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Nanomechanical radio transmitter

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We explore a design possibility for a highly integrated nanoscale radio transmitter, where the key functional component is a mechanically vibrating electrically charged beam.

1 Introduction Radio transmission and reception has a rich history. Within a decade of the experimental discovery of electromagnetic waves in 1888 by Hertz, radio was used for critical communications, for example in shipping. By the 1930s, it had achieved mass popularity, with more than 50 million listeners, as a medium for music and news [1]. Today, radio remains a widely used communications medium that underlies modern technologies from space exploration to computer networking.

The earliest spark-gap transmitters and receivers were large, dangerous, and only capable of transmitting on-off signals such as Morse code. Vacuum tube, solid state transistor, and integrated circuit technologies have transformed both the capability and size of radios. Integrated circuit based radio transmitters now exist that are approximately 1 mm^3 in size [2]. However, this technology is approaching hard physical limits and therefore new technologies focused on nanoscale materials are needed to further miniaturize radio transmitters.

One promising new material is carbon nanotubes, and a number of electrical devices have already been demonstrated including a radio receiver [3], transistors [4], diodes [5] and sensors [6, 7]. Nanotubes, which are essentially rolled up sheets of graphene, have some unique characteristics which make them well suited for electrical and mechanical nanoscale devices. The intriguing electrical properties include both metallic and semiconducting behavior and extremely high current density capability. Mechanically, nanotubes have a high elastic modulus, high tensile strength and sharp mechanical resonance peaks. This unique combination of electrical and mechanical properties enabled the nanotube radio receiver and many of the same properties can be exploited for a carbon nanotube radio transmitter.

2 Nanotube radio transmitter

2.1 Radio transmitter fundamentals A radio transmitter is an electrical device that generates, amplifies and radiates a high frequency carrier signal which has been modulated by a lower frequency information signal. A block diagram of the essential components of a transmitter is shown in Fig. 1. The carrier signal is typically generated by an oscillator and then combined with the information signal by the modulator. This combined signal is then amplified before it is radiated by the antenna.

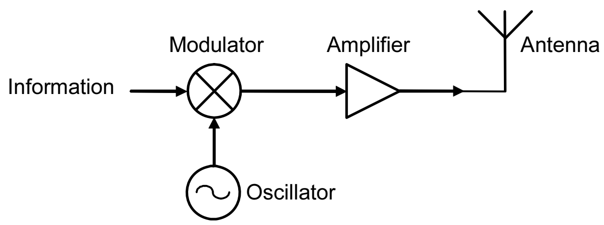

Figure 1 Block diagram for a typical radio transmitter. The four essential components are the oscillator, modulator, amplifier and antenna.

2.2 Nanotube transmitter schematics A schematic of a nanotube transmitter is shown in Fig. 2. The four critical components of a radio transmitter can be implemented by a single nanotube. The key idea in this transmitter is that the nanotube is mechanically oscillating at the frequency of the carrier signal. By applying a dc voltage to the nanotube, charge is concentrated at the tip of the nanotube. Therefore, when the nanotube oscillates it radiates an oscillating electromagnetic field.

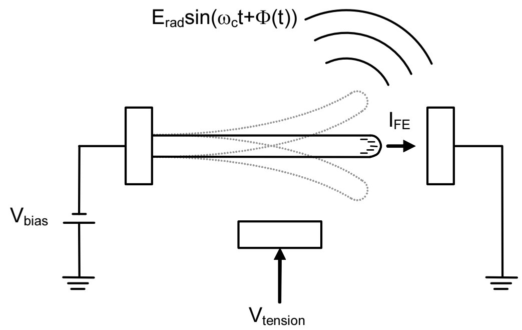

Figure 2 Schematic of the nanotube radio transmitter. Field emission from the tip of the nanotube can induce self-oscillations in the nanotube. In combination with the excess charge in the tip of the nanotube, these mechanical oscillations effectively transmit a radio signal.

2.3 Modulator and oscillator Fundamental to the operation of the nanotube transmitter is mechanical oscillation of the nanotube. An external electrical oscillator could be used to vibrate the nanotube but this would compromise the nanoscale size of the transmitter. Alternatively, it has been shown that self-oscillations can be induced in a single-clamped nanoscale resonator by applying only a dc voltage [8]. These self-oscillations are dependent on field emission from the nanotube to a counter electrode. This concept can be applied to the nanotube transmitter by adjusting V_{bias}, in Fig. 2, to a dc voltage that will cause both field emission and self-oscillations in the nanotube. The nanotube will oscillate at the mechanical resonance frequency.

