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Carbon Nanotube Antennas

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Abstract — A carbon nanotube is a one-dimensional molecular wire. In this paper, we discuss some of the properties of carbon nanotubes as microwave and mm-wave antennas. We also discuss some of the conceptual issues involved with understanding the interaction of microwaves with one-dimensional quantum wires. While we focus on simple dipole antennas, our discussion applies generally to the interaction of microwaves with nano-materials, including nanotube arrays and composites.

I. INTRODUCTION

One of the most fundamental parameters of any antenna is the current distribution on the antenna. This issue has defined antenna theory for many years. In this paper, we consider some conceptual issues associated with the use of carbon nanotubes as antennas (see Fig. 1), especially with regards to the current distribution. We also discuss possible applications of nanotubes in microwave devices, materials, and systems. This paper is a qualitative discussion of the physical effects that occur in carbon nanotube antennas aimed at the electromagnetics community. More quantitative discussions will be published at a later date, and are available in a recent e-print[1].

1 BACKGROUND: NANOTUBES

1.1 Electronic properties

Quantum mechanically, an electron is both a wave and a particle. When a wire is fabricated whose cross-sectional dimensional is comparable to the quantum mechanical (Fermi) wavelength of the electron, the wire forms essentially a single-mode waveguide for the electron waves. The effect of this wave guiding on the dc resistance of narrow wires has been studied by the device physics community for many years. It is by now well-known that the dc conductance of a narrow wire (in the absence of scattering along the length of the wire) is quantized in units of $2e^2/h$, where e is the electronic charge and h is Planck's constant. Numerically, $h/2e^2 = 25k\Omega$. When there is scattering along the length of the wire, the resistance is higher.

Synthesis

Recently (in the last few years), with the advent of nanofabrication technologies (including synthesis techniques for carbon nanotubes and semiconducting nanowires), it has proven possible to achieve this quantum 1d limit at room temperature or even higher. In 2004, several groups (including our own) extending this nanofabrication technology to synthesize aligned arrays of straight, electrically continuous individual single-walled carbon nanotubes with lengths of up to cm[2, 3, 4, 5, 6, 7, 8, 9, 10]. (See Fig. 2.) This length is of order the wavelength of microwave and mm waves, hence motivating our study of the interaction of microwaves with carbon nanotubes.

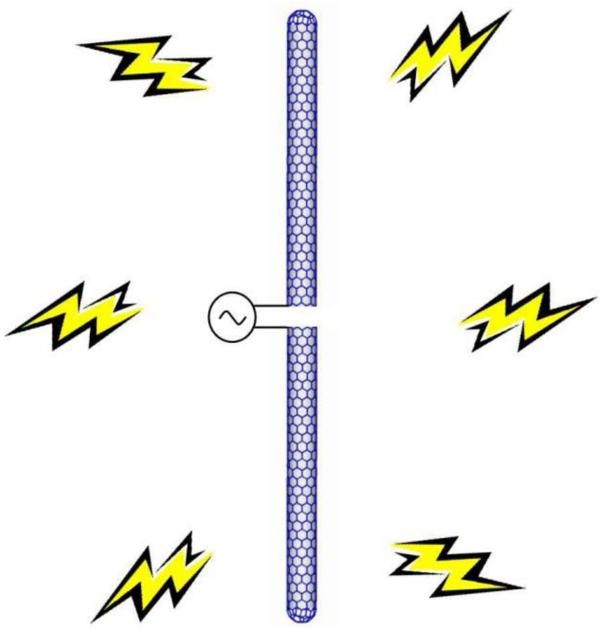

Figure 1: Carbon nanotube antenna.

2 BACKGROUND: ANTENNAS

2.1 Dipole antennas

One of the most fundamental parameters of any antenna is the current distribution on the antenna. This determines the radiation pattern, the radiation resistance and reactance, and many other properties of interest.

Modern work on antenna theory is typically numerical because of the lack of analytical solutions. In contrast, early work on antenna theory (including some pioneers such as Hallen and Schelkunoff[11, 12, 13, 14, 15]) focused on deriving analytical expressions for the current distribution on an antenna.

In their work, the only geometry to which an analytical solution is available (to our knowledge) is the simple dipole antenna. Analytical expressions are available as series expansions in the parameter d/l, where d is the diameter and l the length. Virtually all of modern antenna theory takes as its canonical example the characteristics of a dipole antenna in the limit d/l goes to zero.

2.2 Nanotube antennas

Now, with the advent of cm long carbon nanotubes, it is possible to fabricate conducting wires with unprecedented aspect ratios of order 10^7. This has lead us to propose a nanotube antenna, shown in Fig. 1. At first sight, it would seem that this new system would be the closest physical realization to a dipole antenna (in the sense that d/l is small) mankind has ever manufactured. However, this is not the case, as we elaborate on below.

