1 Publishable summary

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Project acronym: ıQUOEMS

Project title: Interfacing Quantum Optical, Electrical, and Mechanical Systems

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	Project Summary
iquoems interfacing quantum optical electrical mechanical systems	*Period: 10/2013 –09/2014* http://d7.unicam.it/iquoems/

Project objectives and the Consortium

The project objective is the development of interfaces for the coherent conversion of radio and microwave frequencies to the optical domain, utilizing different novel approaches. The project is targeted to achieve such a fundamental step for the development of mature quantum technologies by experimentally realizing various examples of interfaces able to interconvert with high fidelity microwave/rf and optical photons, and enabling their manipulation at the level of few quanta. Such interfaces will be essentially based on micro- and nano-mechanical resonators owing to their ability to interact in a tunable way either electrically, magnetically and optically. The project has the following more specific objectives: *1) realization of a coherent microwave-to-optical link, based on a cavity-electro-optical setup; 2) implementation of coherent interconversion between microwave/optical photons and MHz/GHz phonons; 3) implementation of a nanomechanical interface for microwave-optical interconversion*.

The project is carried out by a consortium formed by six University research groups, combining in a complementary way all the necessary expertise for such an interdisciplinary and challenging goal: i) the laboratory of Photonics and Quantum Measurement led by Tobias Kippenberg at EPFL (Ecole Polytechnique Federale de Lausanne); ii) the group of Quantum Foundations and Quantum Information on the nano- and micro-scale of Markus Aspelmeyer at the University of Vienna (UNIVIE) ; iii) the Ultra-Cold Atoms and Quantum Optics group led by Eugene Polzik at the Niels Bohr Institute in Copenhagen (UCPH); iv) the Theoretical Quantum Optics Group led by Klemens Hammerer at the Leibniz University in Hannover (LUH); v) the Nano group of the Low Temperature Laboratory led by Pertti Hakonen at Aalto University in Helsinki (AALTO); vi) The Quantum Optics and Quantum Information group led by David Vitali at the University of Camerino (UNICAM).

The members of the Consortium possess a well established knowledge of the most relevant and promising experimental platforms for the exploitation of opto- and electro-mechanical devices as flexible interfaces for quantum and classical information processing. EPFL has already fabricated and operated at an exceptional control level various optomechanical devices, such as silica toroidal microcavities, silicon nitride nanowires, photonic crystal membranes, crystalline nanoresonators. Coherent excitation transfer between mechanical and optical degrees of freedom, and tunable slowing and advancing of light have been demonstrated with these platforms. UNIVIE has developed and demonstrated several quantum optomechanical techniques including cavity-based radiation-pressure cooling of a micromechanical system (also at cryogenic temperatures), the strong coupling regime between an optical cavity field and a micromechanical oscillator, or, in collaboration with the group of Oskar Painter (Caltech), laser-cooling a nano-optomechanical resonator into its quantum ground state of motion. UNIVIE has also pioneered the fabrication of novel micro-optomechanical systems, in particular epitaxially grown free-standing micromechanical Bragg mirrors. AALTO has shown top-level skills in the nanofabrication and operation of cryogenic electromechanical systems, providing the first demonstrations of parametric optomechanical microwave amplifier and of circuit electromechanics. UCPH provided the first demonstration of quantum teleportation, of quantum information storage and interfacing with atomic ensembles, and it is now exporting these unique skills in the development of opto-electro-mechanical interfaces based on nanomembranes. These unique laboratory skills are perfectly complemented by the theoretical expertise of UNICAM and LUH groups, which have authored many relevant proposals in the field of cavity quantum optomechanics. UNICAM in particular has pioneered the use of optomechanical system for quantum information processing, while LUH coordinator has a well established experience in quantum interfaces and memories.

