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Tunable Nanoresonator

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Abstract. We have created a tunable mechanical nanoscale resonator with potential applications in precise mass, force, position, and frequency measurement. The device consists of a specially prepared multiwalled carbon nanotube (MWNT) suspended between a metal electrode and a mobile, piezo-controlled contact. By exploiting the unique telescoping ability of MWNTs, we controllably slide an inner nanotube core from its outer nanotube casing, effectively changing its length and tuning its flexural resonance frequency.

INTRODUCTION

Due to their low mass, low force constants, and high resonance frequencies, nanoscale resonators are currently being used to weigh single bacteria, detect single spins in magnetic resonance systems, and probe quantum mechanics in macroscopic systems [1]. These resonators are typically micromachined from silicon; however, because of their low density, high Young's modulus, and atomically perfect structure, carbon nanotubes provide an alternate, nearly ideal building material. Some progress has been made in constructing nanotube-based resonators [2]. However, these resonators have a narrow frequency range and obey a complicated physical model. We propose a fundamentally different nanotube resonator, which takes advantage of one of carbon nanotubes' most interesting properties. MWNTs, which consist of multiple, concentric nanotubes precisely nested within one another, exhibit a striking telescoping property whereby an inner nanotube core may slide within the atomically smooth casing of an outer nanotube shell [3]. Already this property has been exploited to build a rotational nanomotor [4] and a nanorheostat [5]. Future nanomachines such as a gigahertz mechanical oscillator are envisioned [6]. By harnessing this versatile telescoping property in a new fashion, we have created a tunable nanoscale resonator.

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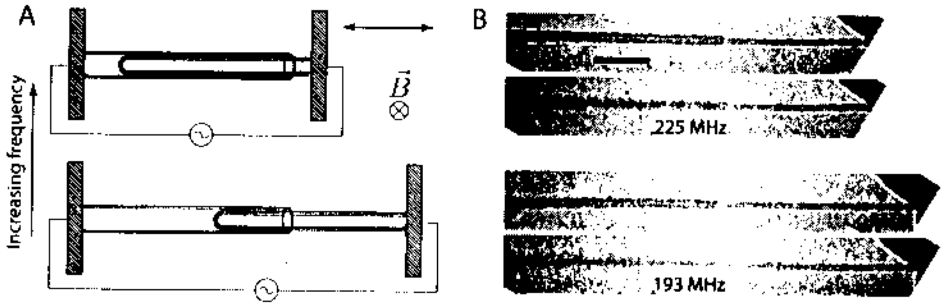

FIGURE 1. (A) Schematic of tunable nanoresonator. A specially prepared MWNT is suspended between a metal electrode and a mobile contact. Telescoping the nanotube in or out changes the effective length of the beam and tunes its resonance frequency. (B) Device in action. The top two images show the nanoresonator at one extension before resonance (sharp) and during resonance (blurred). The bottom two images show the nanoresonator with a lower resonance frequency after the inner nanotube has been telescoped out.

DEVICE OPERATION

Figure 1(A) is a schematic drawing of our tunable nanoresonator. A MWNT is suspended between a metal electrode and a mobile, piezo-controlled contact. By peeling the outer shell of the MWNT [7] and exposing the inner core, we exploit its unique telescoping ability. Like a trombone player shifting notes, we controllably slide the inner nanotube from its casing using the mobile contact, effectively changing the length of the MWNT and tuning its resonance frequency. In the top image, the resonator is fully retracted and has a relatively high resonance frequency. In the bottom image, the resonator is extended and consequently has a lower resonance frequency. By operating the device in an external magnetic field and applying alternating current through the nanotube, we can excite the mechanical vibrations of the nanotube via the Lorentz force. With a transmission electron microscope (TEM) it is possible to detect these vibrations through the physical displacement of the beam.

TEM micrographs in Fig. 1(B) show our tunable nanoresonator in action. The first two images show the nanotube beam at one extension before resonance (sharp) and during resonance at 225 MHz (blurred). The final two images show the nanotube beam after the inner nanotube has been telescoped out 50 nm. The resonance frequency has shifted downward to 193 MHz.

