Design and assessment of carbon-nanotube-based remote links to nanodevices

Pierre Franck, Dominique Baillargeat, Beng Kang Tay

► To cite this version:

Pierre Franck, Dominique Baillargeat, Beng Kang Tay. Design and assessment of carbon-nanotube-based remote links to nanodevices. Microwave Symposium Digest (IMS), 2013, Jun 2013, Seattle, United States. pp.1-3, 10.1109/MWSYM.2013.6697613 . hal-00937755

HAL Id: hal-00937755

<https://hal.science/hal-00937755>

Submitted on 11 Oct 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Design and Assessment of Carbon-nanotube-based Remote Links to Nanodevices

Pierre Franck^{1,2}, Dominique Baillargeat^{1,2}, Beng Kang Tay^{1,3}

¹ CINTRA CNRS/NTU/THALES, UMI 3288, Research Techno Plaza, 50 Nanyang Drive, Border X Block, Level 6, Singapore 637553

² XLIM UMR 7252, Université de Limoges/CNRS, 123 Avenue Albert Thomas 87060 Limoges

³ School of Electrical and Electronics Engineering, Nanyang Technological University, Block S1, 50 Nanyang Avenue, Singapore 639798

Abstract — We use 3D FEM simulation to study realistic designs of electrically-short carbon-nanotube-based antennas and their application to wireless on-chip communication. We first expose the simulation technique we use. We then describe a feasible planar dipole antenna made of carbon nanotubes aligned over a quartz substrate and our preliminary fabrication results. We extensively study the various parameters involved in its design. From this study, an appropriate design is selected and studied in an antenna-to-antenna transmission link.

Index Terms — Carbon nanotubes, Dipole antennas, Electromagnetic modeling, Millimeter wave communication, Nanoelectronics, Nanotube devices.

I. INTRODUCTION

Ever reducing dimensions in electronics has brought us to the physical limits of conventional fabrication techniques. Alternative technologies thus need be investigated. Nanotubes, nanowires and more recently graphene are of particular interest owing to their inherent nanometric scale and extraordinary physical properties. They have been explored for transistors and have recently demonstrated performances over state-of-the-art technology [1].

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 achievable density. Furthermore ohmic contact to nano-objects is still difficult to achieve and highly variable.

Wireless communication with these devices could be an alternative. Furthermore single-wall carbon nanotubes (SWCNTs) are predicted [2], [3] to display a high kinetic inductance, leading to slow propagation of electromagnetic waves along their axis – hence making for shorter antennas at nominal frequency. The existence of the kinetic inductance has been verified experimentally [4]. Bundled CNTs may however be necessary to overcome some experimental challenges such as high contact resistance at CNT-metal junctions [5], poor efficiency of single-tube devices or impedance matching of the antenna with fabricated devices. The antenna link would in this last case act as an impedance transformer.

II. METHODOLOGY

SWCNTs are modeled using the material with complex EM properties originally described in [6]. It was derived from authoritative models [2], [3] and uses published values for the phenomenological constants. This is implemented in HFSS, a frequency-domain 3D electromagnetic solver relying on the finite-elements method. This modeling approach was validated by direct comparison with published theoretical and experimental results [7]. We then study bundles of CNTs in a planar dipole configuration to shed light on the specific 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.

III. PARAMETRIC STUDY OF THE CNT DIPOLE

A. Design and experimental realization

The planar dipole antenna design consists of two identical strips of metal aligned longitudinally on the surface of a substrate and separated by a gap, as shown on Fig. 1. An EM field is then applied in the gap through a lumped port. 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 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 with this technique range 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. The foregoing fabrication process employs conventional techniques such as photolithography and RIE. Using standard photolithography a 2- μm resolution can be achieved and hence, using the appropriate CNT density, the number of CNTs is controlled with a precision ranging from 1 to 100 CNTs – as a trade-off to antenna width.

We have obtained preliminary results of CVD growth of such CNTs. We produce high-purity SWCNTs on quartz. A metal-CNT fabrication process has also been established – a fabricated CNT characterization structure is shown Fig. 1.

Many parameters influence the frequency response of this antenna. A parametric study is thus carried out with EM simulation in HFSS to draw design rules as a follow-up to [8].

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

B. CNT characteristics

The values γ_0 (overlap integral determining the Fermi velocity in CNTs) and τ (plasmon lifetime in CNTs) used in the model are phenomenological constants that depend mainly on the SWCNTs quality and arrangement. We have studied their effect on the frequency response of a CNT plasmon antenna and report the main findings – detailed results can be found in [9]. The ranges of values chosen correspond to those found in literature. For γ_0 varying in its experimental range ($\pm 10\%$), the effect is rather limited – it translates as a 10%-magnitude variation of conductivity. For τ varying in its experimental range – one order of magnitude – the effect is very pronounced. As expected, the antenna is over damped when its fundamental resonance frequency is below $F_v(\tau)$ which can vary from 50GHz to 1THz. High-quality CNTs are thus a critical element to produce plasmon resonances.

C. 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 a planar dipole antenna design with 78μm-long 80-SWCNT arms – but we vary the arms width and the gap width to study their influence.

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, Fig. 2 a) shows a logarithmic progression of width from 1 to 32μm. 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 resonance frequency gradually shifts lower which can be interpreted as increased arm-to-arm capacitance. From 5 to 10 CNTs/μm up the effect is moderate.

