Cavities for light and sound: a cavity-enhanced platform for quantum acoustics

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Summary

Surface acoustic waves are mechanical waves that are confined to the surface of a material. These waves occur naturally during earthquakes and have also been engineered for use in miniaturized devices, playing a crucial role in sensing and processing of ultra-high-frequency electric signals. Artificial surface acoustic waves typically operate at frequencies of hundreds of MHz or higher, with wavelengths on the micrometer scale, and surface displacements of hundreds of picometers - comparable to the size of an atom.

Excitation of these waves can be done via electromechanical conversion by an interdigital transducer on a piezoelectric material. Surface acoustic waves can have very low loss which, in combination with the ability to couple to a number of quantum systems via strain or electric fields in piezoelectric materials, has recently enabled exploration of the field of quantum acoustics.

This coupling is possible both at the classical level, where a large number of coherent phonons interact with the quantum system, and at the quantum level, where the quantum system ideally couples to a single phonon. This is of interest not only for quantum physics research, but also for applications ranging from quantum sensing to quantum transduction, where a quantum signal is converted from one type of carrier (e.g. photon) to another (e.g. phonon).

In this thesis we work with surface acoustic waves on GaAs, which is both a piezoelectric material and a semiconductor. In this way, surface acoustic waves can be generated in the same medium that hosts InGaAs quantum dots, which are optically active quantum systems. The coupling between surface acoustic waves and quantum dots can be enhanced by confining the phonons in an acoustic cavity and placing the quantum dot in an optical microcavity to enhance the optical readout. To this end, we describe here the realization of a platform comprising an acoustical cavity and an open-access optical microcavity which, in the near future, will be used for quantum acoustics experiments with gigahertz surface acoustic waves and InGaAs semiconductor quantum dots.

Fabrication of high-finesse surface acoustic wave cavities is not trivial due to a number of loss mechanisms. Because of the system's complexity, finite element simulations are time-consuming and not easy to perform. Therefore, fabrication of high-finesse surface acoustic wave cavities usually involves an optimization process based on iterating sample fabrication and characterization. In our case, we nanofabricate surface acoustic wave cavities via electron beam lithography and evaporation of Al on GaAs. These cavities operate at 1 GHz, and contain an interdigital transducer for surface acoustic wave excitation.

In Chapter 2, focusing on the characterization of surface acoustic wave cavities, we build a fiber-based scanning optical interferometer for measuring the amplitude and phase of the displacement of GHz surface acoustic waves, as well as for imaging their spatial distribution in an acoustic cavity. Characterization of surface acoustic wave cavities is usually done with all-electrical measurements employing the same interdigital transducer used for wave excitation. We find that this method is incomplete and can result in misleading information, especially regarding the distribution of the acoustic field inside the cavity. We show this by imaging transverse modes in a surface acoustic wave cavity

and demonstrating that the superposition of these modes leads to unconventional mode profiles.

One of the loss mechanisms in surface acoustic wave cavities is the scattering of surface waves into bulk waves from the surface acoustic wave mirrors. In Chapter 3 we investigate spurious bulk acoustic waves in surface acoustic wave cavities. This investigation has been possible due to the high spatial resolution of our scanning interferometer, enabling the analysis of the acoustic-wave interference fringes in surface acoustic wave cavities. We also show that amplitude-only measurements of the surface displacement are sufficient to detect bulk waves, due to the interference between surface and bulk waves. This method can be valuable for exploring geometries that minimize bulk wave scattering.

A particular feature of our interferometer is its single-mode fiber splitter. This led to the unexpected observation of the dynamical Talbot effect, where the standing waves in a surface acoustic wave cavity behave as an oscillating diffraction grating. As a result, oscillating replicas of the optical field at the grating are produced at specific locations away from the grating. In Chapter 4 we report the observation and investigation of this phenomenon.

In Chapter 5 we describe the realization of an open-access optical microcavity compatible with a tabletop closed-cycle cryostat. The high mechanical stability of 5.7 pm rms, obtained when the cryostat is operated at 4 K, allows stable operation of a cavity with finesse $F \sim 1800$. In particular, our design has free-space optical access, essential for full polarization control. Tunability and small mode volume makes it compatible with semiconductor quantum dots.

At the time of writing this thesis, the surface acoustic wave cavity is being integrated with the open-access optical microcavity. For this, a GaAs substrate is first coated with an AlAs/GaAs Bragg mirror, and then a layer of InGaAs quantum dots is embedded in the middle of a 260 nm thick GaAs layer. This optically reflective GaAs substrate constitutes the flat mirror of our open-access optical microcavity. The optical microcavity has a mode volume $V \sim 10\,\lambda^3$ ($\lambda = 935\,\mathrm{nm}$) and a finesse $F \sim 1800$, while the surface acoustic wave cavity (the short cavity presented in Chapter 3) has a mode volume $V_{SAW} \sim 3500\,\Lambda^3$ ($\Lambda = 2.8\,\mu\mathrm{m}$), and finesse $F_{SAW} \sim 40$ at room temperature. With these parameters, the estimated single-phonon displacement is $U_0 \sim 0.01\,\mathrm{fm}$.

We plan to first study the interaction between surface acoustic waves in the classical regime and a quantum dot, and then explore this interaction with surface waves at the quantum level, ideally with the goal of detecting a single phonon by its modulation of the quantum dot frequency. According to our estimates, single-phonon detection is possible even with our rather large mode volume surface acoustic wave cavity, even though milli-Kelvin temperatures are needed to prepare the acoustic system in the ground state.