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New concepts for nanophotonics and nano-electronics

Review of two microwave applications of carbon nanotubes: nano-antennas and nano-switches

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Abstract

This paper provides an overview of two potential applications of carbon nanotube devices in microwave technology. Firstly, the main structural, mechanical, thermal and electronic properties of carbon nanotubes are briefly reviewed. Then, the possibilities offered by metallic carbon nanotubes as nano-antennas in the E- and W-bands and further are investigated: comparison with macroscopic wire antennas is made, the major advantages brought by nanotubes but also technical issues to be addressed are discussed. Finally, the integration of carbon nanotubes in nano-electro-mechanical-systems (NEMS) is studied through nano-switches: the contribution of carbon nanotubes is detailed, state-of-the-art is described, as well as our future approaches for such nano-devices. ***To cite this article: S. Demoustier et al., C. R. Physique 9 (2008).***

Résumé

Revue d'applications des nanotubes de carbone aux micro-ondes : nano-antennes et nano-commutateurs. Ce papier présente une vue d'ensemble de deux applications potentielles des nanotubes de carbone pour les technologies micro-onde. Les principales propriétés structurelles, mécaniques, thermiques et électroniques des nanotubes de carbone sont d'abord brièvement rappelées. Puis, les possibilités offertes par les nanotubes de carbone métalliques utilisés comme nano-antennes entre 60 et 110 GHz et au-delà sont examinées : nous effectuons une comparaison avec les antennes filaires classiques puis nous discutons des avantages apportés par les nanotubes mais aussi des problèmes à lever. Enfin, nous évoquons l'intégration des nanotubes de carbone dans les systèmes nano-électro-mécaniques (NEMS) par le biais des nano-commutateurs : l'apport des nanotubes dans ces systèmes est suivi d'une revue de l'état de l'art ainsi que de la description de l'orientation de nos travaux pour la réalisation de ces futurs nano-systèmes. ***Pour citer cet article : S. Demoustier et al., C. R. Physique 9 (2008).***

Keywords: Carbon nanotube; Nanotechnology; Microwave; Dipole antenna; Switch; NEMS

Mots-clés : Nanotube de carbone ; Nanotechnologie ; Micro-onde ; Antenne dipolaire ; Commutateur ; NEMS

1. Introduction

Microelectronics have already fulfilled many expectations for daily use in the fields of mobile phones, the automotive industry, inertial sensors, etc. This has been achieved thanks to the size reduction from macroscopic to microscopic

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scales of chips and transmitting devices, as well as to their constantly increasing frequency range. However, the need for faster, more portable and discreet systems, able to communicate between themselves at high rates, is greater than ever and requires that we continue shrinking the size of the electronic devices down to nano scales. State-of-the-art micro-electronic designs are now confronted with the issue of decreasing the size of devices like antenna, while keeping working at the usual frequencies.

Since their discovery in 1991 [1], the fundamental electrical properties of carbon nanotubes are well understood and are promising for further electronic developments. Along with their thermal and mechanical properties, carbon nanotubes are attractive for a wide range of application fields: they will be used as nano-scale transmission lines, active and passive nano-components such as transistors or switches in high density circuits or in biotechnologies, for instance. One of the technical issues that scientists have to face to bring nanotechnologies to reality is communication and data exchange at high rates between the nano-sized devices or organisms and the macro-world. Nano-antennas based on nanotubes for wireless communications could solve this issue.

In telecommunication networks, RF switches are key parts for realizing the following sub-functions: (i) Transmit/receive switching, band switching (such as handset phones); (ii) Phase shifters in electronic beam steering antennas (satellite antennas, airborne radar, car antennas tracking satellites such as the Inmarsat ones); (iii) Switching matrix to provide redundancy capabilities for critical functions (such as satellite antennas); (iv) Tunable filtering (such as VCO).

Today, the introduction of NEMS (Nano-Electro-Mechanical-Systems) technology into the field of microwaves presents a considerable interest for circuit designers, because it allows the realization of very high performances switches with electrostatic command. Performance is expected as follows: low insertion loss and high isolation, a switching time below 0.1 μs, which is one order of magnitude lower than the state of the art for MEMS switches, an operating voltage below 1 V, high power RF signals handling capability, very low current consumption, low cost and high integration density.

NEMS are characterized by small dimensions, which are relevant for the function of the devices. Critical feature sizes may be from hundreds to a few nanometers. New physical properties, resulting from these small dimensions, may dominate the operation of the devices, and new fabrication approaches may be required to make them. The introduction of carbon nanotubes in NEMS is particularly interesting due to their exceptional electrical and mechanical properties.

Firstly, we will present fundamental properties of carbon nanotubes (Section 2), then we will show their potential use as nano-antennas (Section 3) and then as nano-switches (Section 4).

2. Carbon nanotube properties

2.1. Structural and mechanical properties

Carbon nanotubes (CNTs) are allotropes of carbon. A Single Wall Carbon Nanotube (SWCNT, see Fig. 1(b)) can be roughly approximated by a rolled-up graphene sheet (i.e. mono-atomic layer of graphite whose structure is honeycombed, see Fig. 1(a)) with at least one end like a half-sphere composed of hexagonal and pentagonal carbon groups (Fullerene structure) in order to allow the graphene sheet to roll-up. Multi-walled nanotubes (MWCNT, see Fig. 1(c)) consist in concentric multiple layers of graphite rolled in on themselves to form a tube shape. The spacing between shells in a MWCNT is given by the van der Waals distance between grapheme layers in graphite, and can be approximated to $\delta = 0.34$ nm.

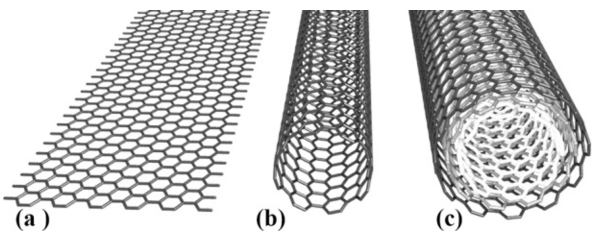


Fig. 1. (a) Graphene sheet, (b) SWCNT, (c) MWCNT.

