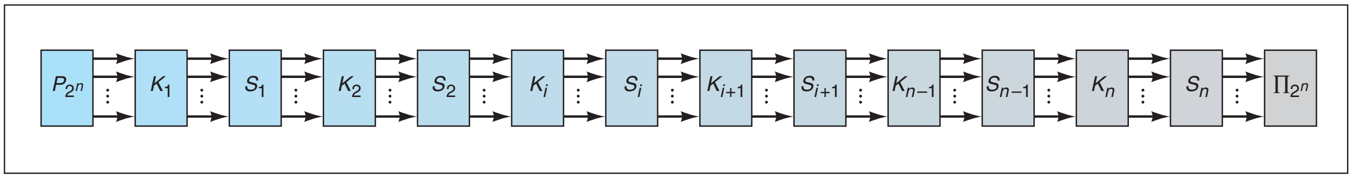

Figure 2. A **Hybrid of VLSI and QCA Circuit Modules** would perform a parallel, systolic computation of an FFT. The particular circuit architecture is based on a matrix factorization of the FFT.

and binary wires could be constructed, in principle, by arraying QCA of suitable design in suitable patterns.

Again, for reasons too complex to describe here, in order to ensure accuracy and timeliness of the output of a QCA array, it is necessary to resort to an adiabatic switching scheme in which the QCA array is divided into subarrays, each controlled by a different phase of a multiphase clock signal. In this scheme, each subarray is given time to perform its computation, then its state is frozen by raising its interdot potential barriers and its output is fed as the input to the successor subarray. The successor subarray is kept in an unpolarized state so it does not influence the calculation of preceding subarray. Such a clocking scheme is consistent with pipeline computation in the sense that each different subarray can perform a different part of an overall computation. In other words, QCA arrays are inherently suitable for pipeline and, moreover, systolic computations. This sequential or pipeline aspect of QCA would be utilized in the proposed FFT-processor architecture.

Heretofore, the main obstacle to designing VLSI circuits for systolic and highly parallel computation of FFTs (and of other fast transforms commonly used in the processing of images and signals) has been the need for complex data permutations that cannot be implemented without crossing of signal paths. The proposed hybrid VLSI/QCA FFT-processor architecture would exploit the coplanar-signal-path-crossing capability of QCA to implement the various permutations directly in patterns of binary wires (that is, linear arrays of quantum dots), as in the example of Figure 1. The proposed architecture is based on a reformulation of the FFT by use of a particular matrix factorization that is suitable for systolic implementation. The reformulated FFT is given by

$$F_{2^n} = \Pi_{2^n} S_n K_n S_{n-1} K_{n-1} \ldots S_{i+1} K_{i+1} S_i K_i \ldots S_2 K_2 S_1 K_1 P_{2^n} ,$$

where n is an integer; F_{2^n} is a radix-2 FFT for a 2^n-dimensional vector; Π_{2^n}, S_i (where i is an integer), and P_{2^n} are various permutation operators or matrices; and the K_i are arithmetic operators.

Figure 2 depicts the proposed architecture. The permutation operators would be implemented by QCA modules, while the arithmetic operators K_i would be implemented by VLSI modules containing simple bit-serial processing elements. Each processing element would receive input data from two sources and would produce two outputs by performing simple multiplication and addition operations. Aside from being driven by the same clock (in order to obtain the necessary global synchronization), the processing elements would operate independently of each other; because of this feature, the processing modules would be amenable to large-scale implementation in complementary metal oxide/semiconductor (CMOS) VLSI circuitry. To obtain the necessary global synchronization, the VLSI and the QCA modules would be driven by the same clock.

This work was done by Amir Fijany, Nikzad Toomarian, Katayoon Modarres, and Matthew Spotnitz of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1). NPO-20923*

Arrays of Carbon Nanotubes as RF Filters in Waveguides

Advantages would include compactness and high Q.

