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Quantum optical lever sensing on a SiN string

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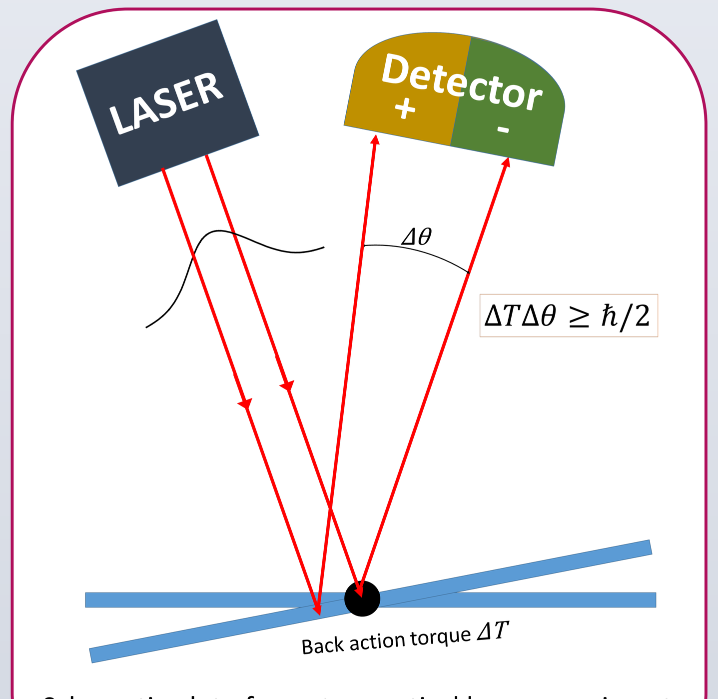
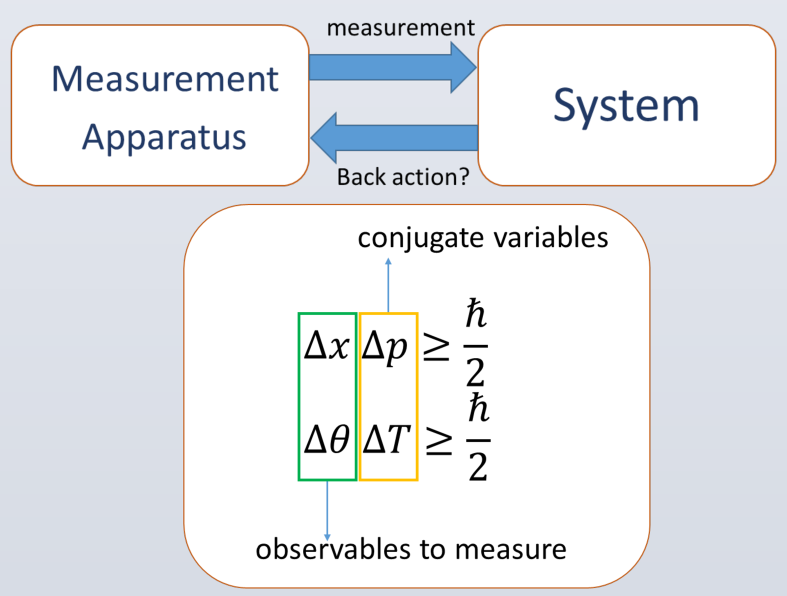
Introduction

Measurement in quantum mechanics necessarily entails back action, where the measurement process perturbs the system being measured. The precision of a measurement is limited by this back action in a fashion governed by a Heisenberg uncertainty relation. In this project, we explore the quantum limits of optical lever angular displacement sensing and will attempt to harness correlations in the quantum noise of our system to evade the effects of quantum back action.

Our optical lever detection scheme is similar to the standard AFM cantilever where light reflecting off the surface of a bending or tilting mechanical resonator is used to measure the angular derivation $\Delta\theta$. A back action torque, ΔT, occurs when photons recoiling off of different locations of the mechanical resonator provide random angular momentum kicks.