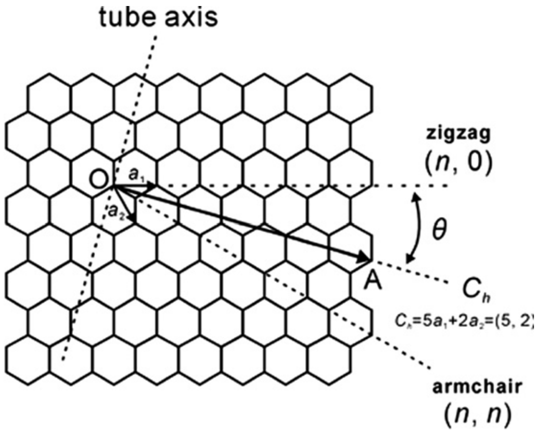


Fig. 2. Lattice basis vectors for CNT.

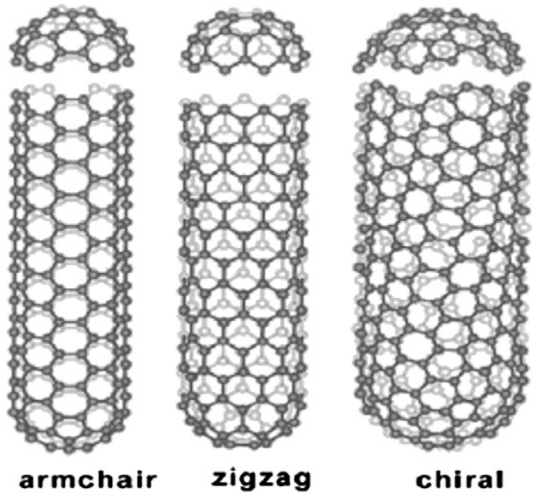


Fig. 3. CNT structural orientation.

Table 1
Comparative Young modulus and elastic range of CNTs and common materials

	SWCNT	MWCNT	Steel	Aluminium	Copper	Gold	Tungsten
Young modulus	1.06 Tpa	4 Tpa	210 Gpa	70 Gpa	124 Gpa	78 Gpa	406 Gpa
Elastic range	130 Gpa		200–800 Mpa	70 Mpa	60 Mpa	124 Mpa	1 Gpa

Table 2
Comparison of thermal conductivities between carbon nanotubes and bulk materials [6]

Bulk materials	Germanium	Silicon	Aluminium	Gold	Copper	Diamond	MWCNT	SWCNT
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	60	148	237	317	485	1000	2000–3000	2500–6600

The structural orientation of the SWCNT, determined by the lattice basis vector (Fig. 2), is split up into three groups presented on Fig. 3: armchair, zigzag or chiral. Electrical and mechanical properties are directly dependent on the SW-CNT orientation: armchair SWCNTs are metallic while zigzag and chiral SWCNTs can exhibit both semiconducting or metallic behaviours [2]. MWCNT all exhibit metallic electrical properties.

Moreover, due to these structures, SWCNT and MWCNT present exceptional mechanical properties. First their Young Modulus is over a TeraPascal, which is far bigger other known material value, as shown in Table 1. This gives the CNT a very wide elastic range and once again far over other known materials before bending becomes permanent.

These exceptional mechanical properties are obtained through a CNT particularity: the carbon group recombination [3]. When a stress is applied with enough strength, by bending, twisting or elongating the CNT, the hexagonal structure breaks up and recombines into groups of pentagonal, hexagonal and heptagonal carbon in order to obtain a new structure as stress-less as possible, but unstable, and will recombine to the original hexagonal structure once stress is no longer applied.

2.2. Thermal properties

The thermal properties of carbon nanotubes ares essentially marked by their outstanding thermal conductivity, which is between 600 and 3000 $W\,m^{-1}\,K^{-1}$ for MWCNTs, between 2500 and 6600 $W\,m^{-1}\,K^{-1}$ for SWCNTs, and between 15 and 250 $W\,m^{-1}\,K^{-1}$ for a bulk CNT films, for temperatures higher than 100 K [4,5]. These values are among the highest ever measured, compared to other bulk materials, as shown in Table 2.

This thermal conductivity increases with temperature (Fig. 4), which is a classical behaviour of semiconductor materials. Fig. 5, extracted from [7], shows experimental results on the thermal conductance variation as a function of temperature for an individual MWCNT (diameter: 14 nm, length: a few μm).

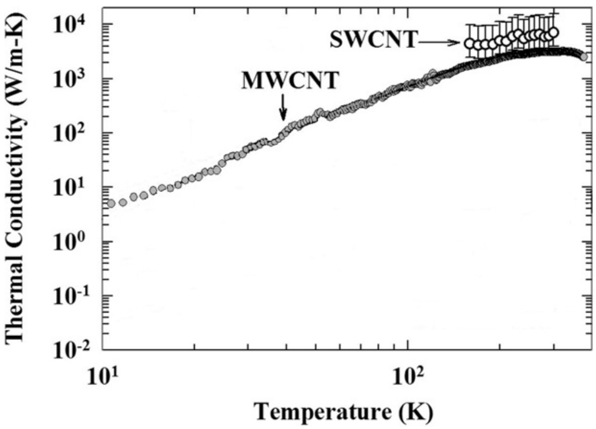


Fig. 4. Thermal conductivity of a SWNT and MWNT alone and in bundle in function of the temperature [8].

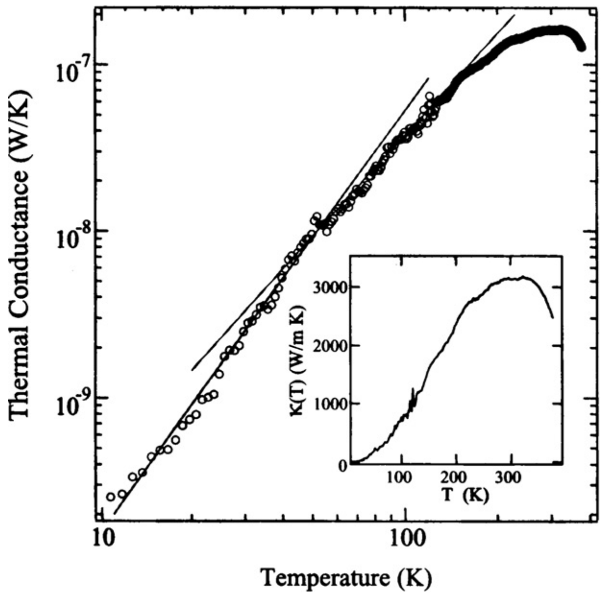


Fig. 5. Temperature variation of thermal conductance of an individual multi-wall carbon nanotube (diameter: 14 nm, length: a few μm). Insert: thermal conductivity [7].

