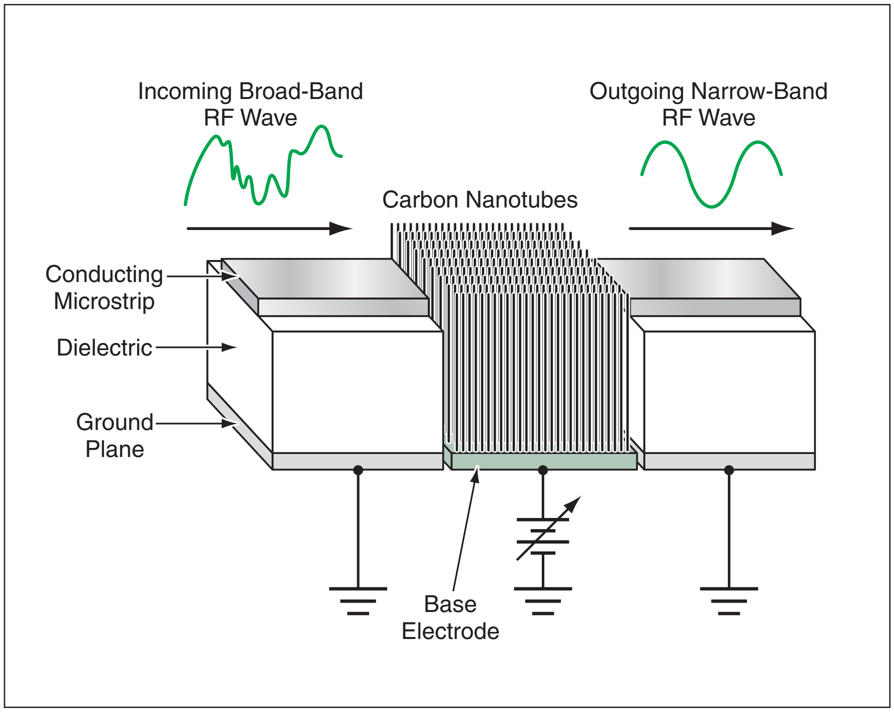

Figure 2. A **Brushlike Array of Carbon Nanotubes** embedded in a microstrip waveguide would act as a band-pass filter.

SAW devices tend to be large and are not easily integrated into electronic circuits. MEMS structures have been integrated into circuits, but efforts to extend MEMS resonant frequencies into the GHz regime have been difficult because of scaling problems with the capacitively-coupled drive and readout. In contrast, the proposed devices would be much smaller and hence could be more readily incorporated into advanced RF (more specifically, microwave) integrated circuits.

During the past few years, techniques for fabricating highly-ordered, dense arrays of nearly uniform carbon-nanotube cantilevers like so many bristles of a brush (see Figure 1) have provided the essential basis for this new device. The basic principle of operation of such an array as band-pass filter is excitation of a mechanical (acoustic) deformation of the nanotubes by an incident RF wave (Figure 2). Coupling between the RF signal and the nanotubes is provided by Coulomb forces on electric charges in the nanotubes. The device functions as a narrow-band RF filter because incident waves are reflected from the metallic nanotubes, except at the mechanical resonant frequency of the array. The high-Q mechanical resonance of the uniform nanotube array filters the incoming RF signal and couples the RF wave at the resonance frequency into the output electrode.

The resonance frequency of a nanotube cantilever depends on its diameter and length. For example, it is estimated that the resonance frequency of a carbon nanotube 10 nm in diameter and 100 nm long would be about 4 GHz. By adjusting the dimensions of the nanotubes in the array, it should be possible to select resonance frequencies that range from below 100 kHz up to tens of GHz.

There have also been attempts to make mechanical resonators using silicon cantilevers. However, the silicon devices investigated thus far have been limited to operation at frequencies below 400 MHz, whereas carbon-nanotube devices with Q values of the order of 10^3 at a frequency of 2 GHz have been demonstrated. Moreover, there are experimental data that suggest that carbon nanotube resonators should exhibit linear response over a larger dynamic range relative to silicon mechanical resonators.

This work was done by Daniel Hoppe, Brian Hunt, Michael Hoenk, and Flavio Noca of Caltech for **NASA's Jet Propulsion Laboratory** *and by Jimmy Xu of Brown University. Further information is contained in a TSP (see Page 1).*

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Carbon Nanotubes as Resonators for RF Spectrum Analyzers

Compact, high-speed, high-Q spectrum analyzers could be integrated with other circuits.