Schematic plot of quantum optical lever experiment



Heisenberg's uncertainty principle

In order to access the quantum regime where quantum back action becomes important, we are working to reduce the noise in our experiment:

- Nano-fabrication of SiN string mechanical resonators with high quality factor, which minimizes the thermal noise
- Developing laser source with low intrinsic noise
- Implementation of actively balanced detection methods to reduce the effects of laser intensity noise

References

1. Yutaro Enomoto et al., Physical Review A 94, 012115 (2016)
2. T. P. Purdy et al., Science 339, 801 (2013)
3. D. Mason, et al., Nature Physics 15, 745 (2019).
4. Ghadimi et al., Science 360, 764–768 (2018)

Acknowledgement

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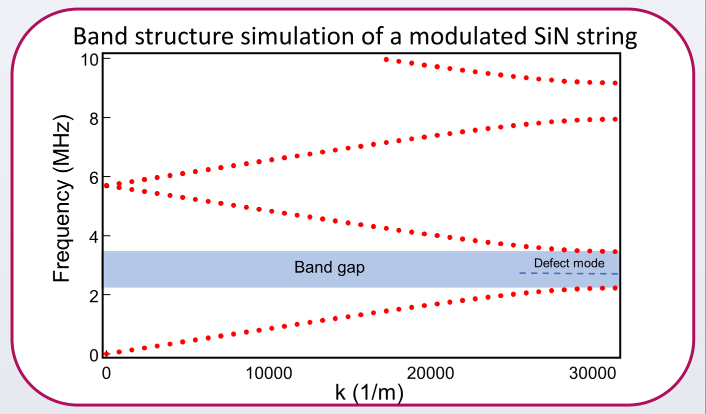
Charles E. Kaufman Foundation

SiN strings with ultra-high quality factor

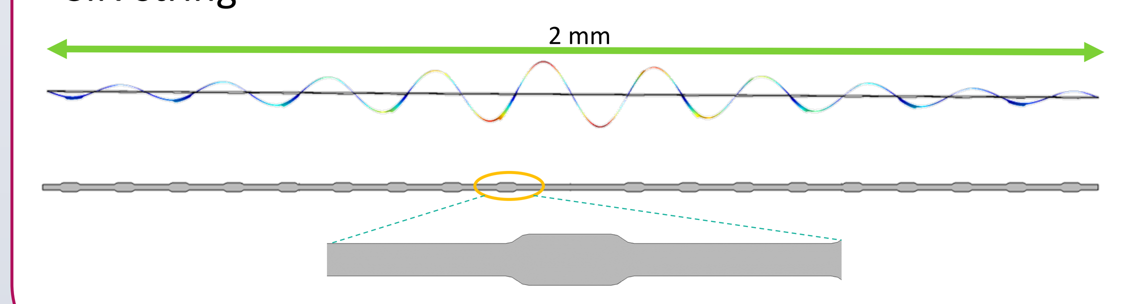
Simulation

Nanomechanical resonators use multiple design strategies to reduce mechanical dissipation:

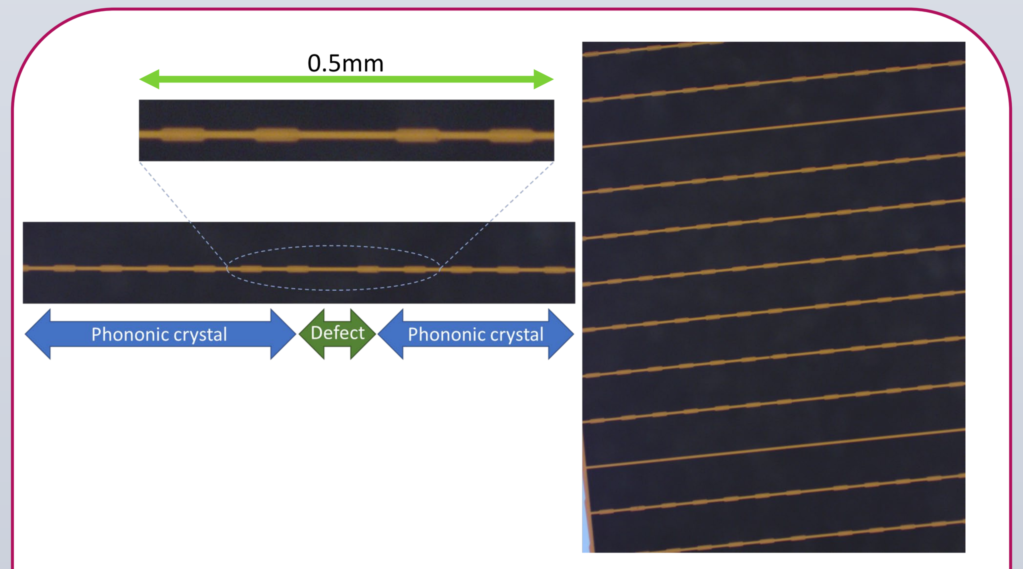
- **Dissipation Dilution** High tensile stress increases mechanical resonance frequency by many orders of magnitude.
- **Mechanical Band Structure Engineering** Periodic modulation of string width produces a band gap. Localized defect modes in the gap are protected from clamping and radiation losses.



COMSOL simulation of a localized mode of the modulated SiN string



Fabrication



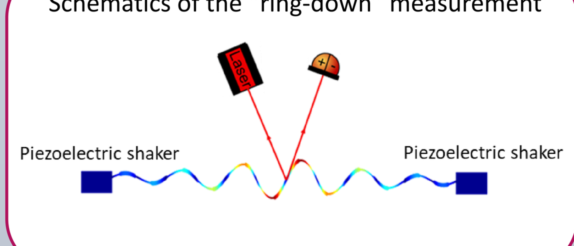
Optical microscope image of SiN strings

- Reactive Ion Etching to define the strings, and wet KOH etching to release the SiN strings from the substrates.
- We made the lengths of the strings 1mm, 2mm or 5mm with different shape modulations in order to find the optimal design with highest quality factor in the subsequent experiments.

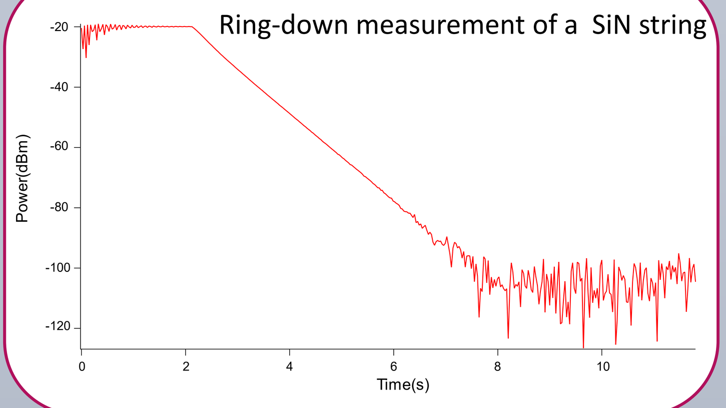
Device characterization

- We performed "ring-down" measurements to obtain the quality factor of our samples by measuring the time constant of the exponential decay of mechanical energy, after driving the sample with a specific frequency.
- Right figure shows our ring-down measurement result as an example. The driving frequency is 0.554 Mhz and the obtained quality factor is 1.03×10^6.
- The best quality factor to date $\sim10^7$.
- The "ring-down" experiments we have performed so far indicates that our SiN string samples indeed have very low thermal noise. Yet more efforts should be made to lower the noise to the level where quantum back action becomes important.