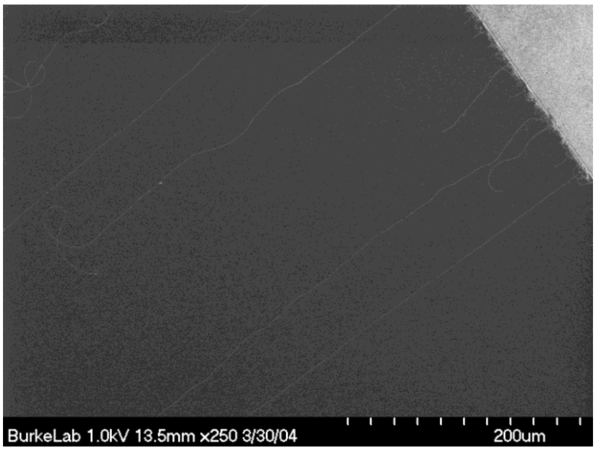

Figure 2: SEM image of arrayed, ultra-long singlewalled nanotubes synthesized in our labs.

II. NANOTUBE ANTENNAS

2.3 What is different

In original theoretical work on dipole antennas, it was assumed that the dipole radius was larger than the skin depth, *and* that the resistive losses were low enough to be neglected in determining the current distribution on the antenna. Both of ≈these assumptions break down for nanotube antennas. Therefore, the original theory and hence the only analytical theory breaks down in the limit d/l becomes sufficiently small.

2.4 1d transport

In a one-dimensional conductor such as a nanotube, the concept of skin-depth is almost meaningless, since 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 the electron transport occurring in only one dimension, we also have two more important effects: large resistance, and large inductance.

2.5 Resistance

While copper is typically used in applications where high conductivity is required, it does not maintain its bulk conductivity when scaled to nanometer dimensions[16]. In contrast, nanotubes have better conductivity than copper when scaled to their diameter. We recently showed[3] that the dc resistance per unit length of a single-walled carbon nanotube at room temperature is about 6 $k\Omega/\mu m$. A copper wire with the same diameter (1.5 nm) would have an even higher resistance per unit length.

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.

A question arises whether the ac resistance and the dc resistance are the same for a nanotube. Recently, we showed[17] that they are, up to about 10 GHz.

2.6 Kinetic inductance

The distributed magnetic inductance and electrostatic capacitance on a two-wire transmission line gives rise to a wave-velocity that is typically of order 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[18, 19].

A simple argument for the existence of this kinetic inductance is as follows: The energy stored in the kinetic motion of the electrons is proportional to the velocity squared. Since the velocity is proportional to the current, therefore the kinetic energy is proportional to the current squared. We claim this translates into a kinetic inductance, since the energy stored is proportional to the current squared. To date this claim has not been experimentally verified.

This large inductance causes the nanotube to behave as a quantum transmission line for RF voltages. The characteristic impedance of this line is of order $h/4e^2$ $6k\Omega$. In addition, the wavelength is about 100 times smaller than the free space wavelength for a given frequency. This dramatically changes the current distribution compared to a thin-wire antenna, and must be accounted for.

III. APPLICATIONS

Our modeling has only considered one or two parallel nanotubes, and not yet extended to mats of oriented or random arrays, or to multi-walled nanotubes. Thus, we are embarking on the studies of a new material systems with potentially very different microwave properties than either bulk metals, semiconductors, or insulators. For microwaves propagating in free space, potential applications include conducting composite materials for isolation, quasi-optical polarizers, and possibly antennas for communicating between integrated nanosystems and the macroscopic world. Other possible applications include active[20, 21] (FET) and passive (interconnect)[17] microwave nano-devices.

IV. FUTURE WORK

Our initial modeling work[18, 19] and also this paper discuss the limit of a pure 1-d wire. However, it would be interesting to extend our analysis to the case of multi-walled 1d wires such as multi-mode carbon nanotubes and also copper nanowires. Understanding the advantages and disadvantages of these in antenna and interconnect technology would be the goal of such a study. Currently, we do not have a clear understanding of the transition from classical thin wire antenna performance to purely 1d quantum wire performance.

Additionally, experiments need to be performed that will validate the predicted behavior of carbon nanotube antennas.

Finally, more sophisticated geometries including 1d arrays and other geometries more suited to the unique electronic properties of carbon nanotubes need to be carefully considered.

V. CONCLUSIONS

It is somewhat ironic that the conclusions of this paper are that the only analytical theory available for antenna properties actually does not apply at all in the small-diameter limit assumed: When the diameter is nanometer, the antenna behavior is quite distinct.

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