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Electrical thermo-optic tuning of ultrahigh-*Q* microtoroid resonators

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The ability to tune resonant frequency in optical microcavities is an essential feature for many applications. Integration of electrical-based tuning as part of the fabrication process has been a key advantage of planar microresonant devices. Until recently, the combination of these features has not been available in devices that operate in the ultrahigh-*Q* regime where device quality factors (Q) can exceed 100 million. In this letter, we demonstrate an electrically tunable resonator on a chip with ultrahigh-quality factors. Futhermore, the devices have demonstrated tuning rates in excess of 85 GHz/V^2 and are capable of tuning more than 300 GHz. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1825069]

Ultrahigh-*Q* (UHQ) optical microresonators represent a distinct class of microcavities[1] with applications ranging from optical communications and biosensing[2] to fundamental studies of nonlinear optical effects[3] and cavity quantum electrodynamics (CQED).[4] Although wafer-scale tuning control has been available for devices operating in the *Q* regime below 100,000, such methods have not been available in the UHQ regime, where *Q* can exceed 100 million. Nonetheless, there remains keen interest in finding more practical ways to implement tuning control in this regime.[5,6] In this letter, we introduce electrical control of resonant frequency in an UHQ microtoroid by themooptic tuning. The significance of this result is that this represents an example of a UHQ microresonator with "integrated" electrical tuning. By including only two additional processing steps (lithography and metallization) into the prior fabrication process for the UHQ microtoroids, electrical control is implemented. The end result is a highly reproducible process through which chip-based electrically tunable microtoroids with *Q* factors in excess of 100 million are fabricated. Furthermore, since the devices themselves are produced on a silicon substrate and significant tuning range at subvolt levels is demonstrated, the integration of complementary metal–oxide–semiconductor control circuitry with the devices is also possible. In addition to characterizing the static tuning characteristics of these devices, we also investigate their dynamic response including the use of a helium ambient atmosphere to isolate the specific source of the tuning time constant.

The fabrication process with the exception of metallization steps is described in detail elsewhere.[7] Briefly, it proceeds as follows (see Fig. 1). First, photolithography is performed on a highly *p*-doped $(.001-.006\ \Omega\ \mathrm{cm})$ silicon wafer with a 2 μm thick thermal oxide. The unexposed photoresist is used as an etch mask during immersion in buffered HF. These two steps define oxide disks of 100 μm diameter with a 25 μm wide contact hole concentrically located on the disk. All oxide on the back side of the wafer is also removed. A second photolithography step is performed in order to define a metal lift-off mask. 1000 Å of aluminum are thermally evaporated on both sides of the wafer in sequential deposition steps. The wafer is then immersed in acetone overnight releasing the excess aluminum and leaving aluminum contacts in the center of the oxide disks as well as the backside of the wafer. Ohmic contacts are formed by annealing the wafer in a tube furnace at 500 °C in a nitrogen ambient. The remaining oxide disks act as etch masks during exposure to xenon difluoride (XeF_2) gas at 3 torr. Xenon difluoride isotropically etches the silicon substrate leaving the perimeter of the silica disk isolated from the higher index silicon. To eliminate lithographic blemishes along the perimeter of the oxide, each microdisk is orthogonally exposed to a CO_2 laser beam resulting in surface tension induced reflow and formation of the microtoroid.[7] During this process, the central region of the pillar is unaffected and therefore the aluminum contact remains pristine. The resulting device possesses a surface finish with near atomic roughness in addition to integrated metal contacts [Fig. 1(d)].

The tuning range and frequency response of the tunable microtroid resonators were measured in the optical telecommunication band (1550 nm). To create a low resistivity electrical path, the substrate (now containing an array of microtoroids on one side) was placed on a metal, electrically

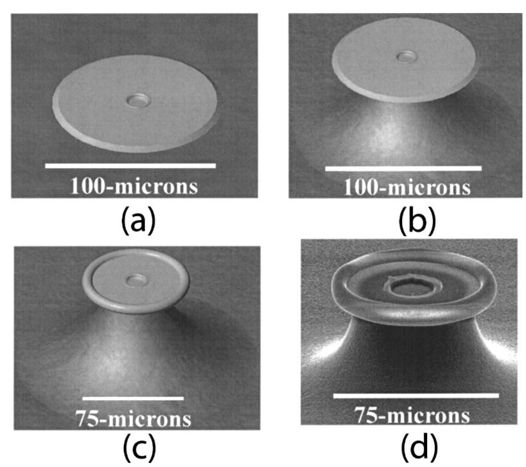

FIG. 1. Fabrication process flow outline for the tunable microtoroid resonators. (a) Oxide is lithographically defined and etched leaving oxide disks followed by metallization via evaporation on both sides of the wafer in order to create the electrical contacts. Ohmic contacts are formed by annealing in a nitrogen ambient at 500 °C in a tube furnace. (b) The wafer is isotropically etched using xenon difluoride. (c) The oxide disks are exposed to a CO_2 laser in order to reflow the disks, creating the tunable UHQ microtoroids. (d) A scanning electron micrograph of a tunable microtoroid resonator.

