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[Quantum Accelerator] Multi-Parametric Quantum Transduction Between
Microwave, Optical, and Mechanical States

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14. ABSTRACT We have developed radio frequency bulk and surface acoustic wave piezo-mechanical resonators for applications in quantum information. Our micromechanical devices are ultimately capable of supporting very long-lived quantum states that will act as an integrated quantum memory for microwave quantum information or intermediate state in microwave -optical quantum transduction. Our mechanical resonators are fabricated from low-loss single crystal quartz and are shielded from external loss with periodic structures acting as acoustic mirrors. These radio frequency devices will communicate with microwave quantum information systems via a superconducting nonlinear mixing element capable of high fidelity frequency transduction between microwave and radio frequency signals.					
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Final Research Progress Technical Report

[Quantum Accelerator]: Multi-Parametric Quantum Transduction Between Microwave, Optical, and Mechanical States

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Accomplishments

- Research Objectives

The main objective of this project was to develop long lived piezo-mechanical resonators for integration into microwave quantum information and optomechanical transduction systems. Ultralow dissipation nanomechanical systems are strong candidates for quantum information storage, with the potential for compact, scalable memory elements with seconds scale quantum coherence times. Such a memory would outperform many other quantum memory technologies, such as passive microwave resonators, in terms of lifetime and footprint. Additionally, mechanical elements are a viable option as an intermediary in quantum transduction between microwave and optical qubits. Quantum coherent microwave – optical transducers will serve as the on-ramp to the long-distance, fiber-optic quantum networks necessary to coherently link disparate and distance quantum information processing systems.

Our technical goal was to design, fabricate, and characterize piezo-mechanical resonators, suitable for integration as a quantum memory element. Our approach was to develop radio frequency (RF), 10^0 - 10^2 MHz, mechanical resonators from a low-loss piezoelectric material such as α -quartz. Single crystal quartz has been shown to support mechanical quality factors of over 10^9 in the relevant frequency range, opening the possibility for seconds scale quantum state lifetimes. We intended to couple this RF resonator to superconducting microwave quantum information circuits using a specially tailor 3-wave mixing element, a superconducting nonlinear asymmetric inductive element (SNAIL) that has been shown to allow for high fidelity quantum signal transduction and routing across GHz frequency differences. This approach offers numerous technical advantages over current sub-micron scale microwave piezo mechanical systems coupled directly to microwave quantum circuits and over very low frequency mechanical devices that employ electrostatic coupling.

- By introducing a parametric frequency conversion step between the microwave and mechanical systems, we vastly open up the space accessible mechanical systems. We can choose from a wide range of mechanical topologies such as bulk acoustic wave, surface acoustic wave, and flexural resonators. Strong parametric pumping can increase the overall information swap rate, even when the bare couplings are modest. Turning off the parametric pump nearly completely decouples the systems, allowing the mechanical state to evolve unperturbed by the rest of the system while information is being mechanically stored.
- By storing information at lower frequencies, we are essentially gearing down the rate of both the evolution and decoherence in our quantum memory, greatly reducing the necessary mechanical quality factor times mechanical frequency ($Q \times f$ product) to achieve a given T_1 lifetime.
- The typical wavelength of our chosen ~ 100 MHz acoustic frequency scale naturally leads to devices with a length scale of 10s of micrometers. Compared to sub-micron devices, our larger scale mechanical resonators provide better fabrication tolerances and easier alignment between mechanical and electrical elements. These larger scale devices also have a more advantageous surface area to volume ratio, rendering them less susceptible to decoherence from two-level system defects ubiquitously found on surfaces.

Specifically, our plan was to evaluate three mechanical topologies in terms of potential lifetime and microwave – mechanical coupling, and fabricate and characterize the most promising designs. The three mechanical designs that were evaluated via finite element simulation of their piezo-mechanical properties were (1) a single crystal quartz bulk acoustic wave resonator suspended from a 1D phononic crystal

shielded tether (Fig. 1), (2) a surface acoustic wave (SAW) resonator defined by a 1D phononic crystal acoustic waveguide etched into a single crystal quartz surface (Fig. 2), and (3) a suspended 1D phononic crystal shielded, high stress, flexural resonator constructed from a bilayer with a piezoelectric layer on top of a high stress dielectric thin film.