It is also noticeable that the electrical resistance linearly decreases when the nanotube temperature increases, with a thermal-resistance coefficient varying from a few hundredth of 1% to a few % per degree, according to different experiment configurations and nanotubes [9,10]. Finally, a temperature gradient along the nanotube can cause a potential difference, due to the charge carrier scattering from hot to cold. This gives rise to the diffusion thermoelectric power, increasing with temperature and equal to 80 $\mu V\,K^{-1}$ at room temperature for the same 14-nm-diameter multi-wall nanotube as in Fig. 5.

2.3. Electrical properties

Size reduction toward nanometric scale changes the electromagnetic properties of the conducting elements. When a wire is fabricated whose cross-sectional dimension is comparable to the quantum mechanical (Fermi) wavelength of the electron, the wire forms essentially a single-mode waveguide for the electron waves. Then, in a one-dimensional conductor such as a nanotube, the electrons are only free to move along the length of the wire, and not in the transverse direction. Therefore the current distribution is effectively one-dimensional.

In addition to electron transport in only one dimension, two more important effects appear: a larger resistance and a larger inductance. While copper is typically used in applications where high conductivity is required, it does not maintain its bulk conductivity when scaled to nanometric dimensions [11]. In contrast, nanotubes have better conductivity than copper when scaled to their diameter. It has recently been showed that the dc resistance per unit length of a single-walled carbon nanotube at room temperature is about 6 $k\Omega\,\mu m^{-1}$ [12]. Moreover, it can be seen from Fig. 6 that the conductivity of CNTs (bundle of SWCNTs and MWCNT) increases with the length of nanotube, whereas the conductivity of a copper wire does not increase with the length, but with its diameter [13]. This resistance per unit length is quite large compared to the characteristic impedance of free space, as well as typical radiation resistances in traditional antennas. Therefore, it cannot be neglected. Recently it has been proven that the ac and dc resistances are similar for a nanotube up to about 10 GHz [14].

The distributed magnetic inductance and electrostatic capacitance on a two-wire transmission line give rise to a wave-velocity that is typically in the of order of the speed of light. However, in a carbon nanotube, there is another inductance, due to the kinetic energy of the electrons. Numerically, this inductance is typically 10 000 larger than the magnetic inductance, and so it dominates [15,16]. This large inductance causes the nanotube to behave as a quantum transmission line for RF voltages. The characteristic impedance of this line is in several kΩ order. In addition,

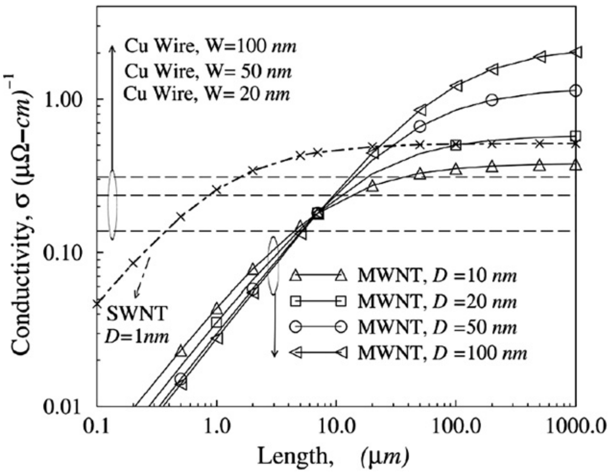


Fig. 6. Conductivity of MWCNTs with various diameters and bundles of densely packed SWCNTs versus length [12].

the wavelength is about 50–100 times smaller than the free space wavelength for a given frequency [17,18]. This dramatically changes the current distribution compared to a thin-wire macro antenna, and must be accounted for.

The conductivities of nanotubes and metallic wires are different because in a metallic wire the charges are relatively free of movement. This flux of charge is concentrated on the surface of the conductor in what is called the ‘conductivity skin depth’. Due to nanotube special structures, there is very little possibility for an electron to move in the same manner as in a macro metal wire. In case of short nanotubes, the electron movement is made by ballistic transport through the nanotubes with path length of about 100 nm in the tubular structure [3] or via tunnelling across gaps [19] with an associated high tunnelling resistance.

Following these particular electrical properties of the nanotubes are the quantum and electrostatic capacitances. For a macro metal wire an electrostatic capacitance can be defined between the wire and a ground plane, and can be approximated by a 1-D model when the distance between the wire and the ground is larger than the length of the wire. This approximated value is 50 $\mathrm{aF\,\mu m^{-1}}$ [15]. A carbon nanotube can be assimilated to a quantum 1-D electron gas, and, due to quantum physics properties, an electron can only be added under specific conditions, leading to an average 1-D quantum capacitance of $C_Q \approx 100\ \mathrm{aF\,\mu m^{-1}}$ [15].

Next we consider the wave velocity in a carbon nanotube, as previously mentioned. This wave velocity is lower than in a macro wire antenna. Experiment and theoretical calculations have shown that this wave velocity was in the order of the Fermi velocity (ν_f) rather than the speed of light. For a carbon nanotube the propagation velocity is about $6.2\nu_\mathrm{f} = 0.02c$ [17].

Lastly the characteristic impedance and the damping mechanisms associated with the carbon nano-tube are discussed. Considering the kinetic inductance $L_\mathrm{K} \approx 16\ \mathrm{nH\,\mu m^{-1}}$ and the quantum capacitance, the characteristic impedance is equal to the quantum resistance which is $\sqrt{L_\mathrm{K}/C_Q} \cong 12.6\ \mathrm{k\Omega}$. Due to the small size of the structures, damping needs to be considered as well and is so far represented as a distributed resistance per unit of length.