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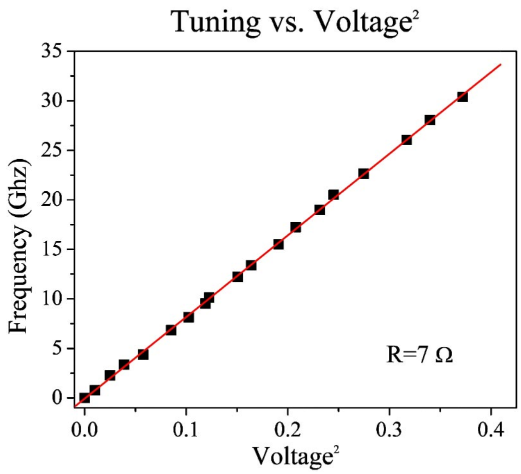

FIG. 2. (Color online) Resonant frequency shift versus voltage (see Ref. 2). The quadratic coefficient is 85.56 GHz/V^2.

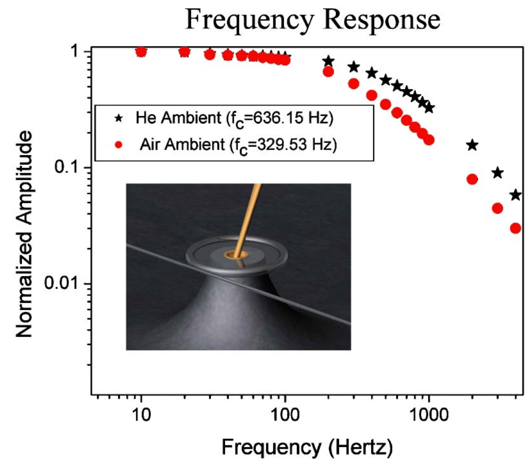

FIG. 3. (Color online) The frequency response of the tunable microtoroid resonators in both air and helium ambient atmospheres. Inset: A rendered depiction of the tunable microtoroid device coupled to a tapered optical fiber while being contacted by a metal probe.

grounded platform mounted to a three-axis stage with a 100 nm step resolution. The stage allowed the substrate to move freely so that the taper waveguide could couple to a single microtoroid. Two microscopes were used to simultaneously image the microtoroid from both the top and side. Optical power was coupled to the microtoroid using a tapered fiber waveguide.[8] The tapered fiber was formed by stretching a standard optical fiber (SMF-125) while heating it with a hydrogen flame. As the adiabatic condition is maintained during the stretching process, the resulting tapered fiber exhibits losses typically less than 5%. Further details regarding tapered fiber fabrication and properties are provided elsewhere.[9,10] It should be noted that during characterization of both tuning range and frequency response the microtoroid and fiber taper waveguide were in contact to prevent any thermally induced loading variations.

With the taper and microtoroid in contact, the aluminum pad in the center of the microtoroid is electrically contacted and voltage is applied while the silicon substrate is grounded. Typical electrical resistance of the devices were consistently less than 10 Ω. The induced ohmic heating and rise in temperature that occurred in the silicon pillar was thermally conducted to the silica microtoroid, subsequently increasing the temperature of the silica in the path of the optical whispering gallery mode. This temperature increase resulted in a frequency shift of the resonant frequencies.

The tuning rate and tuning range were determined by scanning a single-frequency external-cavity laser (coupled to the tapered fiber waveguide) across a frequency span of approximately 50 GHz and in the spectral vicinity of a high-Q resonance. Transmission power through the taper was monitored on an oscilloscope during scanning to measure tuning. With the laser continuously scanning, voltage was incrementally applied to the microtoroid resonator. Figure 2 shows an example of a typical tuning curve for a microtoroid resonator with a resistance of 7 Ω and tuning rate of 85 GHz/V^2. The tuning is plotted against V^2 in order to stress the dependence of tuning on applied electrical power (V^2/R).

The frequency response characteristics were measured by first tuning the laser near a resonance, and simultaneously a function generator was used to apply a small-signal sinusoidal modulation voltage. A lock-in analyzer was set up to detect the modulation induced in the optical power transmission and was referenced to the modulation frequency of the function generator. The frequency response of the tunable microtoroid resonators in both air and helium was measured and is plotted in Fig. 3. The measured frequency response contains features consistent with the existence of a single low-frequency pole.

There are several possible cooling mechanisms which could account for this single low-frequency pole. The authors postulate that the primary cooling mechanism is thermal conduction to the ambient. Therefore, this cooling mechanism should exhibit a dependence on the coefficient of thermal conduction of ambient atmosphere around the resonator. To confirm this hypothesis, the frequency response was measured while helium gas was introduced into the testing chamber. As can be seen in Fig. 3, the corner frequency doubled in the presence of helium, a result of helium being five times more thermally conductive than air.

In summary, we have demonstrated the ability to electrically tune UHQ microresonators on a chip. Furthermore, tuning ranges as large as 300 GHz have been observed. The corner frequency of the tuning process was measured to be 330 Hz in air and is attributed to thermal dissipation to the ambient. Moreover, an understanding of the cooling processes associated with the corner frequency was demonstrated by introducing helium into the air ambient and observing the resulting increase in corner frequency. While not suitable for high-speed applications, such a device has several important applications. The ability to tune nearly one full free spectral range makes the tunable microtoroids ideal for use as an tunable optical filter or as a tunable laser source[11–15] based on the UHQ properties. Tuning is also an essential feature in application of UHQ devices to CQED.[4] Additionally, the ability to detect small changes in its ambient surroundings can lead to applications in both biosensing and gas detection. Finally, tunable microtoroid resonators would be well suited for the realization of CROW devices.[15]

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