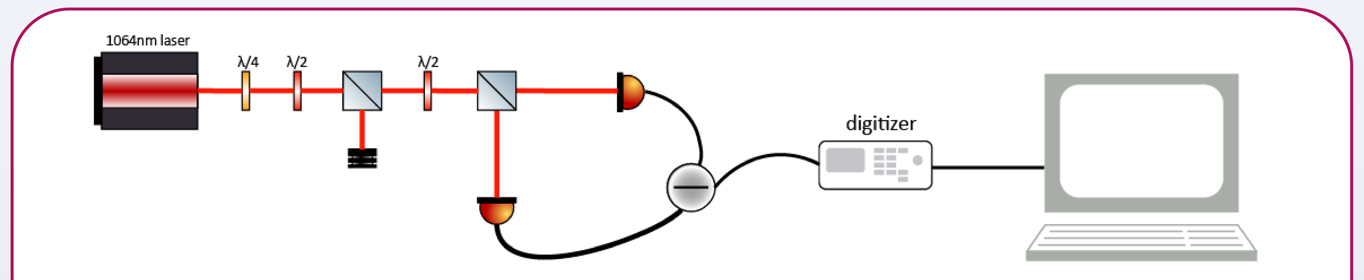
Schematics of the "ring-down" measurement



Ring-down measurement of a SiN string

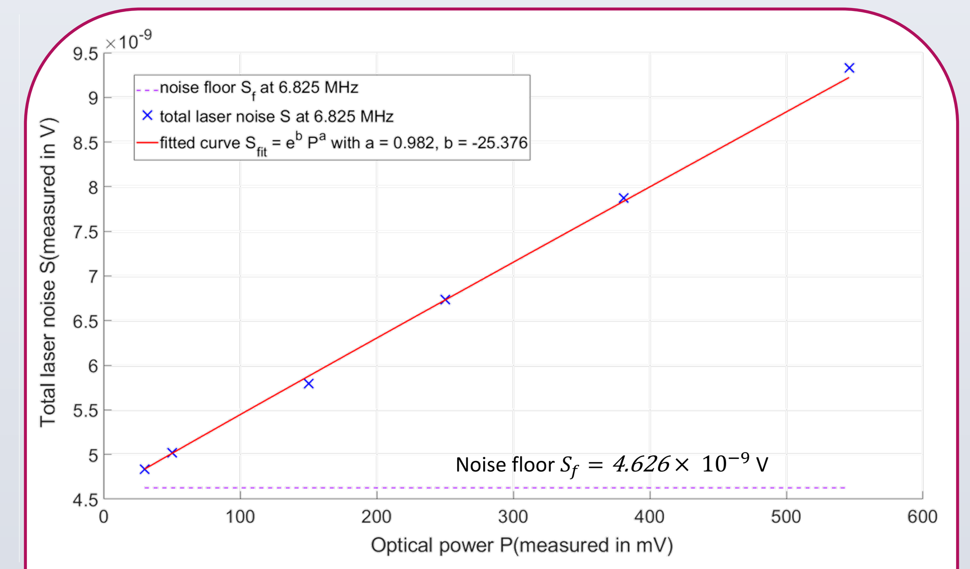


Noise Characterization of laser

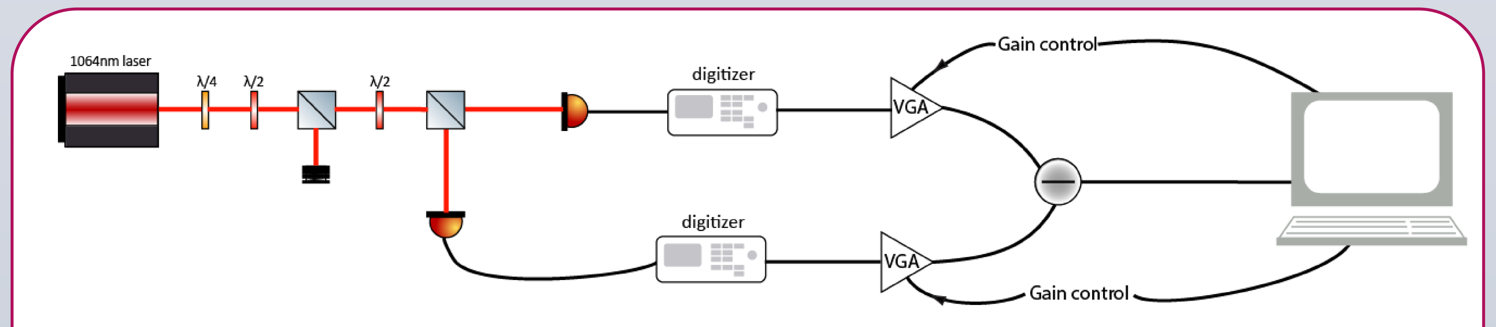


Optical diagram of the noise characterization using balanced detection

- To characterize the intrinsic laser noise, we performed the **balanced detection** to cancel its intensity noise of the laser.
- We found that there is an approximately linear relation between the laser noise and the optical power, indicating the intrinsic noise is governed by the shot noise obeying Poissonian statistics.
- We are working on a software based **auto-balancing system** to better cancel the laser intensity noise dynamically and its optical diagram is shown below.

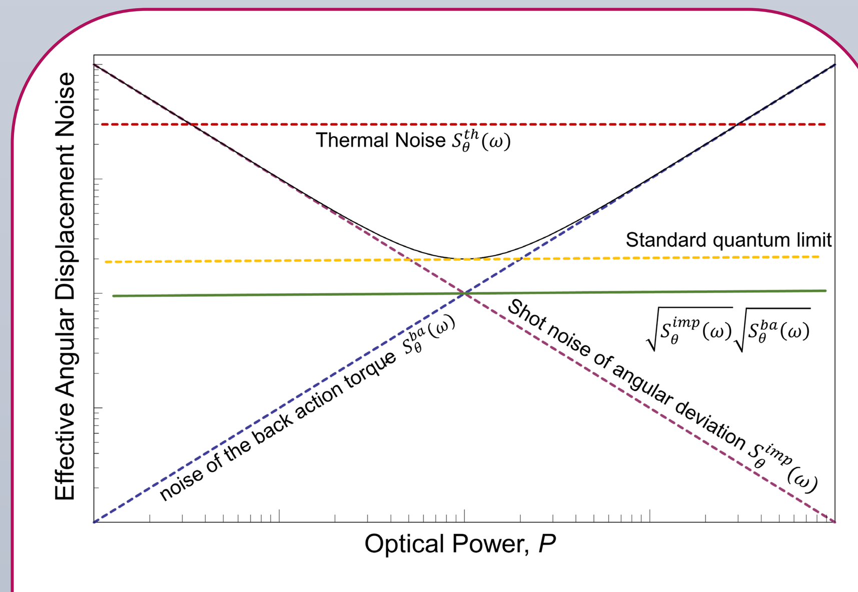


Characterization of the intrinsic laser noise using balanced detection. The intrinsic laser noise is found to be governed by the Poissonian statistics.



Optical diagram of the noise characterization using auto-balanced detection(work in progress)

Next steps



$S_\theta^{imp}(\omega) \propto 1/P$: shot noise of the angular deviation
$S_\theta^{ba}(\omega) \propto P$: shot noise of the back action torque
$S_\theta^{th}(\omega) \propto P^0$: Thermal motion

- We plan to further reduce the thermal and laser noise to approach a measurement at the standard quantum limit.
- By adding a lens to our measurement setup we will cause destructive interference between the shot noise induced angular deviation and the back action torque induced to angular deviation. We hope this measurement scheme will lower the noise below the standard quantum limit therefore realizing the quantum back action evasion.