First year results

In its first year, the project has achieved all its relevant milestones, and we underline here the following results:

1) **the experimental demonstration of optical detection of radio waves through a nanomechanical transducer** by the UCPH node, which has been published in Nature [1]. The radio-frequency signals are detected as an optical phase shift with quantum-limited sensitivity. This performance competes with current state-of-the-art operational amplifiers at room temperature and it can be improved with further advances. The device will be of interest in sensing applications (NMR, radio astronomy etc.) where it is coupled to a cold signal input and the Johnson noise is strongly suppressed. Compared to existing detectors, this approach has the advantage of working at room temperature, and the signals produced can be readily transferred into standard optical fibres.
2) **the first experimental demonstration of a graphene-based electromechanical resonator,** in which a graphene flake is capacitively coupled to a microwave cavity. Such a coupling has been used for sideband cooling the mechanical motion down to n = 40 thermal quanta, which is the lower phonon occupation recorded to date with graphene resonators [2].
3) **a proposal for quantum-limited amplification and parametric instability in the reversed dissipation regime of cavity optomechanics** [3], in which a damped mechanical oscillator can be used to cool or amplify a microwave cavity; such a study opens a practical way to achieve a quantum-limited optomechanical amplifier with a large gain-bandwidth product complementing phase-sensitive amplifiers based on superconducting Josephson junctions.

In its first year the consortium has achieved further relevant milestones, which represent as well results at the forefront of the research activity for the realization of reliable and robust interfaces able to convert and redistribute information, both at the classical and quantum level. We recall here i) the realization of a **crystalline $LiNbO_3$ resonator coupled to a macroscopic LC resonator**; ii) the development of novel wideband Josephson microwave amplifiers; iii) the design and fabrication of **novel InGaP nanomembranes**, which are particularly suited for the integration in opto-electro-mechanical systems, and which have shown very high mechanical quality factors [4]; iv) the operation of electromechanical system in the nonlinear Duffing regime [5]; v) operation of silicon optomechanical crystal resonators at millikelvin temperatures [6]. On the theory side the consortium is studying new schemes for the exploitation of nanomechanical transducers within quantum networks in which the upconversion to optical field in fibers is then used to redistribute information and robustly entangle superconducting qubits or microwave fields at distant sites [7].

Expected impact

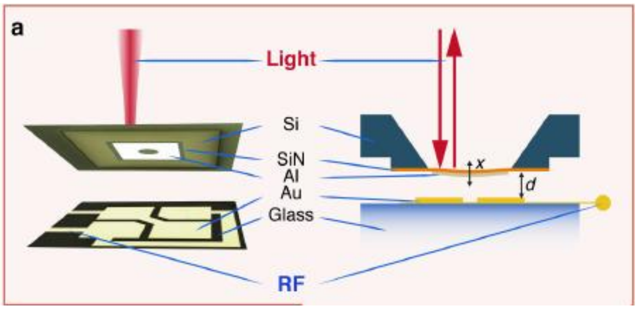
By the end of the project, we expect to build and test significant examples of nanomechanically-based microwave-optical interfaces operating at the quantum level. The project results may have a profound impact on the methods currently used for information processing. In fact, in the last decade, the transformation of light into electrical signals and/or microwave signals has significantly improved; nonetheless these techniques cannot be straightforwardly scaled down to the quantum domain. In fact, quantum communication requires a coherent storage interface, a truly quantum interface. We expect to reach the regime where the coherent transfer between photons and phonons can be realized opening interesting perspectives for the development of quantum opto-electro-phononics.

A further important consequence of the success of our project is related to the possibility to detect microwave and radiofrequency signals with the same high efficiency and comparable speed currently attainable only with optical signals. Moreover, nanomechanical resonators could be operated in the nonlinear Duffing regime and used as mixers or in circuits for amplifying purposes; one could get revolutionary achievements if they could be operated up to the largely unexplored THz regime for the realization of terahertz spectrum analyzers operating at room temperature, highly sensitive detectors for molecules, stand-off security imaging, and medical diagnostics.