3. Nano-antennas

3.1. Introduction

The feasibility of using a carbon nanotube as an antenna is now being studied by a few research groups over the world which has already given us an insight of the possibilities opening of such nano-sized communicating devices. Nanotubes exhibit particular electrical properties compared with a copper wire of same length and diameter. The first relevant point is the nanotube conductivity that has been measured approximately equal to twice the one of the copper: $10^8\ \mathrm{S\,m^{-1}}$ for a carbon nanotube diameter of 1.5 nm and $5.8 \times 10^7\ \mathrm{S\,m^{-1}}$ for the bulk conductivity of copper [20]. The second point is the displayed wave propagation speed in carbon nanotubes that starts around 1/50th of the light speed and seams to decrease to 1/100th as the frequency excitation approaches resonance [17].

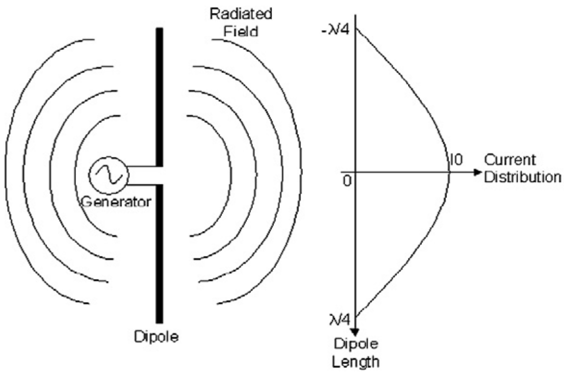


Fig. 7. Current distribution and free-space radiated field of a half-wavelength dipole [18].

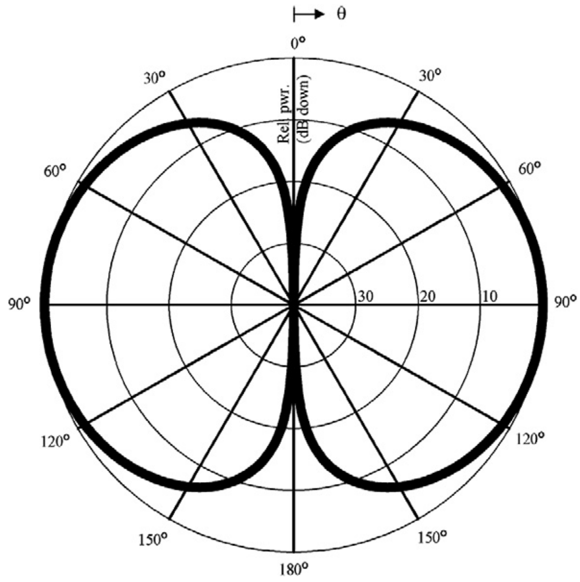


Fig. 8. E-plane typical wire antenna pattern [23].

The typical length of nanotubes enables to consider realistically THz and GHz antennas for wireless communication between the macro-world on the one hand and the nano-devices on the other hand. This section is focused on the feasibility of GHz antennas using nanotubes as resonant dipoles. Already several theoretical studies of the fundamental electrical properties of carbon nanotubes have been made and some have raised major technical issues that might strongly limit the potential efficiency of such antenna. These technical issues are mainly the ohmic losses and the high relaxation frequency of the electron [17,18,21,22]. Nevertheless, no experimental demonstration of nano-antennas have ever been realized to confirm or invalidate these theoretical studies.

Before going through the physics of nano-antenna, we briefly introduce separately the basics of antennas and then of nanotubes. Thus, we will go from the macro wire antenna model to the nano wire antenna model and review the similar and different parameters between the both scales.

3.2. Basics of linear wire antenna theory

Wire antennas are the oldest and most versatile antennas suited for various applications. It is a simple device to understand most of the radiation mechanism and the dipole structure simplification of radiating elements. The typical configuration is made up of two conductor wires, with a length of $\lambda/2$, as shown in Fig. 7.

The current distribution in the conductor wire can be considered in one dimension, and its time variation will generate a radiated electromagnetic field in the surrounding space. Maxwell's equations lead to the classical relation between the current variation $I(z)$ and the radiated field E_θ in the far field space [23]:

$$E_\theta = \mathrm{i}\eta \frac{k\mathrm{e}^{-\mathrm{i}kr}}{4\pi r} \sin\theta \left[\int_{-l/2}^{+l/2} I(z)\mathrm{e}^{\mathrm{i}kz\cos\theta}\,\mathrm{d}z \right]$$

where η is the characteristic impedance of free space, k the constant propagation, l the dipole length, r and θ the radius and elevation angle coordinates. The 3-D emission pattern is said to be omni-directional because it only depends on θ. Fig. 8 shows the typical radiation pattern of a wire antenna in a plane containing the z axis.

Along with the radiation pattern is a set of other key parameters that are used to quantify an antenna and its performances [23]:

– the input impedance is the impedance the power input circuit will have to match in order to transmit the maximum power to the radiating device;
– the gain is the ratio of intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna was radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the input power accepted by the antenna divided by 4π;
– the directivity is the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity average over all directions;
– the radiation efficiency which is the ratio of the radiated power over the accepted power and is a dimensionless combined factor of both the conduction efficiency (losses through metal conduction) and dielectric efficiency (losses through propagation in dielectric space).

