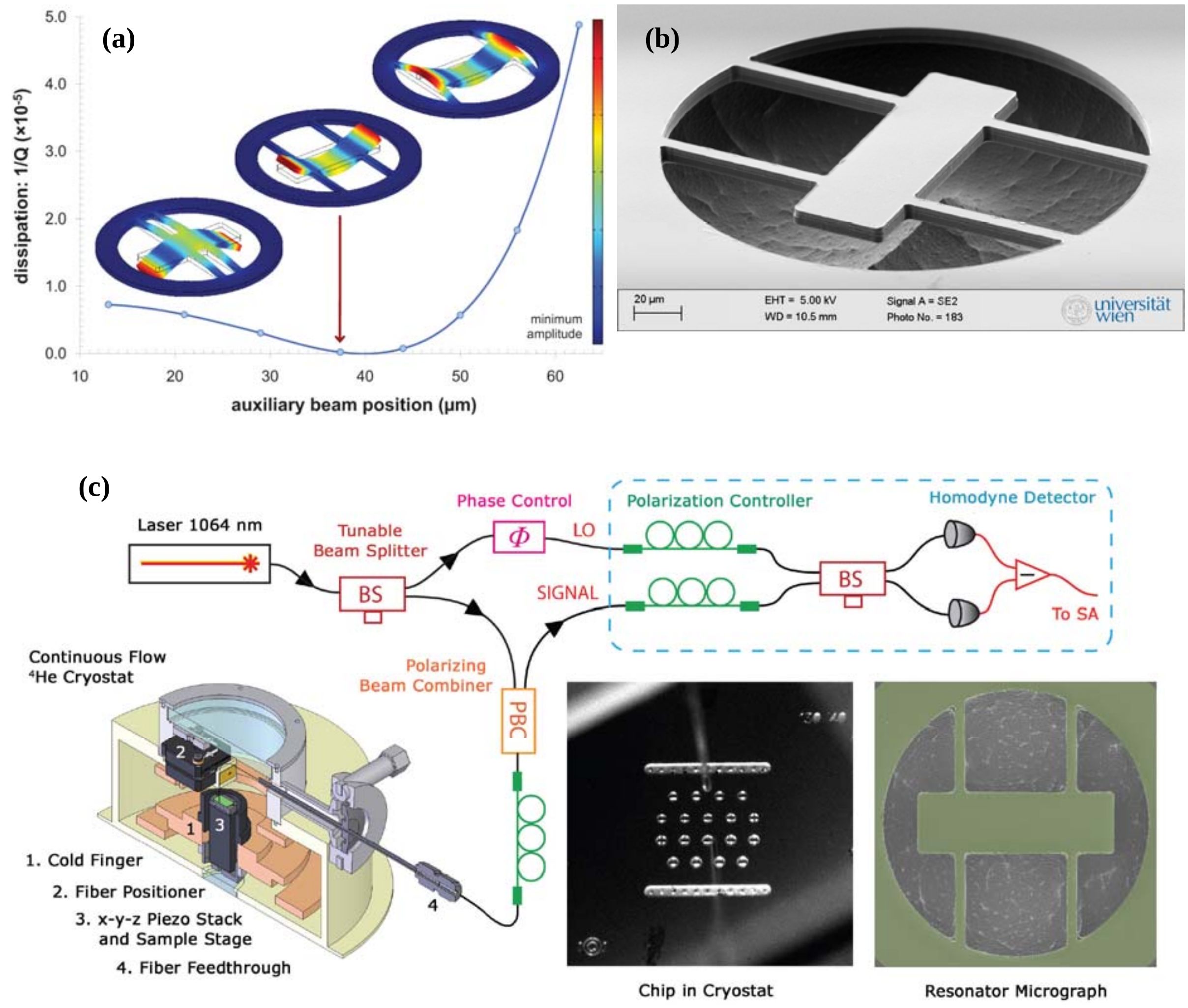
Marie Curie IIF-Project “Integrated Quantum Optomechanical Systems” (IQOS)

Publishable Summary

The objectives of the Marie Curie IIF-Project “Integrated Quantum Optomechanical Systems” (IQOS) were to bridge the gap between the engineering expertise necessary to design and fabricate high performance optomechanical systems and the fundamental scientific knowledge required to explore the quantum physical aspects of these devices, as well as to bring Dr. Cole’s expertise and know-how in this field together with IQOQI’s (now University of Vienna’s) expertise in the field of cavity quantum optomechanics and combine these two approaches into novel design architectures for experimental quantum optomechanics. The EC-funded research effort IQOS has been highly successful in achieving these objectives. It has been instrumental in advancing this nascent field by enabling a number of developments in the design of low-loss mechanical resonators coupled to high-finesse cryogenic optical cavities. Working towards the goal of macroscopic quantum state preparation—one of the ultimate aims of this field of research—the discoveries enabled by IQOS have additionally led to a number of technologically relevant spin-off applications including the development of a numerical solver for support-mediated losses in mechanical resonators [1] as well as new strategies for the development of low-noise multilayer mirrors with application in high performance interferometry and high stability optical reference cavities [2]. IQOS has generated a significant impact in the field of cavity optomechanics, which has recently been highlighted by *Nature*, *Science*, and the American Physical Society (APS) as one of the hottest areas of experimental physics [Nature Milestones Photons, May 2010; Science Magazine, 328 (5980): 812-813, May 2010; APS March Meeting, Trend Session, talk “Optomechanical devices].