NASA's Jet Propulsion Laboratory, Pasadena, California

Brushlike arrays of carbon nanotubes embedded in microstrip waveguides provide highly efficient (high-Q) mechanical resonators that will enable ultraminiature radio-frequency (RF) integrated circuits. In its basic form, this invention is an RF filter based on a carbon nanotube array embedded in a microstrip (or coplanar) waveguide, as shown in Figure 1. In addition, arrays of these nanotube-based RF filters can be used as an RF filter bank.

Applications of this new nanotube array device include a variety of communications and signal-processing technologies. High-Q resonators are essential for stable, low-noise communications, and radar applications. Mechanical oscillators can exhibit orders of magnitude higher Qs than electronic resonant circuits, which are limited by resistive losses. This has motivated the development of a variety of mechanical resonators, including bulk acoustic wave (BAW) resonators, surface acoustic wave (SAW) resonators, and Si and SiC micromachined resonators (known as "microelectromechanical systems" or MEMS). There is also a strong push to extend the resonant frequencies of these oscillators into the GHz regime of state-of-the-art electronics. Unfortunately, the BAW and

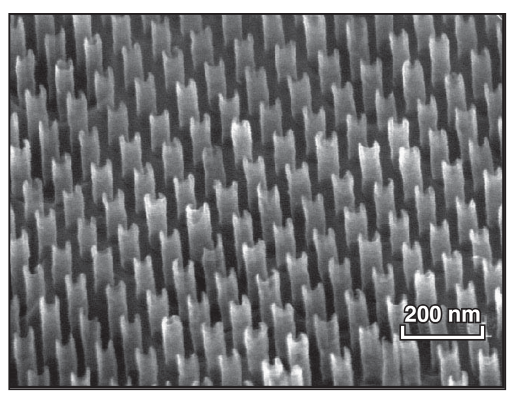

Figure 1. This **Array of Carbon Nanotubes**, with a diameter nonuniformity of <5 percent, was fabricated in a process that included the use of a nanopore template (J. Xu et al.).

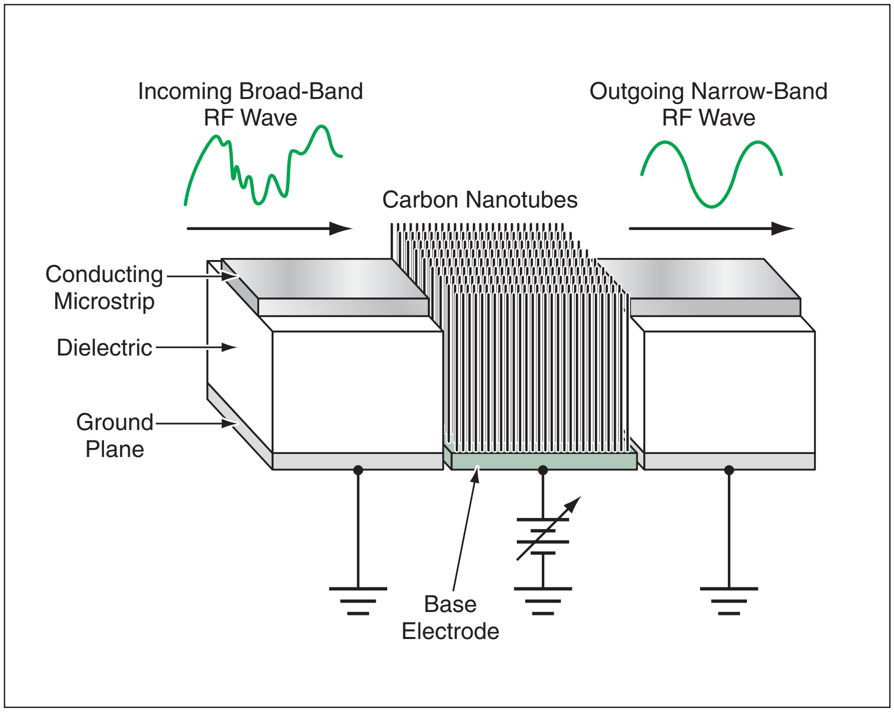

Figure 2. A **Brushlike Array of Carbon Nanotubes** embedded in a microstrip waveguide would act as a band-pass filter.

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 tun-