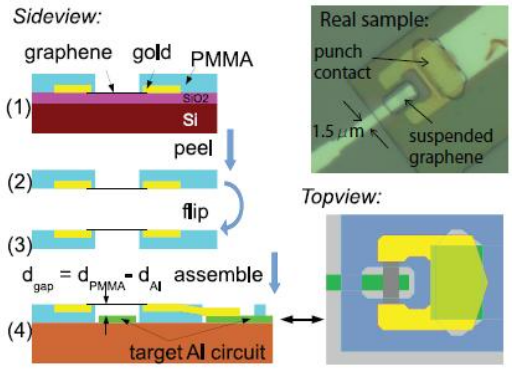
A prerequisite for the realization of efficient nanomechanical interfaces is the ability to build and operate nanomechanical resonators with mechanical quality factors above one million and at the same time very good optical or electrical properties. These devices could be useful in other technological areas: for example, the possibility to integrate mechanical elements with considerably long relaxation times within optoelectronic solid-state devices will provide unique opportunities for the realization and integration of classical and quantum memories with extremely long lifetimes.

[1] T. Bagci et al., "Optical detection of radio waves through a nanomechanical transducer", Nature **507**, 81–85 (2014)
[2] X. Song et al., "Graphene Optomechanics Realized at Microwave Frequencies", Phys. Rev. Lett. **113**, 027404 (2014)
[3] A. Nunnenkamp et al., "Quantum-Limited Amplification and Parametric Instability in the Reversed Dissipation Regime of Cavity Optomechanics", Phys. Rev. Lett. **113,** 023604 (2014)
[4] G. D. Cole et al.,, "Tensile-strained InxGa1xP membranes for cavity optomechanics", Appl. Phys. Lett. **104**, 201908 (2014).
[5] F. Hocke et al., "Determination of effective mechanical properties of a double-layer beam by means of a nano-electromechanical transducer", Appl. Phys. Lett. **105,** 133102 (2014)].
[6] S. M. Meenehan, J. D. Cohen, S. Groblacher, J. T. Hill, A. H. Safavi-Naeini, M. Aspelmeyer, and O. Painter, "Silicon optomechanical crystal resonator at millikelvin temperatures", Phys. Rev. A **90**, 011803(R) (2014)
[7] M. Abdi et al.,"Entangling two distant non-interacting microwave modes", Ann. Phys. (Berlin), 1–8 (2014) / DOI 10.1002/andp.201400100

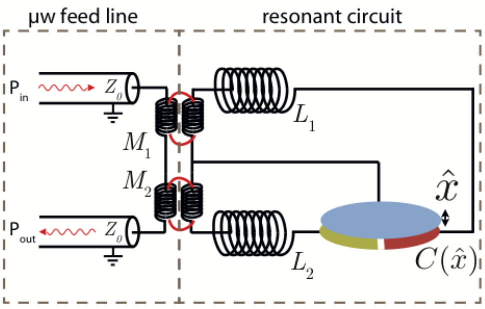
First year iQUOEMS Highlights



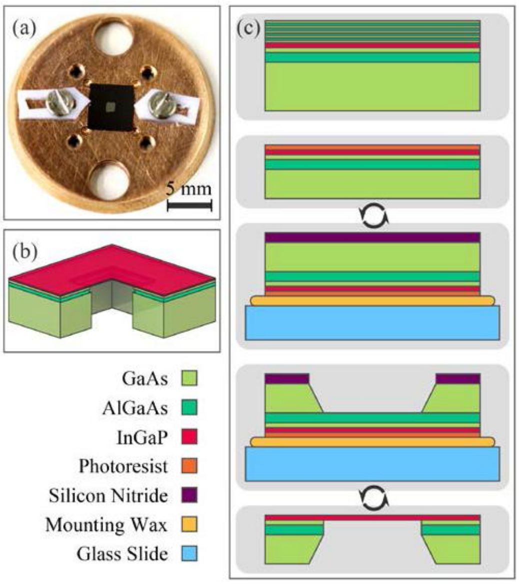
1) **Optical detection of radio waves through a nanomechanical transducer [1]**



2) **Graphene optomechanics ad sideband cooling at microwave frequencies [2]**



3) **Quantum limited microwave amplification in the reversed dissipation regime [3]**



4) **High-Q InGaP membranes for strong coupling optomechanics [4]**