- Accomplishments

Simulation and Design

We began the project by developing finite element simulations of the mechanical properties and piezomechanical coupling rates for our three mechanical topologies. Our simulations were used to extract the mechanical resonance frequencies for a given device geometry while accounting for the anisotropic properties of the piezoelectric material. We were also able to estimate the mechanical quantum state lifetime due to loss mechanisms including acoustic radiation into the supporting substrate as well as internal bending induced dissipation due to the finite mechanical loss tangent of the materials. Our simulations also allowed us to extract an effective device impedance as seen by a given electrode geometry. Using these numerically simulated device parameters, we developed an analytic circuit impedance model for a superconducting microwave resonator coupled to piezo-mechanical resonator, in order to estimate the microwave – mechanical information swap rate. Our goal was to use these simulation tools to evaluate different geometries and topologies for use as a mechanical quantum memory, and generate the most promising designs for fabrication.

We learned several things from our simulations. First, we found that suspended, phononic crystal shielded, bulk acoustic wave resonators are able to achieve internal-dissipation-limited Qs for such devices ($Q > 10^9$, based on material properties of quartz at cryogenic temperatures measured in published literature), as well as strong electromechanical coupling. However, these devices present a fabrication challenge in creating a patterned, suspended single-crystal quartz structure on the scale of 10s of micrometers. Second, for SAW devices, we were able to minimize acoustic radiation losses into the supporting substrate from our initial device designs. However, the resonators parameters were very sensitive to the accuracy of the device geometry dimensions, and we were concerned that we would not be able to fabricate devices with sufficient dimensional accuracy. We subsequently put a large effort into redesigning devices with much better geometric tolerances. The results are a new geometry for 1D phononic crystal waveguide confined SAW resonators, where the waveguide width is tapered adiabatically, and sensitivity to fine details of the geometry is greatly reduced. Details of this new design are given later in the technical update section. Third, for both the surface and bulk acoustic wave devices, the expected electromechanical coupling rates are slightly lower than anticipated based on our initial surveying of devices made from different material with stronger piezoelectric properties (e.g. Lithium niobite) and devices geometries at smaller length scales. This small bare coupling rate can be made up for by increased parametric pumping strength. Additionally, based on this finding, we decided to modify our overall system design. We are now working to incorporate our SNAIL converter by directly flip-chip bonding a superconducting chip to a piezo-mechanical chip. This will provide overall stronger coupling than our initial plan, which was to couple the piezo-mechanical device to the nonlinear circuit via a dipole antenna. Fourth, we were unable to simultaneously obtain both high mechanical quality factor (Q) and large electromechanical coupling with high-tension flexural devices. The basic lesson is that the designs which give the highest Q minimize the curvature and bending the structure to minimize internal dissipation, while strong electromechanical coupling requires the piezoelectric material to strain. Based on this negative simulation result, we opted not to pursue flexural designs further.

Device Fabrication

Based on our simulation results, we worked to fabricate two designs, an optimized surface acoustic wave device and a suspended bulk acoustic wave device. These two devices share many common fabrication steps in terms of deep reactive ion etching (DRIE) of quartz. However, the bulk acoustic wave device requires additional fabrication steps to release the device from its substrate. To that end, we have developed a nickel-masked quartz etching process capable reaching the etch depths of many micrometers necessary to fabricate our devices. We have successfully fabricated SAW devices using this process. We are still developing a process to suspend bulk acoustic wave devices, which has proved to be a greater fabrication challenge than anticipated. We are pursuing two methods to make suspended quartz devices. First, we pattern the outline of our device with the developed DRIE process and then undercut the device with a focused ion beam (FIB) milling process. We have successfully suspended test structures using this technique, and continuing to improve the device cleanliness and dimensional accuracy for the process. In a second method, we are working to procure thin-film crystal quartz bonded to a silicon handle wafer. We pattern the device outline in the quartz device layer using our DRIE process, and then release the device by etching away the silicon substrate layer. We have had difficulties and delay in obtaining our thin quartz bonded to silicon wafers that have greatly slowed down this portion of the effort. We will continue to pursue this process when the next round of bonded wafers arrives (expected in June).