3.3. Toward carbon nanotube based nano-antennas

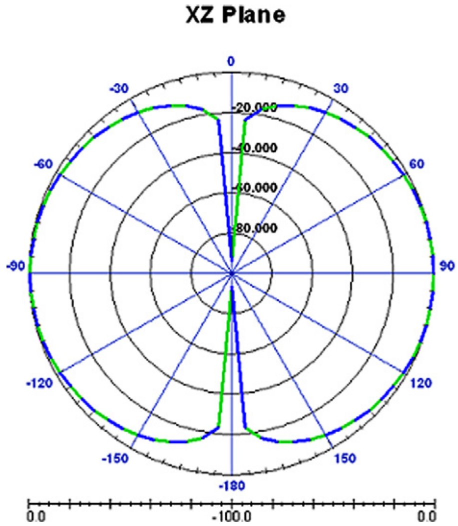
It ensues from the electrical transport properties described in Section 2 the theoretical behaviour of a nano-tube antenna. These characteristics are the same ones we acknowledge for a macro antenna but with very different values. To illustrate the impact of the difference of size between a traditional macroscopic wire antenna and a nanometric antenna, we have made a preliminary simulation of the radiation of a nanometric diameter wire antenna (diameter = 30 nm), made of a virtual material having the same conductivity of carbon nanotubes (10^8 S m^{-1}). The dipole length has been adjusted to fit a resonant frequency around 100 GHz. The simulation results are presented in Fig. 9. It is worth noting that the gain and radiation efficiency obtained with this nano-sized antenna are far below the typical values obtained with a macro-sized wire. The matching impedance is also far higher.

One of the most apparent changes in characteristics is the wave propagation velocity and the resonance frequency. In a macro model, the resonance wave velocity is equal to the speed of light whereas it goes otherwise for a nanotube antenna. As was stated earlier, the wave propagation velocity in a nano-tube transmission line is around 0.02c. When used as a resonant dipole, the wave resonance in the nanotube can be associated with plasmons by the transmission line developed in [18], where the propagation velocity of the antenna was found to be $v_p = 3v_f = 0.01c$ [17]. However, this is only a theoretical rough approximation of the reality. Further calculation and experiment give value around $0.015c$ and $0.017c$ [17]. Consequently, the length of a nanotube antenna should be in the order of 10 to 25 μm for a 100 GHz resonant frequency.

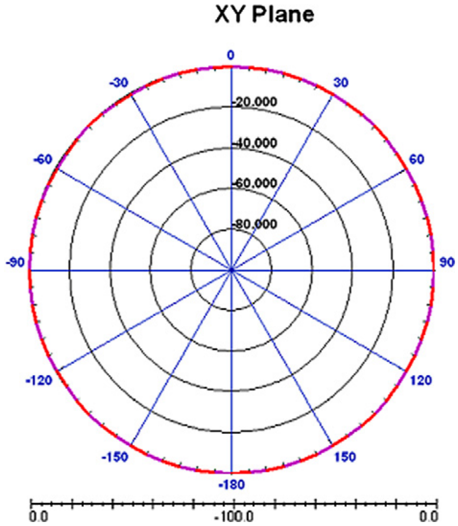
Another characteristic to be considered is the input impedance. As a macro antenna, this impedance was around $50\Omega \pm 50\%$; as a nanotube antenna, it is at least equivalent to the quantum resistance of the carbon nano-tube, around 12.6 kΩ. This is a basic characteristic impedance that will characterize all nano-sized transmitting devices, whether a transmission line or an antenna or any other component. Apart from the size matching between a nanotube and the feeding microscopic lines, the impedance matching between them is a key issue to be solved to make the nanotube antenna a reality.

Another severe issue to be addressed in the route toward a carbon nanotube antenna is its low predicted radiation efficiency. Indeed, a carbon nanotube antenna will show a very low gain and radiation efficiency compared to macro antennas [17]: the author of reference [18] predicts a gain as low as -60 to -70 dB for a nanotube antenna working around 100 GHz. This is due to a strong damping at this nanometric dimension, to be directly connected to the relaxation frequency of the electrons in the carbon nanotube, which can vary from 50 GHz to 1 THz [22]. Thus, it is now unbelievable that carbon nanotube could work at frequencies lower than 50 GHz. However, at higher frequencies, many applications can be considered, as mentioned in the conclusion.

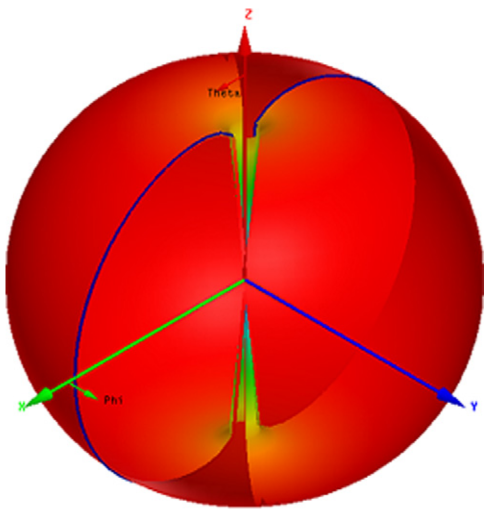
One of the major worldwide objectives is to achieve antennas able to communicate with nanometric components or bodies, by wireless means. Indeed, the potential high-density nano-electronics possible with nanowires and nanotubes will loose their interests if they are contacted with the microscopic, lithographically, for instance. One potential solution to this problem is to use nano-antennas, which can be densely packed. If each interconnect is connected to a nanotube of a different length (hence different resonant frequency), then the problem of multiplexing input/output signals can be translated from the spatial domain to the frequency domain, hence overcoming inherent limitations to make electrical contact to nano-systems. Another application is in the area of sensing. For example, nano-devices could be use as chemical and biological sensors or activators. This would be an RFID technique, where each component of the wireless systems was made of a nanodevice, including the antenna. Such devices even potentially could be implanted into living organisms to monitor biological activity in real time in vivo.



(a)



(b)



(c)

Parameter	Value
Wire diameter	30 nm
Wire length	1150 μm
Conductivity	$S\,m^{-1}$
Working frequency	102.5 GHz
Bandwidth	14.4 GHz
Impedance matching	2350 Ω
Max gain	−2 dB
Directivity	2.24
Radiation efficiency	25%

Fig. 9. Simulation of a nanometric diameter wire antenna. (a)–(c) Radiation patterns in the XZ plan, XY plan and in 3-D; (d) table of the key parameters.