Equally important to any radio transmitter is the ability to modulate the high frequency carrier signal with a lower frequency information signal, which can be done by modulating either the amplitude or frequency of the carrier. Frequency modulation (FM) in the nanotube transmitter could be accomplished by modulating the fundamental mechanical resonant frequency of the nanotube. By changing the tension on the nanotube with a voltage on the $V_{tension}$ electrode in Fig. 2, the nanotube would bend and therefore change the resonant frequency. The information signal could be applied to this electrode to modulate the frequency of the self-oscillations.

2.4 Antenna and amplifier The sole purpose of the antenna in a transmitter is to radiate modulated electromagnetic waves. Typically an amplifier drives an oscillating current in a metal wire antenna which in turn radiates the signal. In the nanaomechanical transmitter, mechanically oscillating charge in the tip of the nanotube acts like a small antenna. The movement of the electrons creating the electromagnetic wave is driven by mechanical motion as opposed to electrical current in a standard antenna.

In a typical radio transmitter an amplifier is used to drive the antenna. However, in this transmitter the oscillator and the nanotube are actually the same element. Therefore, an amplifier is not necessary to drive the antenna. Although an amplifier is not needed, there are a number of ways to control the radiated power. First, by changing magnitude of the mechanical self-oscillation the power of the transmitted signal would be altered. Although the exact relationship between magnitude of the self-oscillations and the field emission current is not clear, it is believed that higher current leads to larger oscillations [8]. Second, by increasing the charge in the nanotube, the magnitude of the radiated field would also change. Finally, an array of nanotubes could be used to further increase the transmitted power. In addition to controlling the output power, these methods could also be used for amplitude modulation.

3 Nanotube transmitter simulations Shown in Fig. 3 is a finite element simulation of the magnitude of the electric field surrounding the nanotube when it is bent and straight. First, it is interesting to note that the large electric fields are almost entirely concentrated at the tip of the nanotube. This electric field results from the excess charge concentrated in the tip. Second, the change in the magnitude of the electric field at the tip of the nanotube when it is bent versus when it is straight is apparent in the insets of Fig. 3.

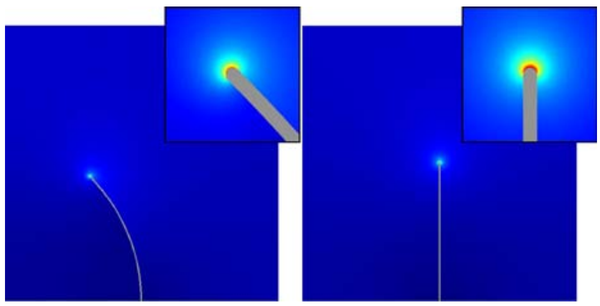

Figure 3 Simulations of the electric field amplitude surrounds the nanotube when it is bent (left) and straight (right).

4 Applications The nanotube radio's primary advantage over previous radio transmitters is, of course, its size. A typical volume for the active element (i.e. the nanotube) is only 3.9×10^4 nm^3. This is small enough to travel in the human bloodstream or even fit within a single cell. Thus, a host of new biomedical applications are possible. For example, it may be possible to place radio-controlled medical devices in the bloodstream to perform diagnosis or to control drug delivery. Due to its size, a nanotube transmitter could also be used on a conventional integrated circuit to distribute signals that would otherwise require dedicated wires. Along these lines chip to chip wireless communications could reduce both the size and cost of conventional electronics. Other potential applications for nanoscale radios include “smart dust” [9], enhanced radio frequency identification (RFID) tags, or simply smaller, cheaper wireless devices such as cellular phones.

Besides its small size, the nanotube radio has numerous other advantages. As it is chemically inert, it can operate in a variety of chemical environments. Also, as it is partially composed of mechanical elements, the nanotube radio is naturally radiation hardened and can operate in the presence of severe ionizing radiation (e.g. in space). Finally, because many nanotube radios, each with a different resonance frequency, can be incorporated on the same chip, it is possible to make extremely broad bandwidth devices.

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