Device Characterization

We are currently building a custom scanning laser doppler vibrometer with in-situ scanning microwave impedance microscopy to characterize SAW and bulk acoustic devices. We had originally envisioned a much simpler optical characterization setup that would be best suited to extract the frequency and Q of bulk acoustic wave devices. But, in understanding the intricacies of the SAW device geometries, we have opted to build a characterization tool that can map out in detail the spatial and frequency dependence of the mechanical and electrical modes of our devices. When complete, we will have a dedicated facility to fully characterize our devices, gaining a better understanding of the spatial mode profile, spatial distribution of any acoustic wave scattering, and the spatial dependence of the electromechanical coupling. This tool will allow for much more rapid iteration through device geometries and the meaningful comparison between experimental measurements and simulation necessary to validate our designs. This more complex characterization tool has added time to the project, but we expect it to be operational this summer.

Device integration

The final goal in our research plan was to integrate a piezo-mechanical device with a superconducting circuit. We have made progress towards that goal, but not yet completed it. We started to develop a flip-chip bonding process to combine separately fabricated piezo-mechanical quartz chips on top of a sapphire superconducting circuit chip. We anticipate achieving few micron chip separation and lateral alignment tolerances. Our next iteration of bonding process will include in-situ force measurements so that we can reproducibly apply a well-defined pressure in the bonding process to achieve consistent results. We have come up with a set of design parameters for the superconducting circuit SNAIL chip that are optimized to couple to the as-designed bulk acoustic wave devices, and will fabricate this chip using already developed fab processes once the piezo-mechanical device has been characterized and validated.

- Dissemination of Results

Our preliminary results on device fabrication have been reported at the 2022 APS March meeting at talk B34.00001: High-Q bulk acoustic resonator for building long-lived Quantum Memory. The PI has presented an overview of our scheme in a colloquium at the University of Rochester and Seminar at the University of Maryland.

Impacts

This grant supported the training and education of one graduate student at the University of Pittsburgh, who carried out much of the device simulation and fabrication. Additionally, several undergraduate students were trained in the lab during this project through the First Experience in Quantum Research program, recently started at the University of Pittsburgh. These students gained broad exposure to the topics of quantum transduction and quantum memories. As well, they participated in an open-ended project to simulate and explore bulk and surface acoustic wave devices similar to those employed in this work, with a goal of gaining an understanding of phononic band structure, how surface and bulk acoustic waves couples, and more generally, why low dissipation mechanical systems are useful in the context of quantum information. Generally, training in quantum information fields is topic of growing importance in STEM education, as it becomes necessary to build a quantum-savvy workforce to further advance and utilize the outcomes of the recent increasing scale of investment in quantum information technology at the academic, industrial, and commercial level.

Changes

- Problems and delays

We experienced several delays in obtaining materials and in obtaining custom bonded thin quartz on silicon wafers (long lead times and wafers broken during processing). This slowed down our overall progress towards completing an integrated piezo-mechanical – superconducting circuit device.

Technical Updates

A summary of our two piezo-mechanical devices is provided below.

Bulk Acoustic Wave Resonator

We designed and simulated a suspended, width-extension bulk acoustic wave resonator (Fig. 1). The device is made from z-cut α -quartz. The tethers act as phononic crystal mirrors, with a band gap for acoustic waves centered around the resonance frequency of the bulk acoustic wave mode. Our simulations show that the acoustic radiation Q can be made much higher than even that expected from the quartz at cryogenic temperatures. From our simulated impedance (Fig. 1c), we estimate a bare (unpumped) electromechanical coupling rate in the kilohertz range. This rate can be brought up to the MHz range with strong parametric pumping.

The device is fabricated in a two-step process. First, the outline of the devices formed via a DRIE process that we developed to etch up to several micrometers deep. Second, the device is released. Fig. 2(b) shows a test structure that is released by undercutting with a FIB milling process. Alternately, we are developing a different fabrication process that should result in devices that are much cleaner and more

dimensionally accurate. We are working with vendors to create a sub-10 micron thick layer of high quality single crystal quartz bonded to a silicon handle wafer. The quartz device layer will be patterned with DRIE and then suspended by wet etching the silicon under the device. The first attempt at bonding thick quartz to silicon and then thinning device layer lead to unacceptably large variation in device layer thickness, as well as excess stress during the thinning process that ultimately broke the handle wafer. In our next iteration the quartz is thinned before bonding.