4. Carbon nanotube based Nano Electro Mechanical Systems (NEMS)

4.1. Introduction

Over the past several years, developments in Micro Electro Mechanical Systems (MEMS) have promoted exciting advancements in the field of microwave switching. Micromechanical switches were first demonstrated in 1979 [24] as electrostatically actuated cantilever arms used to switch low-frequency electrical signals. Since then, these switches have demonstrated useful performance at microwave frequencies. MEMS technology introduction in the range of microwaves presents a considerable interest for the circuit designers, because it allows the realization of switches with electrostatic command. Performance is as follows: (i) Cost and size are similar to those based on PIN diodes or FET; (ii) Insertion losses are very low compared to diodes or FET devices and compete with ferrite (<-0.1dB @10 GHz); (iii) Current consumption is negligible (<1 μW).

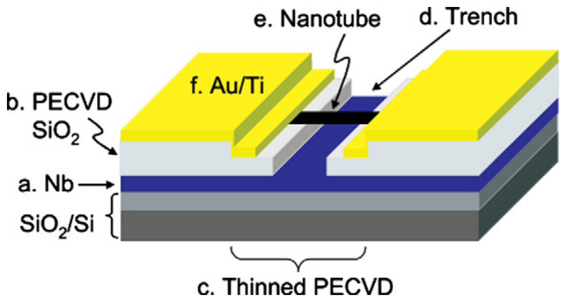


Fig. 10. Schematic of the CNT based switch [34].

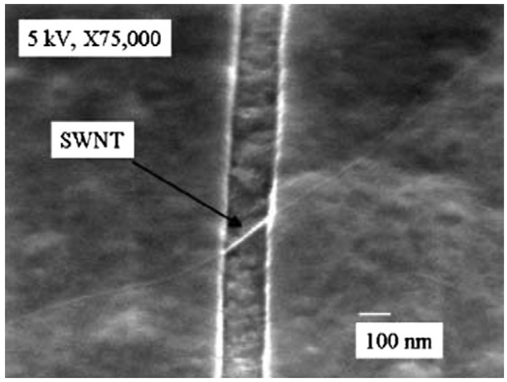


Fig. 11. High-magnification SEM micrograph shows a single nanotube bridging the 130 nm wide trench [34].

As microfabrication is pushed into the nano regime, MEMS research has transitioned into nano-electro-mechanical systems (NEMS). A NEMS switch can offer several advantages over traditional microelectronic switches and newer technologies such as ferroelectric, magnetoresistive and phase change switches, including low power operation, negligible off-state leakage and scalability. For defence and space exploration applications, resistance to radiation and electromagnetic disturbances are particularly important advantages realized by a NEMS switch. In particular, NEMS switches are seen as key devices for fast switching of microwave signals since they can be operated at much higher frequencies than their micrometric counterparts.

Several technical realizations and application perspectives have been reported in the recent literature, and it is noticeable that a majority of them are based on carbon nanotube. They are indeed ideal candidates for the bottom-up fabrication of NEMS devices due to their well-characterized chemical and physical structures, and exceptional mechanical and electrical properties (see Section 1).

First, the size property of carbon nanotubes allows one to decrease both the actuation voltage and the switching time. Secondly, the exceptional electrical and mechanical properties allow one to sustain high RF power. Moreover, it is possible to increase the integration density of such devices. Decreasing the actuation voltage will also permit a decrease in size and prize of control circuit. It has to be pointed out that some prototype of carbon nanotube based NEMS have already been demonstrated such as nano-tweezers [25], random access memory [26], actuators [27], nano-relay [28] and switches (see Section 4.2).

4.2. Carbon nanotube based switches – a review

Several teams have already achieved carbon nanotube based switches with low actuation voltage. Most structures are based on a suspended CNT between two electrodes [29–34] and reported actuation voltages are in the range 1–10 V. Figs. 10 and 11 show an example of a switch based on a CNT suspended between two electrodes realized by A.B. Kaul and co-workers [34]. In this particular case, the pull voltage is less than 5 V.

Switches based on vertically aligned CNTs (Fig. 12) have also been reported [35,36] with actuation voltage around 20 V (Fig. 13). The actual values reached by these NEMS switches in terms of actuation voltage and switching time are nowadays comparable to those of MEMS, but we expect that they will dramatically decrease in the upcoming years respectively down to less than 1 V and below 50 ns.

However, these devices were never related to microwave switching. It is important to notice that the reversible state of such CNT NEMS has been demonstrated in these papers. A careful control of the forces involved is necessary to design a switch with a volatile behaviour. Only one paper reports the switching time of a carbon nanotube based switch, down to a few nanoseconds [34]. Compared to state of the art MEMS devices, the switching time of such CNT switches (air bridge) is several orders of magnitude smaller. In fact, the ultra low mass, exceptionally high spring constant and extremely low capacitance of the CNT all contribute to the small response and rise time in the CNT switch.

Concerning the high power handling capability of such carbon nanotube based switches, it is defined as the power at which the MEMS device fails to operate properly. The two types of failures are RF latching and RF self-actuation. RF

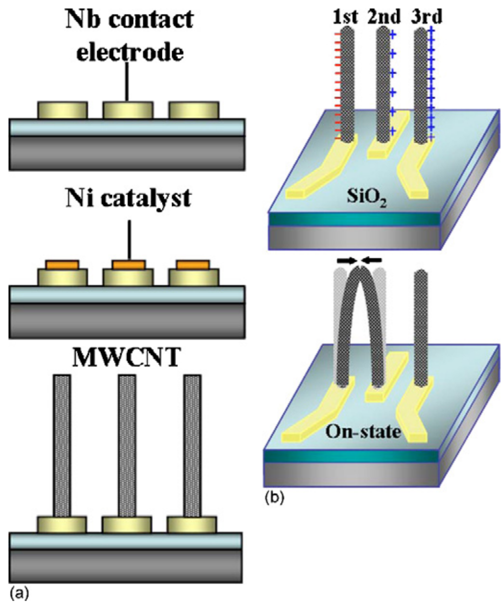


Fig. 12. A schematic illustration of the CNT-based electromechanical switch device. (a) Schematic of fabrication process: Three Nb electrodes were patterned by electron-beam lithography, sputtering, and lift off. Similarly, Ni catalyst dots were also formed on the predefined locations for the growth of MWCNTs. The MWCNTs were then vertically grown from the Ni catalyst dots using dc-PECVD. (b) Illustration of CNT-based electromechanical switch action [35].

