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Nanotube Radio

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ABSTRACT

We have constructed a fully functional, fully integrated radio receiver from a single carbon nanotube. The nanotube serves simultaneously as all essential components of a radio: antenna, tunable band-pass filter, amplifier, and demodulator. A direct current voltage source, as supplied by a battery, powers the radio. Using carrier waves in the commercially relevant 40–400 MHz range and both frequency and amplitude modulation techniques, we demonstrate successful music and voice reception.

Radio has had a profound effect on civilization from its early use in critical communications, such as with ships at sea, to its later use during the "golden age" of radio in the 1930s as a mass medium for news and entertainment, and finally to its more recent uses in cellular phones, wireless computer networks, and the global-positioning system. Historically, applications of radio have been tightly linked to available technology. For example, early spark-gap receivers were only capable of receiving on/off signals such as Morse code. Vacuum tube technology enabled cheap, reliable audio communication. Perhaps most strikingly the solid-state transistor transformed the radio from a bulky, power-hungry, and stationary unit to a device that could be carried in a shirt-pocket.[1] Today, the same silicon-based technology that gave us the transistor is fast approaching hard physical limits, and it is expected that future progress will require new nanoscale materials,[2] for example carbon nanotubes.[3−6] Combining many of the unique electrical and mechanical properties of carbon nanotubes,[7−9] we have fabricated a fully functional radio receiver, orders-of-magnitude smaller than previous radios, from a single carbon nanotube. The nanotube radio may lead to radical new applications, such as radio controlled devices small enough to exist in a human's bloodstream, or simply smaller, cheaper, and more efficient wireless devices.

To understand how the nanotube radio receiver operates, it is instructive to examine how radio receivers work in general, specifically envelope detector radio receivers. These radios consist of four essential components: antenna, tuner, amplifier, and demodulator, all shown in the dashed box in the block diagram in Figure 1. The antenna receives the incoming radio transmissions. The tuner then filters this received signal, selecting a frequency range or channel of interest. The amplifier increases the generally weak radio signal power to a more robust level. Finally, the demodulator, typically a nonlinear device like a diode, extracts from the incoming modulated, high-frequency radio signal the lower frequency informational signal that, depending on application, can either be directly amplified and sent to an audio loudspeaker (as shown in the remainder of the block diagram in Figure 1) or further processed by a computer or other instrument.

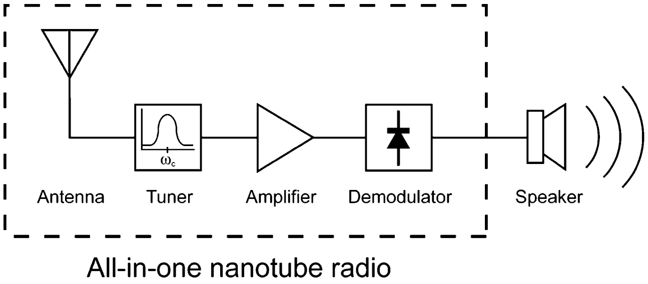

Figure 1. Block diagram for a traditional radio. All four essential components of a radio, antenna, tuner, amplifier, and demodulator may be implemented with a single carbon nanotube.

Amazingly, all four critical radio receiver components can be simultaneously implemented with a single carbon nanotube. A schematic of the nanotube radio is shown in Figure 2a. A model of simplicity, the entire radio consists of an individual carbon nanotube mounted to an electrode in close proximity to a counter electrode. A direct current (dc) voltage source, such as from a battery, is connected to the electrodes and powers the radio. Important for the radio's operation, the applied dc bias negatively charges the tip of the nanotube, sensitizing it to oscillating electric fields. Also, both electrodes and nanotube are contained in vacuum, typically below 10^{-7} Torr. Interestingly, this geometrical configuration is reminiscent of a conventional vacuum tube, and indeed there are some key functional similarities between the two.

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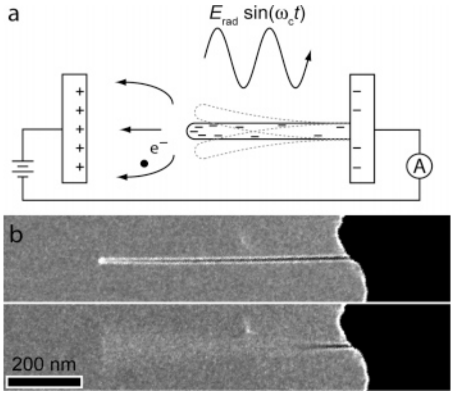

Figure 2. (a) Schematic of the nanotube radio. Radio transmissions tuned to the nanotube's resonance frequency force the charged nanotube to vibrate. Field emission of electrons from the tip of the nanotube is used to detect the vibrations and also amplify and demodulate the signal. A current measuring device, such as a sensitive speaker, monitors the output of the radio. (b) Transmission electron micrographs of a nanotube radio off and on resonance during a radio transmission.