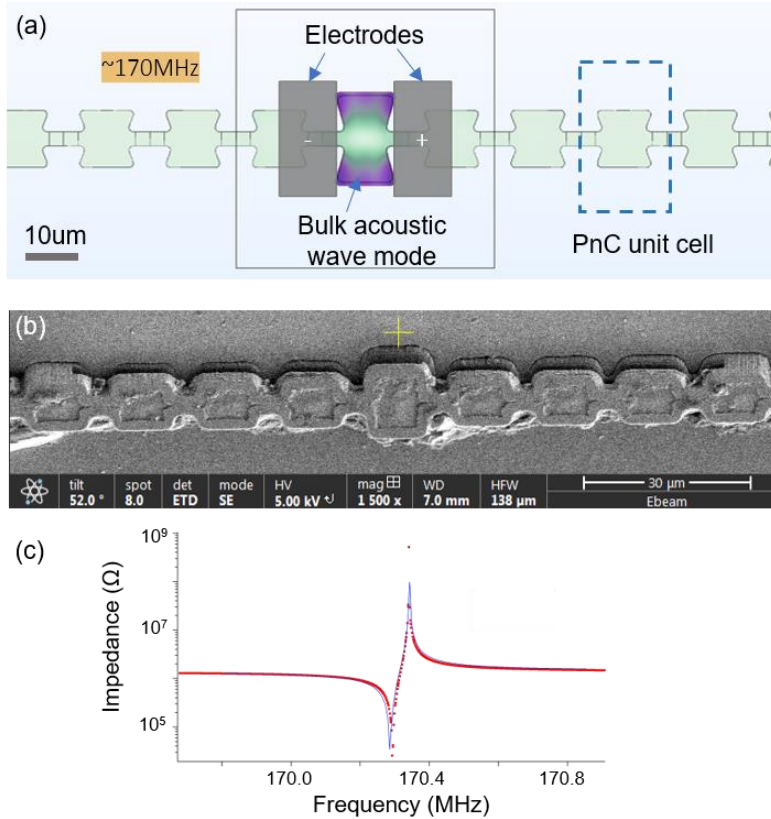


Fig. 1 Bulk acoustic wave resonators. (a) Finite element simulation of width extension bulk acoustic wave mode. (b) SEM image of FIB etch released test device. (c) Finite element simulation of device electrical impedance.

Surface Acoustic Wave Resonators

We have designed and simulated a 1D phononic crystal waveguide surface acoustic wave resonator (Fig. 2). Unlike typical devices where SAW confinement is achieved via interdigitated electrodes patterned on to a surface, our devices use a periodic array of trenches etched into the surface. These trenches form a 1D band gap for surface acoustic waves propagating along the array, as well as providing lateral confinement for the SAW, creating a waveguiding structure. We introduce a defect in the periodic structure by widened the waveguide, and generate a localized resonant mode in the band gap. The width of the waveguide is adiabatically tapered over several unit cells to reduce scattering into the bulk, creating a high Q resonance (Fig. 2(c)). The parameters for this final design are chosen to be maximally insensitive to inaccuracies in the dimensions of the fabricated device. These simulations can become quite large in 3 dimensions, where the full device would require $>10^5$ cubic wavelengths of simulation volume.

The fabrication of this device is relatively straightforward. A nickel hard mask is deposited on the surface of a quartz wafer. Trenches are then created via a DRIE process. Interdigitated electrodes couple the SAW to the SNAIL are fabricated on the SNAIL chip, which will be flip-chip bonded to the

SAW device chip. In this configuration, the metal electrodes do not move. This eliminates mass loading effects and mechanical dissipation from the mechanically lossy polycrystalline metal. By optimizing the geometry and fabrication process of this design, we believe it should be possible to reach the intrinsic mechanical dissipation limit of quartz.