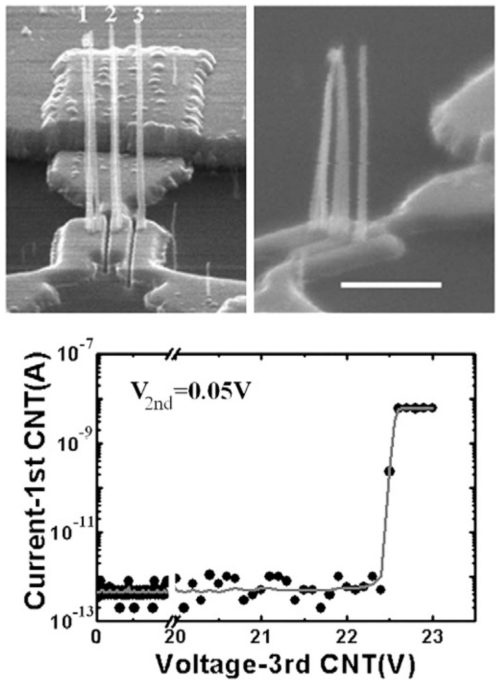


Fig. 13. Electromechanical switch devices consisting of three MWCNTs. (a) SEM image of the device: The length and diameter of the MWCNTs are about 2 μm and 70 nm, respectively. (b) Current-voltage characteristics of switching action in an ambient environment; the electromechanical movement of MWCNTs provides the on and off states. The scale bar corresponds to 1 μm [35].

latching is a situation by which the applied RF power provides enough force on the membrane to hold the switch down when it should have released (i.e. when DC bias is removed). This situation occurs when RF power is continuously (CW) applied to the MEMS circuit. Such a failure means that once a device is actuated, it will not release until the RF power level is lowered below its threshold point. Once the power is lowered, the device is no longer in a failure mode and will continue to operate normally. RF self-actuation is a situation in which the high RF power actually creates enough potential to pull the membrane down into the actuated position without applying a DC bias across the switch. In this case, as soon as the RF power is turned on, all RF MEMS switches in the signal path will be actuated regardless of the intended state. As with the latching failure, if the RF power level is reduced, the switch will behave normally with no ill effects caused by the self-actuation. Another problem is the stiction that occurs when the membrane is stuck irreversibly to the substrate. Here with CNTs we believe that this will no longer be a problem because the contact surfaces are dramatically reduced and charging effects (in the dielectric) will be dramatically reduced.

4.3. Carbon nanotube based switches – our approach

Our approach at Thales Research and Technology is to develop the fabrication process of a RF nano switch based on vertically aligned carbon nanotubes. This kind of switch will consist of CNTs perpendicular to the substrate. The goal is to develop a reproducible technology to fabricate in parallel identical CNT switches on the same substrate and with high integration density.

We are already working on the design of RF nano switches based on carbon nanotubes. Two different architectures, which have already demonstrated efficiency for MEMS component at the micro scale, are imaginable to be studied: a series NEMS switches using ohmic contact between CNTs and a capacitive CNTs based switches implemented in shunt configuration.

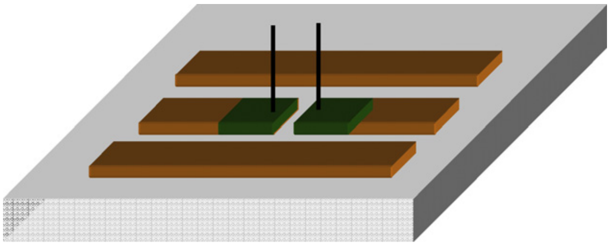


Fig. 14. Proposed NEMS ohmic switch architecture in isolation state.

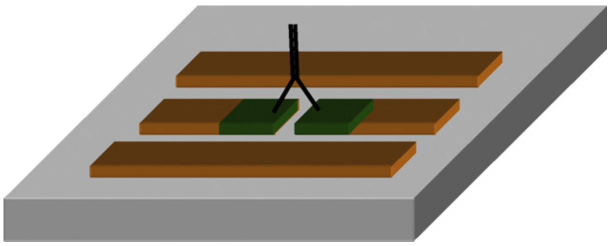


Fig. 15. Proposed NEMS ohmic switch architecture in transmission state.

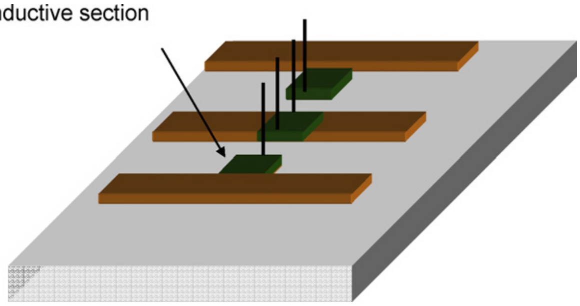


Fig. 16. Proposed NEMS shunt switch architecture in transmission state.

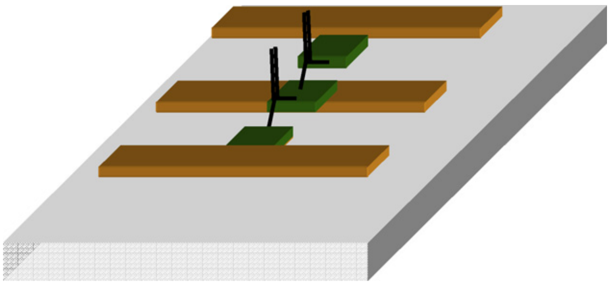


Fig. 17. Proposed NEMS shunt switch architecture in isolation state.

RF NEMS ohmic switch can be simply designed implementing CNTs in both extremity of a coplanar waveguide RF line discontinuity, as shown on Fig. 14. The ohmic contact between each or group of nanotube will allow closing the switch and transmitting the RF signal across the component (see Fig. 15).

For RF NEMS shunt switch architecture, capacitive contact between carbon nanotubes can be considered (Fig. 16). In this case a simple approach will be to symmetrically load a coplanar waveguide RF line using couples of CNTs in so far as to reflect the propagating RF signal by capacitively shunting the component when carbon nanotubes are actuated (see Fig. 17).

