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Quantum optics with quantum dots in photonic wires

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Abstract: We present an exploration of the spectroscopy of a single quantum dot in a photonic wire. The device presents a high photon extraction efficiency, and strong hybrid coupling to mechanical modes. We use resonance fluorescence to probe the emitter's properties with the highest sensitivity, allowing the detection of thermal excitation of the mechanical mode at 4 K.
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Self-assembled semiconductor quantum dots (QDs) are a promising candidate to act as an interface between stationary and flying qubits (photons). They can host spin qubits, and produce spectrally pure, on-demand single-photons. Because of the solid-state environment, the coherence is limited, but the quantum dots can be operated at extremely high speed with optical pulses. Furthermore, the possibility to tailor the electric and photonic environments using nano-fabrication techniques is a key advantage for the realization of high fidelity devices. Over the past decade various strategies have emerged to engineer the quantum dot environment including top-down techniques (photonic crystals, micro-cavities) and bottom-up approach (nanowires). Finally, from a more practical perspective, these artificial atoms constitute a very sensitive probe, with strong potential in precision sensing.

Our approach to engineering both photonic and phononic properties involves the top-down fabrication of 1D photonic waveguides. The proper engineering of the wire's dimension and shape forces the QD to emit into a specific mode of the electromagnetic field, a mode propagating along the wire axis [1,2]. In addition, a tapered section results in adiabatic deconfinement of the mode and limits diffraction losses at the top facet [3]. Optimum coupling between the emitter and the fundamental mode of the waveguide requires lateral dimensions of the photonic structure on the order of λ/n, the light wavelength in the semiconductor. Whether the relative proximity of surfaces affects the coherence properties of the embedded emitter or not has remained an open question so far. Furthermore, photonic wires display reasonably high-Q mechanical resonances which affect the QD state. More specifically, material strain intrinsically couples the mechanical resonator with an embedded QD, resulting in a hybrid QD-opto-mechanical system [4].

Efficient adiabatic deconfinement demands a taper with a very small angle which is cumbersome to fabricate and work with. We present here an alternative, the photonic trumpet, where the deconfinement takes place in the semiconductor itself. The taper angle can be much larger in this case. We demonstrate single photon emission from a single QD with high extraction efficiency [5]. To characterize the QD-in-trumpet properties with the highest sensitivity we drive the QD optical transition with a highly coherent resonant laser. Rejection of scattered laser light is realized with a dark-field microscope based on cross-polarized excitation and detection. The key enabling feature for this experiment is the large top facet of the photonic trumpet, which allows for excellent suppression of the back-scattered laser light. At resonance, count rates on a silicon avalanche photodiode exceed 1 MHz. We measure small QD linewidths similar to the ones in the bulk material showing that there is little if any additional dephasing due to the nanowire surfaces. Using noise spectroscopy of the resonance fluorescence signal, we reveal signatures of the Brownian motion of the nanowire even at a temperature of 4K. This new approach allows us to determine the characteristics of the hybrid QD-opto-mechanical system with ultra-high sensitivity and opens new perspectives in terms of precision sensing: mechanical sensing proceeds by detecting the QD photons and not by an interferometric approach. We show theoretically that this new approach achieves the Heisenberg limit once the device operates perfectly (transform-limited emission and 100% detection efficiency), not yet achieved but within range.

Finally, we show that it is possible to eliminate all the optics between the photonic trumpet and a single-mode optical fibre (typically two expensive objective lenses and a three-axis nano-positioning stage). We achieve excellent trumpet-to-fibre coupling by realizing a "quantum fiber-pigtail" [6]. The device consists of a QD in a photonic trumpet with the end facet bonded directly to the cleaved facet of a single-mode fibre. Proof-of-principle experiments yield an efficiency of 6% and this can be increased with simple modifications. Such a structure is particularly appealing not just for quantum optics experiments but also for surface scanning, the quantum dot acting as a highly sensitive electrometer. Furthermore, the approach can be translated to other materials, for instance diamond, opening the way to creating a simple but highly sensitive magnetometer.

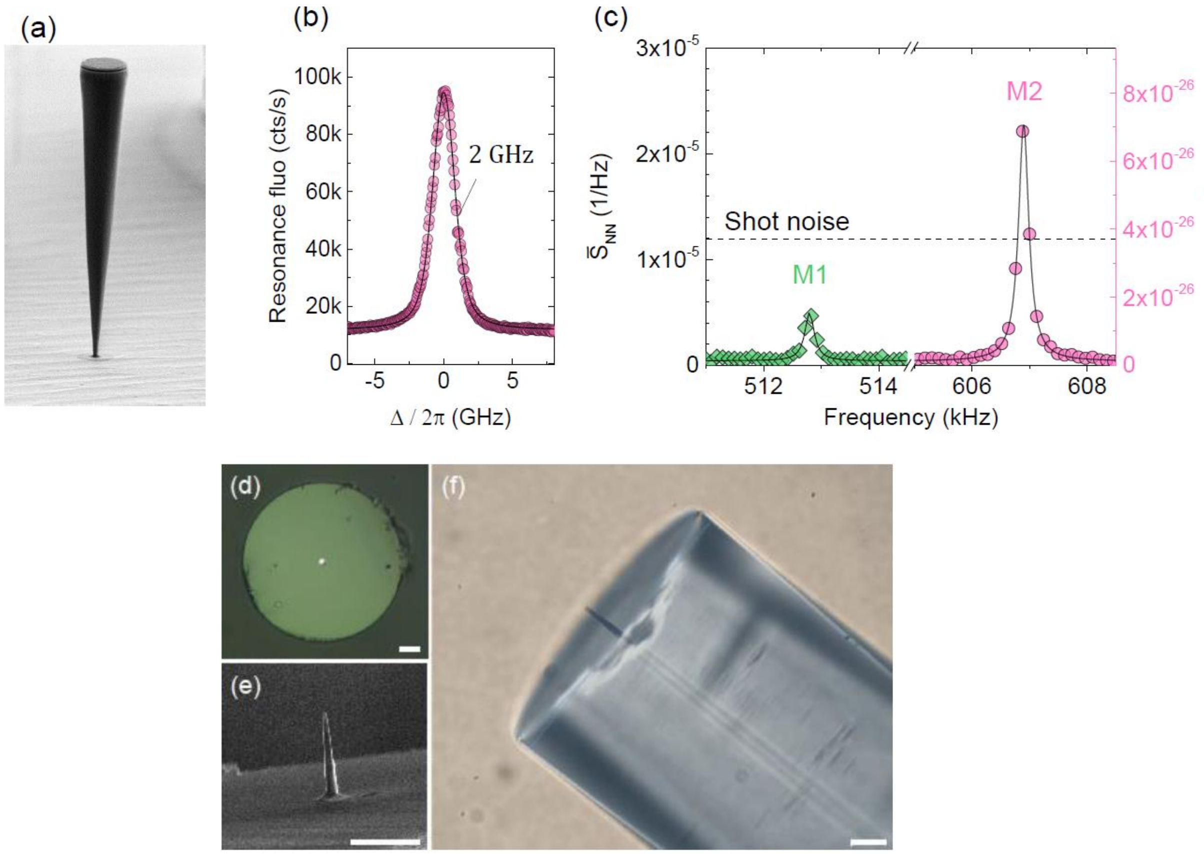

Fig 1. a) SEM picture of a trumpet photonic wire. b) Resonance fluorescence spectrum on a single quantum dot in a photonic trumpet. c) Noise spectrum revealing Brownian motion of the trumpet's fundamental mechanical mode at 4K. d) e) f). Fabrication steps to attach a photonic trumpet to a single mode fibre.

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