Approaching the quantum world with nanospokes

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A chip-scale optomechanical system with extremely low dissipation might enable the observation of quantum behavior in tangible objects visible to the naked eye.

At the beginning of the last century Heisenberg formulated the theory of quantum mechanics. It dictates that mechanical motion—from that of electrons around nuclei to the macroscopic behavior of everyday objects—is quantized. It was only in 1986, more than 60 years after Heisenberg’s initial work, that scientists could directly observe quantum jumps of individual electrons.1

Ten years later, advances in laser techniques and optics enabled the observation of nonclassical motional states of trapped ions,2 which can be 100,000 times heavier than electrons. Yet a fundamental question has remained: Why do larger objects behave classically, rather than following the rules that govern the smallest particles?

So far, experiments have failed to answer this question. Quantum mechanical effects have never been observed in tangible, mesoscopic mechanical oscillators. On the one hand, decoherence—the interaction with the thermal environment—disturbs and eventually destroys the quantum behavior of individual systems. These well-isolated systems would be expected to behave according to the laws of quantum mechanics. On the other hand, measurement sensitivity must be high enough to observe the expected, but tiny, features of quantum effects. Many research groups around the world are presently striving for systems3–5 with both mechanical coherence and high sensitivity.

Quartz oscillators, like those routinely used in wristwatches, exhibit extremely high mechanical quality and would thus satisfy the former criterion. The electrical circuits used to read their mechanical motion, however, are not sensitive enough to detect quantum effects. Therefore, many research groups are combining much more sensitive quantum optical methods6,7 with highly coherent mechanical systems.5 Our work8 combines state-of-the-art optical9 and mechanical coherence properties10 in a single on-chip resonator.

We employed the whispering gallery modes (located around the circumference of a spherical body) of toroidal silica microresonators (see Figure 1). Using this approach, the optical finesse, or the number of roundtrips of an intracavity photon before it decays, exceeded 1 million.9 Laser light was coupled into the toroids via silica nanofibers. A small mode volume and high finesse led to a strong interaction between the toroids’ optical and mechanical degrees of freedom. Thus, mechanical oscillations due to Brownian motion modulate their circumference and imprint themselves on the optical resonance frequencies. On the other hand, the circulating photons exert a radiation pressure force on the toroid pointing radially outwards. Using this mutual coupling, the mechanical oscillations can be monitored optically with a precision on the order of $10^{-19}\text{m/Hz}^{1/2}$.7

Figure 1. (a) Mechanical quality (Q) factors and frequencies (solid lines denote results of a finite element method simulation) of the fundamental mode (inset) for varying relative undercut. Q factors were strongly geometry-dependent due to intermode coupling. (b) Q factors and frequencies of different modes show an avoided crossing, revealing the coupling of the structure’s distinct mechanical modes. L: Length of the free-standing membrane. R: Radius of the cavity.

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To control the mechanical decoherence, it is essential to understand the friction forces that cause the coupling of the mechanical eigenmodes to the thermal bath. The first direct observation of normal mode coupling in a micromechanical system, shown in Figure 1(b), was the key step to understanding the mechanical losses in microtoroids, which were strongly geometry-dependent (see Figure 2). It allowed us to elucidate the coupling of the toroid’s radial breathing mode (RBM), which exhibits the strongest optomechanical interaction, to the thermal bath via flexural modes. This behavior is well described by a coupled harmonic oscillator model, as shown in Figure 1(b). Moreover, it led to a finite element model\(^8\) that gives accurate predictions of the clamping losses for different geometries. This model is a powerful design tool for devising optimized mechanical structures.

By mounting the toroid on the silicon chip with glass nanospokes—see Figure 2(a)—the mechanical Q could be increased substantially. By optimizing the length and width of the spokes, we could tailor the eigenmodes to maximize the impedance mismatch between the RBM of the toroid and the spokes modes. This step produced up to a 1000-fold reduction in clamping losses.\(^5\) For frequencies beyond 30MHz, we achieved quality factors of 80,000 (limited only by material specific losses caused by two-level fluctuators\(^9\)), while preserving the ultrahigh optical finesse of the resonators (see Figure 2).

For the first time, we controlled optical and mechanical degrees of freedom within a single chip-scale device, achieving a combination of mechanical quality factors rivaling those of nano- and microelectronics.\(^10\) This system is similar to quartz oscillators that can be driven by light (instead of electrical current) and read with extremely high precision by a resonant optical circuit. The work is a major step toward observing quantum mechanical effects in macroscopic oscillators. Understanding dissipation is also at the heart of improvements in the timekeeping stability of quartz oscillators, whether in a wristwatch or an atomic clock flywheel. As a next step, we plan cryogenic experiments to decrease the phonon occupation numbers of the structure to approach its quantum mechanical zero point motion.

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