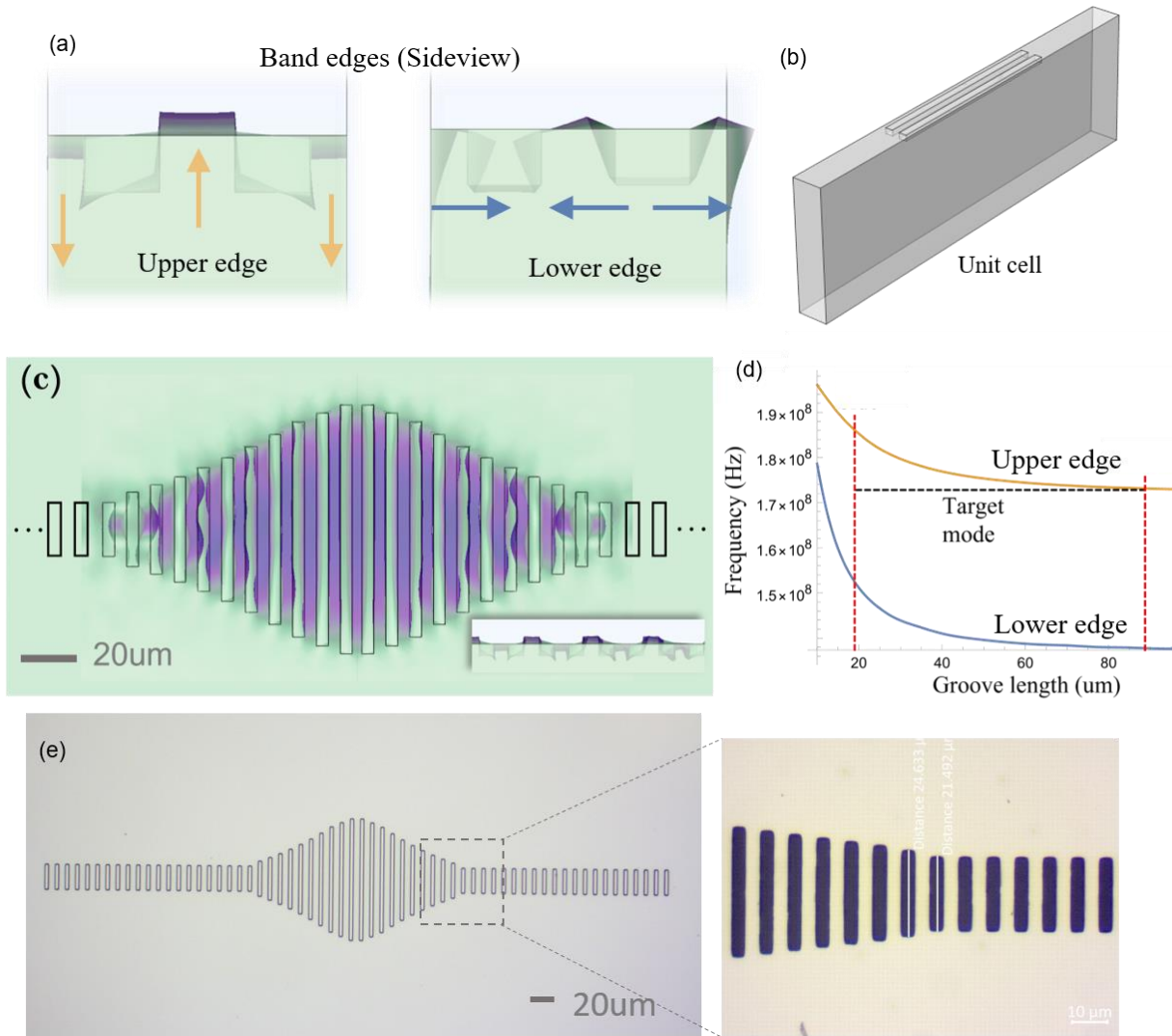


Fig. 2 Surface Acoustic Wave Resonators. (a,b) Simulation of SAW unit cell. (c) Simulation of SAW resonator with adiabatically tapered waveguide width. (d) Band gap of SAW 1D phononic crystal waveguide as a function of waveguide width. (e) Micrographs of quartz SAW device.