The resonance frequency of our tunable nanoresonator obeys the Euler-Bernoulli beam equation, which makes explicit the dependence of the resonance frequency on the total length of the tube. Specifically, the frequency f_n of the nth mode is given by

$$f_n = \frac{\beta_n^2}{8\pi}\frac{\sqrt{r_{outer}^2 + r_{inner}^2}}{L^2}\sqrt{\frac{E}{\rho}}; \qquad \beta_n \approx 4.74, 7.85, 11.00, \ldots \qquad (1)$$

where r_{outer} is the effective radius of the outer wall of the nanotube system, r_{inner} is the effective radius of the inner core of the nanotube system, L is the length of the nanotube system, E is the Young's modulus, and ρ is the density. Effective radii are used to account for the fact that the actual radii are not constant across the length of the nanotube and change during telescoping. Notably, the tension of the beam does not appear in the equation because it is held at a fixed, almost negligible value by the van der Waals attraction between the nanotubes.

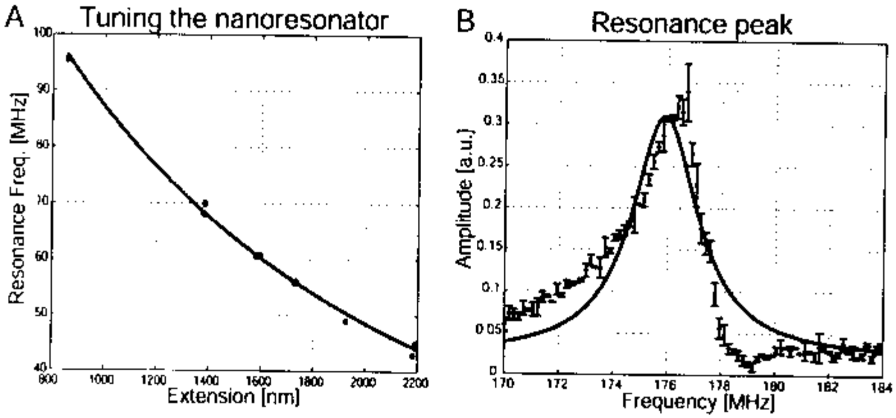

FIGURE 2. (A) Plotting frequency versus extension demonstrates the tuning process. The data follow the $1/L^2$ dependence expected from the Euler-Bernoulli equation. (B) Typical resonance peak with a Lorentzian fit.

RESULTS AND DISCUSSION

As a demonstration of our ability to tune the resonator, we plot the resonance frequency versus extension length for a typical nanoresonator in Fig. 2(A). The resonance frequency follows the predicted $1/L^2$ dependence. Moreover, from the fit we calculate the Young's modulus of a MWNT to be approximately 1.2 TPa in agreement with accepted values [8]. Also apparent in the graph is the extreme sensitivity of the resonance frequency to the extension length; 100 nm corresponds to a 5 MHz shift. Some of our other tunable resonator devices have shown sensitivities as great as 1 nm per 1 MHz shift. The extreme sensitivity of the resonance frequency to the length of the beam suggests possible application as a nanoscale positioning device or an extremely sensitive strain gauge.

Figure 2(B) shows a typical resonance peak that was observed by sweeping frequencies while maintaining the same extension. Our current detection techniques require that the resonator be driven at large amplitudes, likely in the non-linear regime. This could explain the relatively low quality factor (Q=244) and the odd shape of the resonance peak. Magnetomotive detection [9] should allow for smaller amplitudes, which may increase the quality factor.

By harnessing the almost frictionless sliding in telescoping MWNTs, we have created a fundamentally new breed of tunable nanoscale resonator. Our resonator is unique in that it is the only nanoresonator tunable via an effective length change, which suggests various nanoscale-positioning or strain measurement applications. Also because the frequency follows a $1/L^2$ dependence, our resonator has a relatively wide frequency range compared to other tunable resonators. These advantages make our tunable nanoresonator an interesting candidate for further study.

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