -10dB . Note that this is in the case of symmetric transmission, nanodevice to nanodevice, where metal interconnects would be difficult to realize and mismatched in impedance.

Figure 10. Dipole-to-dipole transmission peak due to the plasmon resonance in a dipole made of two 1-um -long SWCNTs. Right: $50\text{-}\Omega$ ports. Spacing increased logarithmically. Left: $1150\text{-}\Omega$ -impedance matches that of the antennas. Hence the transmission is much improved, from -25dB to -10dB .

The best adapted application might be to link classical electronics to nanodevices through a dissymmetric antenna link; a conventional full-size antenna would collect more of the emitted field from the CNT antenna and since it could be matched to 50 ohms while the CNT antenna would be high impedance, it would realize an interesting impedance conversion.

4.2 Bundle of SWCNTs

In this subsection we evaluate the performance of a wireless link using the antenna design selected from the observations in Section 3. We go back to investigating with 50-ohm impedance for the ports as we want to investigate this design for intra-chip communication. We try two configurations: antennas side-to-side on the substrate and antennas on opposite sides of the substrate for 3D-integration. In both cases the distance is varied to observe the maximum suitable. High efficiencies cannot be expected however as, by nature, having a small footprint the CNT antennas will radiation is quasi-isotropic. Hence most of the energy is not collected by the paired antenna.

Horizontal side-to-side transmission is presented Figure 11. Thanks to the plasmon resonance, the performance is better than with similar dimensions with metal and the spacing range – from 10 to 320um – is better suited for this application than what was presented Section 4.1. The transmission appears rather weak still.

Figure 11. Transmission from a CNT antenna to another on the same chip. Inset: Structure simulated in HFSS.

Vertical through substrate transmission for 3D integration is also presented on Figure 12. It displays a resonance where the metal counterpart does not, as seen on the return loss, Figure 13. Hence the transmission is 5dB better at 10um, where coupling plays an important role and up to 15dB better through a 500um substrate.

Figure 12. Transmission from a CNT antenna to another through a substrate. Thickness is varied in a range in accordance to the recent advances in 3D packaging. Inset: Structure simulated in HFSS.

Figure 13. Return loss for the same collection of configurations. Inset: same but with metal instead of CNTs, no resonance.

5. CONCLUSION

We have developed tools to study the various parameters of an experimentally realizable CNT-based electrically-short antenna. We have also used these tools to study various possibilities of wireless on-chip communication. The transmission remains low. The most interesting option seems to be an asymmetric transmission link to bridge micro and nano-electronics.

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