Feeding the dipole with a realistic feed line may require widening its feed gap. Fig. 2 b) demonstrates that, if the arm length remains constant, this 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 100μm has very little influence.

Fig. 2. Effect on the frequency response of a CNT-based antenna of a) Antenna width; note a slight frequency dip for wider values and relatively constant return loss. b) Feeding port gap width, the arms being kept 78μm-long each. Note a constant frequency and only slightly increasing mismatch. If the gap is varied at constant dipole length, the frequency shifts upward, accounting for a shorter effective length due to the different propagation speeds.

D. Bundle parameters and trade-offs

The main design parameters of these electrically-short antennas are the number of CNTs in each arm (N_{CNT}) and their length (L_{CNT}). As CNTs are added in parallel in the same geometrical extent, the total kinetic inductance decreases while the electrostatic capacitance is maintained. Hence the propagation speed along the CNT dipole increases.

A number of simulations were run to cover comprehensively the possible designs. Fig. 3 summarizes these many results. It describes 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 (the different curves). Fig. 3 a) indicates the resonance frequency and input impedance at resonance while b) gives conjugate quantities; size reduction and return loss 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.

Fig. 3 Characteristics of 50-Ω-fed planar SWCNT-based dipoles as a function of (N_{CNT} , L_{CNT}) a) Resonance frequency and input impedance b) Size reduction and return loss. Dipole lengths are 40 (▲), 80 (●), 160 (X), 320 (◆), and 640 (■) μm with 4 μm gap.

IV. TRANSMISSION LINK

We studied the feasibility and interest of a transmission link using CNT-based electrically-short dipoles relying on the structures illustrated Fig. 4. We picked a relevant design in terms of impedance, resonance frequency and size reduction. The planar dipole has 40μm-long 256-CNT arms, resonates at 217GHz and presents 370-ohm input impedance. This makes it 4 times smaller than its metallic counterpart.

For each structure the plasmon resonance of the antennas was translated into a transmission improvement of +5dB and up to +50dB over the same structure made of a perfect conductor. However, the transmission level even at tens of micrometers was too low (-10dB at 10μm, -24dB at 40μm) to use as replacement to usual interconnects. It is still interesting to make a measurement of the antennas themselves or communication to a nanodevice. Furthermore the intrinsically high impedance of these antennas is better suited to connect high impedance devices rather than classical 50Ω ones.

Hence, an interesting application might be to link classical electronics to nanodevices through a dissymmetric antenna

link; a conventional full-size dipole (or a more directive antenna) collects more of the emitted field from the CNT antenna (cf. Fig. 4) when further and can be matched to 50 ohms while the CNT antenna is high impedance, thus realizing an interesting impedance conversion. Additionally, the CNT antenna dimensions are better matched to nanodevices.

Fig. 4. Dipole-to-dipole transmission. Inset: Two CNT antennas on a quartz substrate side-to-side.

V. 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. Opportunities lie in asymmetric transmission link to bridge micro and nano-electronics.

REFERENCES

- [1] A. D. Franklin, M. Luisier, S.-J. Han, G. Tulevski, C. M. Breslin, L. Gignac, M. S. Lundstrom, et W. Haensch, « Sub-10 nm Carbon Nanotube Transistor », *Nano Lett.*, vol. 12, n° 2, p. 758-762, 2012.
- [2] G. Y. Slepyan, S. A. Maksimenko, A. Lakhtakia, O. Yevtushenko, et A. V. Gusakov, « Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation », *Phys. Rev. B*, vol. 60, n° 24, p. 17136, déc. 1999.
- [3] P. J. Burke, « Luttinger liquid theory as a model of the gigahertz electrical properties of carbon nanotubes », *IEEE Transactions on Nanotechnology*, vol. 1, n° 3, p. 129- 144, sept. 2002.
- [4] L. Nougaret, G. Dambrine, S. Lepilliet, H. Happy, N. Chimot, V. Derycke, et J.-P. Bourgoin, « Gigahertz characterization of a single carbon nanotube », *Appl. Phys. Lett.*, vol. 96, n° 4, p. 042109, 2010.
- [5] C. Lan, P. Srisungsitthisunti, P. B. Amama, T. S. Fisher, X. Xu, et R. G. Reifeberger, « Measurement of metal/carbon nanotube contact resistance by adjusting contact length using laser ablation », *Nanotechnology*, vol. 19, p. 125703, mars 2008.
- [6] P. Franck, D. Baillargeat, et B. K. Tay, « Mesoscopic Model for the Electromagnetic Properties of Arrays of Nanotubes and Nanowires: A Bulk Equivalent Approach », *IEEE Transactions on Nanotechnology*, vol. 11, n° 5, p. 964 -974, sept. 2012.
- [7] G. W. Hanson, « Fundamental transmitting properties of carbon nanotube antennas », *IEEE Transactions on Antennas and Propagation*, vol. 53, n° 11, p. 3426- 3435, nov. 2005.
- [8] P. Franck, D. Baillargeat, et B. K. Tay, « Trade-offs in Designing Antennas from Bundled Carbon Nanotubes », in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*, Montréal, Canada, 2012.
- [9] P. Franck, D. Baillargeat, et B. K. Tay, « Performance assessment of optimized carbon-nanotube-based wireless on-chip communication », in *SPIE Optics and Photonics 2012: Nanoscience and Engineering*, 2012, vol. 8462.