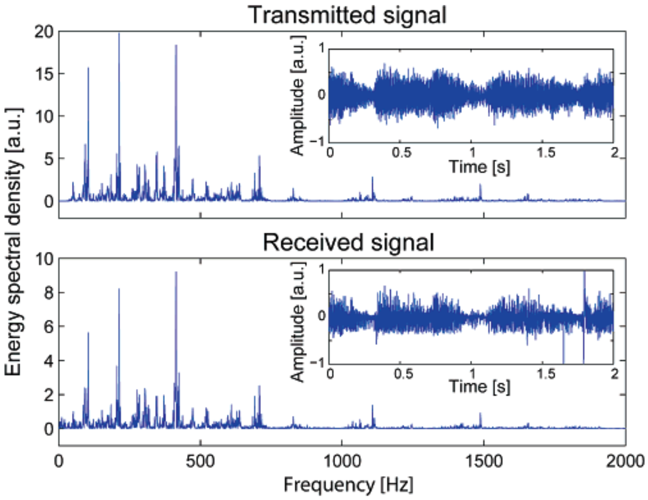

Figure 3. Transmitted and received audio waveforms (inset) and frequency spectra of 2 seconds of the song "Good Vibrations" by the Beach Boys. The nanotube radio faithfully reproduces the audio signal, and indeed the song is easily recognizable by ear (see Supporting Information).

The nanotube radio operates in a radically different manner than traditional radios. Whereas traditional radios are entirely electrical in nature, the nanotube radio functions at least in part mechanically. Briefly, electromagnetic waves from an incoming radio transmission impinge upon the nanotube forcing it to physically vibrate through their action on the charged tip. These vibrations are only significant when the frequency of the incoming wave coincides with the nanotube's flexural resonance frequency. As described in detail below, the nanotube's resonance frequency can be tuned during operation, and hence the nanotube radio, like any good radio, can be tuned to receive only a preselected band of the electromagnetic spectrum. Already, this explains at least superficially how the nanotube serves as both antenna and tuner of a radio.

The amplification and demodulation stages rely on the remarkable field-emission properties of carbon nanotubes, which are due in large part to their needle-point geometry that concentrates the electric field.[7] The dc bias voltage applied across the electrodes in Figure 2a produces a nominally constant field-emission current. Mechanical vibrations of the nanotube modulate the field-emission current,[10] which then serves as the easily detected electrical signal. Because the battery voltage source, rather than the incoming electromagnetic wave, powers the field-emission current, amplification of the radio signal is possible. Also, due to nonlinearities inherent in field-emission, demodulation of the radio signal occurs as well. Thus, all four essential components of a radio receiver are compactly and efficiently implemented by the vibrating and field-emitting nanotube.

Because of the critical role played by mechanical motion of the nanotube during radio operation, visual observation of the nanotube radio is invaluable. We accomplished this by mounting the nanotube radio inside a high-resolution transmission electron microscope (TEM). A sine-wave carrier radio signal (generated for screening reasons inside the TEM) was launched from a nearby transmitting antenna. Figure 2b shows TEM micrographs of the nanotube attached to the cathode (the anode is not shown as it is more than one micron off the image toward the left). In the upper image, the nanotube resonance frequency does not match the transmitted carrier wave frequency; the nanotube is relatively motionless and no radio reception can occur. Apparent in this image is the negative charging of the tip of the nanotube, which manifests itself as a significant brightening toward the nanotube's tip.[11] In the lower image, the nanotube's resonance frequency has been brought into tune with the transmission carrier wave frequency (251 MHz). Here the oscillating electric field of the radio signal resonantly drives the charged nanotube causing it to vibrate vigorously thereby blurring its image.[8] During this resonance condition, radio reception is possible.

To correlate the mechanical motion of the nanotube to actual radio receiver operation, we launched a frequency-modulated (FM) radio transmission (amplitude-modulated (AM) signals work as well) of the song "Good Vibrations" by the Beach Boys. After being received, filtered, amplified, and demodulated all by the nanotube radio, the emerging signal was further amplified by a current preamplifier and sent to an audio loudspeaker and recorded. The upper portion of Figure 3 shows the frequency spectrum and audio waveform of a 2 s segment of the song as transmitted, while the lower portion of the same figure shows the same segment as received by the radio. The nanotube radio faithfully reproduces the audio signal, and the song is easily recognizable by ear (see Supporting Information for audio and video of this song and other nanotube radio classics). As a test, during operation we purposely detuned the nanotube from the carrier frequency, and as expected whenever mechanical resonance was lost so was radio reception. We found it straightforward, even without active feedback, to maintain "lock" on a given radio transmission channel for many minutes at a time. Of course, it is not necessary to operate the nanotube radio inside a TEM. Using a slightly different configuration, we successfully transmitted and received