Experiments in cavity quantum optomechanics rely crucially on the development of high reflectivity and low loss resonators; currently mechanical damping in these structures is the major hurdle for entering the quantum regime with such “macroscopic” systems. In this area IQOS has brought forth significant progress. As outlined above and shown pictorially in the figure below, in the course of this effort we have performed an in-depth study of the design-limited mechanical quality factor, Q, comprising both theoretical and experimental efforts aimed at realizing, for the first time, numerical predictions of support-induced damping, a key loss mechanism in high-quality-factor micro- and nanomechanical resonators [1]. Such studies are vitally important not only for advancing optomechanics experiments, but also for pushing the limits of general micro- and nanomechanical resonators, which have emerged as ubiquitous devices for use in advanced technological applications spanning wireless communications to advanced physical sensors. In order to calculate the design limited Q we have developed an efficient FEM-enabled numerical solver, which employs the recently introduced “phonon-tunneling” approach [13]. This solver represents a substantial simplification over previous methods, allowing for the investigation of complex geometries, as well as taking into account interference effects between the radiated waves. To experimentally verify the results generated from the solver, we characterize sets of custom fabricated resonators constructed via a novel gas-phase etching technique [14]. The results from these devices show excellent agreement with theoretical predictions; thus, in combination with existing models for other damping channels, our phonon-tunneling solver makes further strides towards *a priori* prediction of Q in micro- and nanoscale mechanical resonators, enabling computational design of high performance sensors, filters, etc. without the need for prototype development.

During the course of IQOS we have continued to pursue the development of state-of-the-art monocrystalline resonators in order to further reduce the mechanical damping in our devices. These structures are etched directly from a single-crystal multilayer reflector composed of alternating stacks of ternary $Al_xGa_{1-x}As$ alloys with varying aluminum content, grown via epitaxial deposition methods. Resonators fabricated from this material system utilized an identical geometry to early dielectric devices fabricated by our group in Vienna (employing simple singly- and doubly-clamped beams) and exhibited nearly an order of magnitude improvement in the mechanical dissipation as compared with Ta_2O_5-based devices of identical geometry, reaching Q-values greater than 2×10^4 at eigenfrequencies up to 2 MHz at 4 K [10]. Further investigation indicated that the mechanical loss was ultimately limited by support-induced losses for the geometries studied. Moving to a novel free-free resonator design (with the selection of the ideal layout enabled by the Q-solver described above) has led to the demonstration of cryogenic quality factors approaching 10^5 (9.5×10^4 at 2.4 MHz) [11]. The simultaneous achievement of high reflectivity and low mechanical loss in these crystalline mirrors makes this materials system promising not only for our immediate optomechanics experiments, but moreover for application in high-performance interferometry and optical reference cavities, where coating thermal noise (driven by the mechanical dissipation in the mirror material) currently represents a significant roadblock to the overall cavity stability [12]. Recently, our results on low-loss monocrystalline mirrors have captured the interest of the gravitational wave community (particularly LIGO/VIRGO) as an intriguing alternative for enhancing the ultimate sensitivity of these systems. In this light, IQOS has more than achieved its original stated goals.



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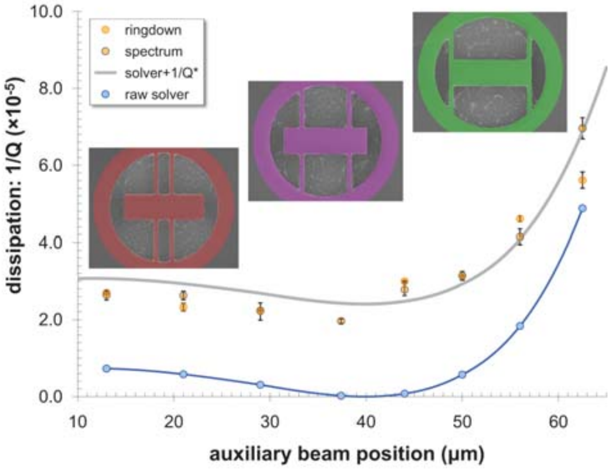

Development of low-loss optomechanical resonators. (**a**) Simulated dissipation as a function of geometry for a set of 8 free-free resonators. The FEM-calculated mode shapes correspond to the three extreme examples of the resonator design. (**b**) Scanning electron micrograph of a completed crystalline resonator. (**c**) Schematic of our custom-built optical fiber interferometer, which allows for temperature dependent *Q* measurements from 300 K to 20 K (sample chip is placed in a continuous flow ^{4}He cryostat), and from atmospheric pressure to vacuum levels of 2.5×10^{-7} millibar. (**d**) Comparison of experimental measurements performed at 20 K, with theoretical dissipation values for a set of crystalline resonators. The inset includes SEM images of the three extreme designs as shown in the FEM model in panel (**a**).

References (IQOS relevant publications are underlined)

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