INVESTIGATING THERMAL NOISE IN GRAM-SCALE SILICON FLEXURES AT 123 K

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Silicon in 3G Detectors

- Strong substrate material candidate for cryogenic GW detectors
- Host for low thermal noise coating (such as aSi-based or AlGaAs-based)
- Low mechanical loss, gets better with low T
- High thermal conductivity, gets better with low T
- Very small thermal expansion near 123K and below 20K
- Many questions to investigate (absorption, scatter, birefringence, emissivity, ...)

Monolithic suspensions for low suspension thermal noise

- Silicon as a suspension material, same (good!) bulk properties as substrate
- Limited elastic regime; brittle
- Flattened geometry for increased flexibility in primary direction
- Spring blades on penultimate stage for vertical isolation
- Many open questions
  - How to fabricate? Surface quality matters, breaking strength is critical
  - Surface to volume ratio very different to fibres
  - Experimental verification of thermal noise in ribbon suspensions

Better thermal noise
Easier cooling
Thermal Noise in Silicon Flexures

- Cantilevers resemble ribbon geometry (aspect ratio)
- Combination of thermo-elastic loss and mechanical loss in flexure (TE loss scales is suppressed by small CTEs but T gradients may occur)
- Measure thermal noise of cantilever to better understand thermal noise and losses in ribbon suspensions
- Preferably measure loss/thermal noise directly at relevant frequencies
- Our approach: model and observe broadband motion of silicon flexures
- HR-coated mirror glued to end of flexure for optical readout
- Trim flexure thickness to localise bending modes
- Must watch out for clamping losses
Flexure Displacement Readout

- Optical cavity-enhanced readout of cantilever motion
- Short cavity (2cm) enhances displacement sensitivity
- Optical and flexure parameters designed to make thermal noise from cantilever dominant
- PZT-actuated mirror extends dynamic range of tracking within cavity linewidth
Displacement Readout Optical Setup

- 1064nm low-noise NPRO laser stabilised via Pound-Drever-Hall method to reference cavity

- Pound-Drever-Hall readout of laser detuning from cavity resonance
- Low bandwidth feedback loop to PZT to compensate cavity length drifts
- Signature of flexure motion found in error signal and feedback signal
Room Temperature Measurement

- The shown noise model is based on a measured Q of 1,800 at room temperature.
- Above 30 Hz we see a good agreement between measurement and model.
- Qs up to 60,000 seen in other, thinned flexures.
- Calculated Qs based purely on structural and thermo-elastic loss are much higher.
- Other losses, such as clamping, contribute to composite Q.
In order to resolve the displacement noise from purely structural losses at 123K, we need to resolve cavity length fluctuations on the order of $10^{-17}$ m/rtHz.

This corresponds to a frequency noise of about 0.1 Hz/rtHz in a cm-scale cavity.

This is technically challenging but not prohibitively difficult.

Needs a very quiet testbed.

For now, only consider radiative cooling and 123K.
Vacuum Chamber and Cryogenic System
Radiative Cooling for Cavity Shell

- Flexure cavity assembly placed into suspended aluminium shell with fins for extra surface area
- Temperature readout with sensor at cantilever base
- Power resistor in flexure clamp for temperature control
- Optional thermal break between flexure and clamp body
Cooling Chain

- Purely radiatively cooled final stage
- Cavity shell is at the bottom of a four-stage torsion suspension system
- Radiation shields are mounted to non-isolated suspension frame
- Electrical wiring co-descends all torsion suspension stages
- Single-stage pulse-tube cooler with 50W extraction power at 80K, 30K ultimate temperature
- Solid ø70mm copper rod links radiation shields to cold head
- Copper braids between cold head and copper rod for additional vibration isolation and thermal expansion
Recent Cooldown Results

• Initial cooldown results similar to modelled expectation
• After warm start, cavity takes about 40 hours to reach 123K
• Copper bar and radiation shield remain below 100K for over 10 hours after turning the cryocooler off
• This will allow us to map the thermal noise around 123K even without active cooling
Ongoing Work and Future Plans

- Heating system upgrade based on cooldown data to maintain 123K
- Monitor optical alignment during cooldown and lock to cold cavity
- Develop a comprehensive noise budget at 123K
- Use finite element analysis to understand and optimise flexure and clamping losses
- Prototype new flexures
  - Thinning of flexure sections (etching, nano-machining)
  - Mirror bonding to surface (vs glue)?
  - Get rid of mirror and directly cover part of the cantilever surface with HR coating?
- Apply coating to flexing region and measure mechanical coating losses with the broadband displacement noise readout method

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