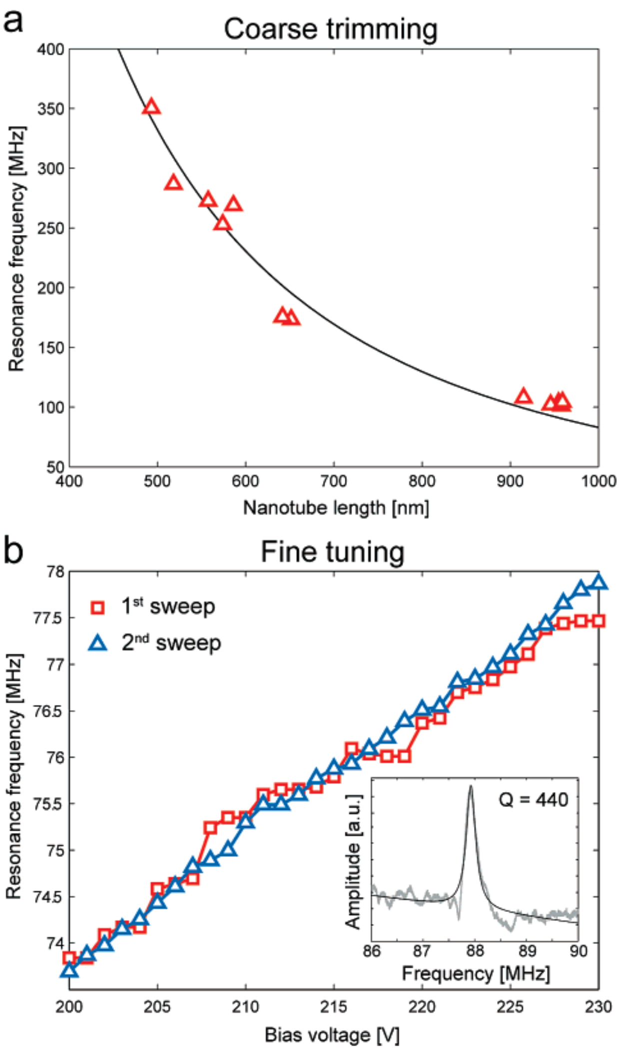

Figure 4. Demonstration of coarse and fine methods for adjusting the center frequency of the nanotube radio's tuner. (a) During coarse tuning or "trimming", the nanotube is controllably shortened thus increasing its resonance frequency. Its resonance frequency closely follows the $1/L^2$ dependence predicted by Euler−Bernoulli beam theory. (b) During fine-tuning, a bias voltage is used to adjust tension on the nanotube. Multiple sweeps of the bias voltage demonstrate the reversibility of the process. Inset is a typical resonance peak with a Lorentzian fit.

signals across the length of our laboratory, a distance of several meters.

We turn now to details of nanotube radio operation and ultimate sensitivity limits. The resonance frequency of the nanotube radio is tuned using a two-step process. An initial "coarse" tuning adjustment sets the operational frequency band by trimming, or shortening, the length of the nanotube. To accomplish this, a high field-emission current, which is much higher than used for radio operation, is run through the nanotube, and as a result carbon atoms are ejected from the end of the nanotube, permanently altering its length.[12] The trimming process is terminated once the nanotube's resonance frequency reaches the target frequency band. Figure 4a demonstrates coarse tuning of a nanotube radio from a lower frequency FM radio band (around 100 MHz) to much higher frequency bands (up to 350 MHz) reserved for applications such as television or emergency services. Fine-tuning of the radio within the desired band is accomplished by tensioning the nanotube with an electrostatic field.[10] Thus, much as a guitar is tuned by tensioning its strings, the nanotube's resonance frequency is tuned (over several megahertz) through small adjustments to the already established dc bias voltage. Figure 4b demonstrates fully reversible fine-tuning of a nanotube's resonance frequency during radio operation.

The antenna is implemented by the charged tip of the nanotube. This is substantially different than other proposals that use nanotubes as scaled-down versions of macroscopic antennas.[13,14] The quantity of charge at the tip critically affects the performance of the antenna. Nanotubes of similar sizes and under similar conditions to the ones used in this experiment ($L \approx 500$ nm, $r \approx 5$ nm, $E_{\text{ext}} \approx 10^8$ V/m) accumulate approximately 3×10^{-17} C of charge (almost 200 unbalanced electrons) at their tips.[15] The tuner filters radio signals through the nanotube's flexural resonance frequency. According to classical Euler−Bernoulli beam theory, the resonance frequency of a cantilevered nanotube is $f_0 = 0.56/L^2\sqrt{YI/\rho A}$, where L is the length of the nanotube, Y is the Young's modulus, I is the areal moment of inertia $[(\pi/4)(r_o^{\,4} - r_i^{\,4})$ for a cylinder with outer and inner radii $r_o\ r_i)]$, ρ is the density, and A is the cross-sectional area.[16] Typical nanotubes used in our experiments had resonance frequencies from 10 to 400 MHz, lying in a commercially relevant portion of the spectrum including FM radio. The bandwidth of the filter is determined by the quality factor of the nanotube resonators, typically around 500 (see Figure 4b).