Electromagnetic FEM (Finite Element Method) and MOL (Method Of Lines) simulations with the constraint of CNTs actuation requirement (proximity, biasing network needed...) are investigated. To achieve the expected performance in the frequency band, the design solution will be envisaged as the introduction of high inductive section in series with nanotube to perform an LC resonance in or close to the targeted frequency band allowing it to reach higher isolation level in the switch isolation state. The thermal behaviour of design switches will be especially studied based on thermal (REBECCA, ANSYS) models and coupled Electromagnetic/Thermal simulations.

All of that coupled with MEMS fabrication experience developed at Thales [37] will allow us to design and then to fabricate high performance RF switches.

We have already demonstrated that very homogeneous carbon nanotube arrays can be grown by DC plasma enhanced chemical vapour deposition (DC-PECVD) [38]. Fig. 18 shows an array composed of 5 µm height and 50 nm diameter multiwall CNTs spaced by 10 µm [39]. This array shows a very good homogeneity with a standard deviation of 4% on CNT diameter and 7% on CNT length. Thus, this growth process will allow the parallel fabrication of identical CNT switches, with the same characteristics, on the same substrate.

Due to strong C–C covalent bonds, CNTs are much less sensitive to electromigration than metallic nanowires and are able to carry very high currents. Due to this unique property, each CNT of the array shown on Fig. 18 can carry a high current density of 10^8 A cm^{-2} (2 mA for a 50 nm diameter CNT). We have measured this on such carbon nanotubes [40].

We are at the beginning of this activity based on carbon nanotubes but we have already achieved some realizations as the design of such RF NEMS and the fabrication of vertically aligned carbon nanotubes. In the future, we will demonstrate the fabrication of CNT switches and the switching of microwave signals.

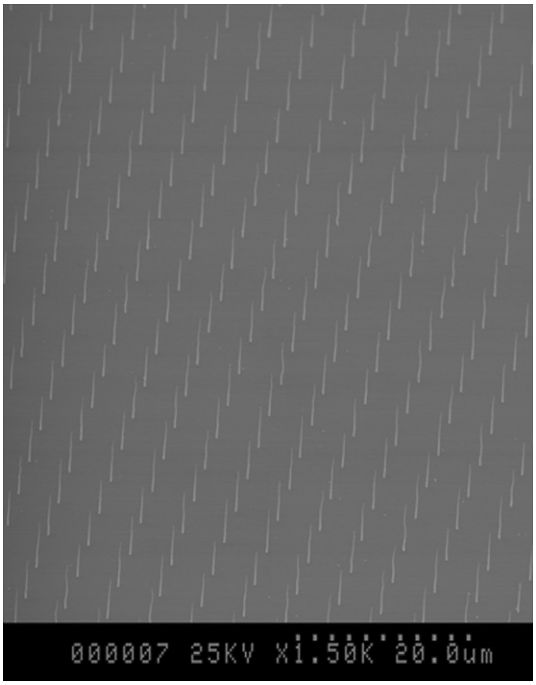


Fig. 18. SEM picture of an array of 5 µm height and 50 nm diameter vertically aligned carbon nanotubes spaced by 10 µm.

5. Conclusion

In summary, we have reviewed the main physical properties of CNTs and two of their potential microwave applications as nano-antennas and nano-switches. These kinds of applications can be enabling elements for communication networks and other applications requiring ultraminiaturized, lightweight components that operate at low voltage, low power, and high speed. Switching has been demonstrated with pull voltages of a few volts, and speed measurements have revealed switching times of a few nanoseconds. Nevertheless, transmission of microwave signals through this type of device still has to be assessed. Concerning the antenna prospects, an excess inductance of the order 10 time of the inductance of a thin-wire antenna has been observed. This provides to CNT antennas this unique property to require a wavelength of current excitation 100 times smaller than the wavelength of the far-field radiation. However, the issue of impedance matching between the nanotube and free space or microelectronics devices still has to be addressed, as well as the poor predicted radiation efficiency. With future, higher mobility nanotubes, better performance would be possible; although, prospects of approaching efficiencies of the order of unity seem dim with the simple thin-wire geometry. For this, alternative geometries may be required.

For industrial research laboratories such as Thales Research & Technology, this kind of long-term research based on new concepts are of high risk but high pay off, by leading to breakthroughs in electronics. There is actually a need for alternative technologies for the realization of a new generation of communication architectures. These technologies present many key features such as high working frequencies, low power consumption and miniaturization which will lead to an overall low cost operation in onboard or mobile applications. They are anticipated to be used in applications concerning fields like mobile and satellite telecommunications and transports, as illustrated by the following examples:

- In the perspective of new standards for mobile phone, data rates much higher than 100 $Mb\,s^{-1}$ at frequencies as high as 66 GHz (WiMax 802.16c norm) will be needed and CNT based devices are of high potential interest as low cost, very efficient and miniaturized broadband devices for future generations of mobile phones;
- On board entertainment (V-Band) would benefit from wireless high data rate distribution in order to reduce the need for existing electrical cables in such systems. Miniaturized nanoscale components could hence greatly diminish the weight and size of the whole system;

– In the field of automotive cruise control (E-Band), strategy analysis predicts that short and long-range distance warning systems will become increasingly common features on passenger vehicles. Two types of sensor, infrared sensors and long-range radar sensors, are particularly well suited to automotive cruise control. However, radar sensors are almost entirely unaffected by weather conditions as opposed to infrared sensors. Moreover, they can be mounted concealed in the front of the vehicle. Radar systems in E-band allow very small antenna sizes, permitting them to be installed almost anywhere;
– Security systems (W-Band) are necessary in air transport to increase safety during night and/or in poor weather and low visibility conditions. In addition to existing infrared systems, microwave radar systems, in which nanoscale components will play a crucial role, allow to extend enhanced situation awareness to 'all-weather' conditions. In the future, these new microwave systems could permit the evaluation of the potential obstacles in the approach path and weigh their priority in order to realize an autonomous approach and landing.

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