NASA's Jet Propulsion Laboratory, Pasadena, California

Electromechanical resonators of a proposed type would comprise single carbon nanotubes suspended between electrodes (see Figure 1). Depending on the nanotube length, diameter, and tension, these devices will resonate at frequencies in a range from megahertz through gigahertz. Like the carbon-nanotube resonators described in the preceding article, these devices will exhibit high quality factors (Q values), will be compatible with integration with electronic circuits, and, unlike similar devices made from silicone and silicone carbide, will have tunable resonant frequencies as high as several GHz.

An efficient electromechanical transduction method for the carbon nanotube resonators is provided by the previously observed variation of carbon nanotube length with charge injection. It was found that injection of electrons or holes, respectively, lengthens or shortens carbon nanotubes, by amounts of the order of a percent at bias levels of a few volts. The charge-dependent length change also enables a simple and direct means of tuning the resonant frequency by varying the DC bias and hence the tension along the tube, much like tuning a guitar string.

In its basic form, the invention is a tunable high-Q resonator based on a suspended carbon nanotube bridge with attached electrodes (see Figure 1). An applied DC bias controls the tension and thus the frequency of resonance. If one were to superimpose a radio-frequency (RF) bias on the DC bias, then the resulting rapid variation in tension or length would set the tube into vibration. If, on the other hand, the carbon nanotube were to be set into vibration by interaction between an incident RF electric field and electric charges in the nanotube, then the vibration would give rise to an RF signal output that is proportional to the RF amplitude at the resonance frequency.

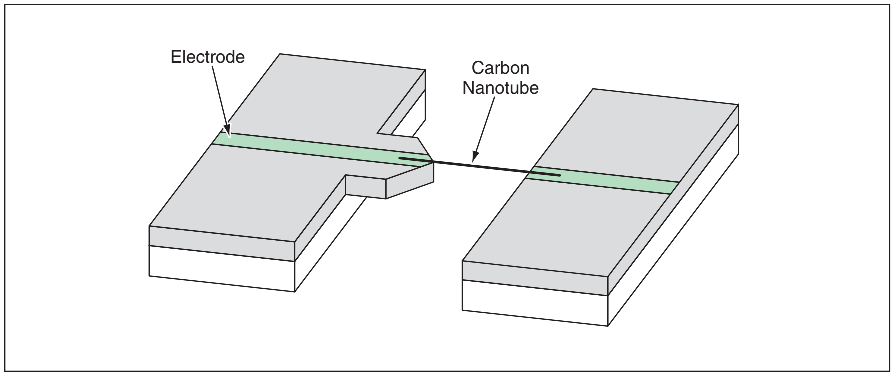

Figure 1. A **Carbon Nanotube Suspended Between Electrodes** could be stretched taut so that it would resonate in the same manner as that of a string on a musical instrument. It could serve as a tunable, high-Q resonator for a signal processor or a sensor.

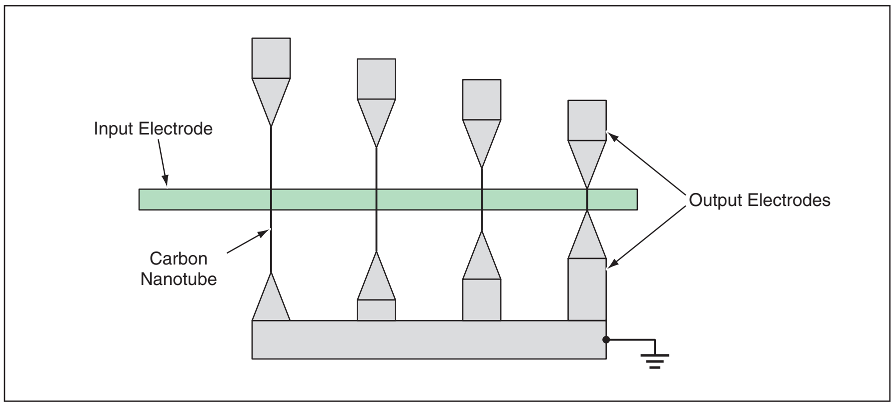

Figure 2. An **Array of Devices** like that of Figure 1, containing nanotubes of different lengths would be combined with an input electrode to construct an electromagnetic-spectrum analyzer that would function somewhat like a cochlea.

Because the transduction mechanism is extremely sensitive and the active volume is only a few nanometers in diameter, this device is not well suited for use as a microwave power device. Instead, this carbon nanotube mechanical resonator would be useful primarily as part of a highly precise, sensitive, frequency-selective detector. An array of such devices featuring nanotubes of different lengths (and thus different frequencies) could be made to operate as a high-speed spectrum analyzer (see Figure 2).

This work was done by Brian Hunt, Flavio Noca, and Michael Hoenk of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1).*

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