By combining theoretical results for the antenna and tuner, it is possible to determine the sensitivity of the nanotube radio to incoming electromagnetic waves. The amplitude of the vibrations of the tip of the nanotube is given by the familiar equation

$$|y| = \frac{qE_{\text{rad}}/m_{\text{eff}}}{\sqrt{(\omega^2 - \omega_0^{\,2})^2 + (\omega\omega_0/Q)^2}} \tag{1}$$

where q is the charge on the tip, E_{rad} is the amplitude of the electric field of the incoming transmission, $m_{\text{eff}} \approx 0.24$ m is the effective mass of the nanotube determined from Euler−Bernoulli theory, and Q is the quality factor. This amplitude may be compared to the thermal vibrations of the nanotube, which ultimately limit the sensitivity of the single nanotube radio. The minimum detectable electric field amplitude while maintaining a bandwidth B is $E_{\text{rad}} = (1/q)\sqrt{4k_BTm_{\text{eff}}\omega_0B/Q}$, which for our experiments was typically 1 V/m/$\sqrt{}$Hz or equivalently 60 dBmV/m/$\sqrt{}$Hz.[17] The nanotube radio's sensitivity can be enhanced by operating at reduced temperature, using a lower resonance frequency, or improving the Q of the oscillating nanotube. Other modifications include attaching an external antenna (this method was found effective for long-range reception described above) or in the interest of preserving the overall small size of the receiver system using multiple nanotubes all tuned to the same frequency.

The final two components of the nanotube radio, amplifier, and demodulator rely on the details of field-emission from nanotube tips. The field-emission current, I, from a carbon nanotube is well described by the Fowler−Nordheim law[18]

$$I = c_1 A(\gamma E_{\mathrm{ext}})^2 \exp\left(-\frac{c_2}{\gamma E_{\mathrm{ext}}}\right) \tag{2}$$

where A is the area from which the nanotube emits, E_{ext} is the external applied electric field, and γ is the local field enhancement factor. The constants c_1 and c_2, which involve only fundamental constants and the nanotube's work function, take the values 3.4×10^{-5} A/V^2 and 7.0×10^{10} V/m, respectively. The field enhancement factor, a measure of the concentration of the local electric field by the nanotube's geometry, distinguishes carbon nanotubes as excellent field emitters and also plays a critical role in the operation of the nanotube radio. To a good approximation, the field enhancement factor for a nanotube is $\gamma = 3.5 + h/r$, where h is the height of the tip of the nanotube above the cathode and r is the radius of the nanotube.[15] As the nanotube vibrates, the height of its tip oscillates resulting in a time-varying field enhancement factor: $\gamma(t) = \gamma_0 + \Delta\gamma(t)$.

The response of the field emission current to the vibrations is determined by substituting $\gamma_0 + \Delta\gamma(t)$ for γ in eq 2. Expanding to second order in powers of $\Delta\gamma(t)/\gamma_0$ and filtering out the zeroth and first powers of $\Delta\gamma(t)/\gamma_0$, which correspond to dc and radio frequency terms, yields

$$\Delta I(t) = I_0(1 + \alpha + \alpha^2/2)(\Delta\gamma(t)/\gamma_0)^2; \qquad \alpha = \frac{c_2}{\gamma_0 E_{\mathrm{ext}}} \tag{3}$$

which accounts for both amplification and demodulation. Amplification occurs because the output of the radio, $\Delta I(t)$, is proportional to the field emission current, I_0, which is powered by the battery voltage source. The power gain, given by the ratio of the power dissipated by the signal current through a load resistor, $P_{\mathrm{out}} = \Delta I_{\mathrm{rms}}{}^2 R_L$, to the power absorbed by the nanotube from a radio signal on resonance, $P_{\mathrm{in}} = m_{\mathrm{eff}}\omega_0{}^3|y|^2/2Q$, was typically on the order of 50 dB in these experiments, though it is easily adjustable over a wide range. Demodulation occurs because $\Delta I(t)$ is proportional to the square of the input signal $\Delta\gamma(t)$, effectively mixing the input signal with itself. In this manner, a field-emitting nanotube operates similarly to standard diode detectors.

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Supporting Information Available: High-resolution TEM video and accompanying audio of the nanotube radio in action and details of the construction of the nanotube radio. This material is available free of charge via the Internet at http://pubs.acs.org.

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