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Reducing Suspension Thermal Noise in KAGRA

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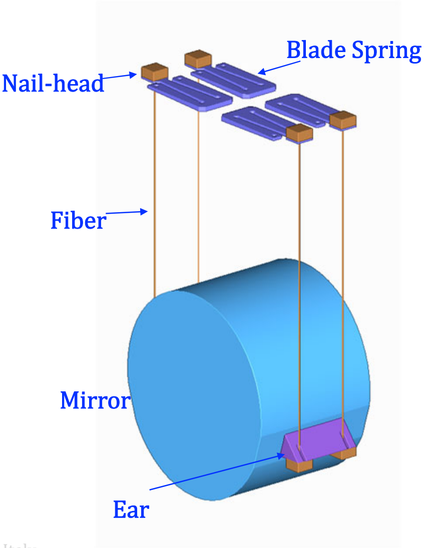
KAGRA Suspension Thermal Noise Overview

KAGRA TM Suspension

- The KAGRA test mass (TM) is suspended within the cryogenic payload by four sapphire blade springs and four sapphire fibers.
- The ears are bonded to the mirror, and nail heads are formed on the fibers in advance.
- The mirror is then hung from the blade springs via the fibers and nail heads.

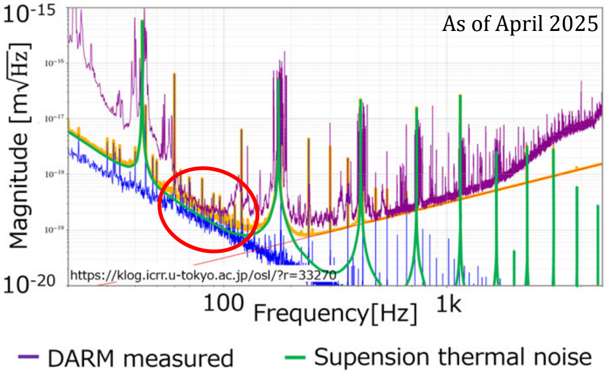


Thermal Noise Limitation Around 100 Hz

Around 100 Hz,
KAGRA sensitivity is limited by suspension thermal noise,

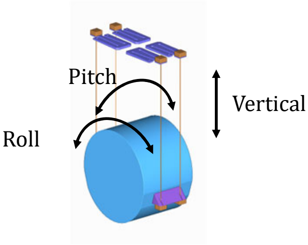
determined by the Q factors of <u>blade springs</u> and <u>fibers</u>.

Note: Thermal noise amplitude $\propto \sqrt{\frac{T}{f\,Q}}$



Blade Spring Q Factors

Measured blade spring Q factors in KAGRA are about two orders of magnitude lower than the design value of 1.4×10^6.

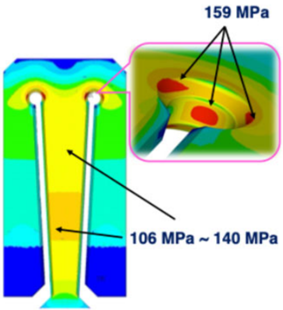


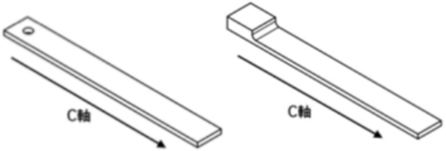
Measured Q factors in KAGRA ($\times 10^4$)

	Pitch	Vertical	Roll
EX	0.96	0.63	0.86
EY	1.8	0.59	2.9
IX	0.98	0.5	0.17
IY	1.8	0.47	3.3

To Decrease Thermal Noise from Blades

- Stress concentration occurs at the through-holes shown above.
- The holes are difficult to polish and retain rough as-drilled surfaces.
  →Excess loss at these holes
  is suspected.
- Alternative designs shown below are being investigated.
- Reducing mis-centering is also expected to reduce this thermal noise.





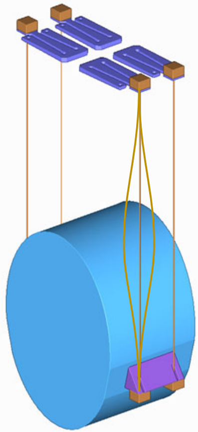
Sapphire Fiber Q factor

Measured fiber Q factors in KAGRA are about two orders of magnitude lower than the design value of 5×10^6.

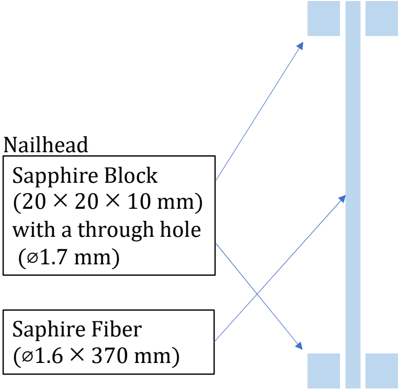
Measured Q factors of 1st violin modes in KAGRA ($\times 10^5$)

TM	Q
EX	1.57
	1.02
EY	0.98
	0.90
IX	0.72
	0.84
IY	0.97
	0.88

1st violin mode



Possible Sources of Fiber Q degradation



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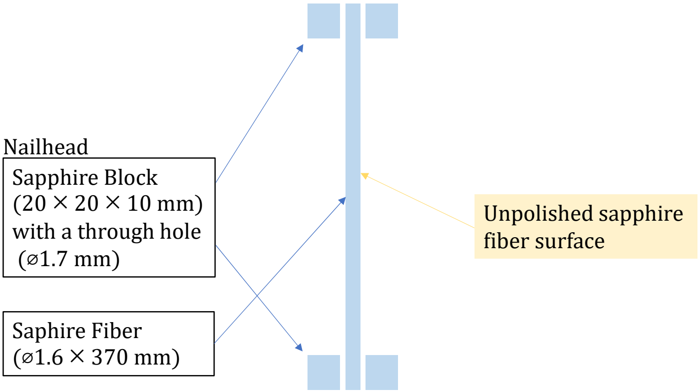
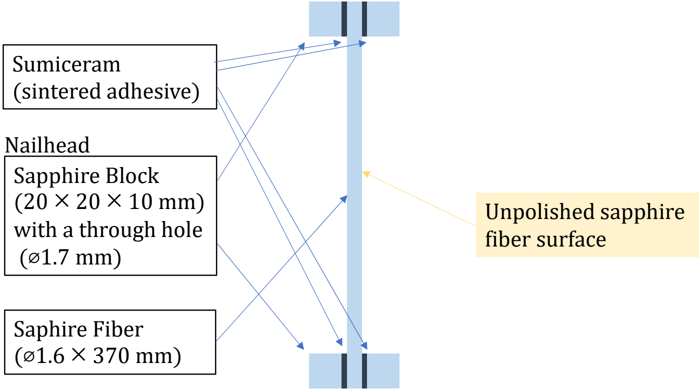
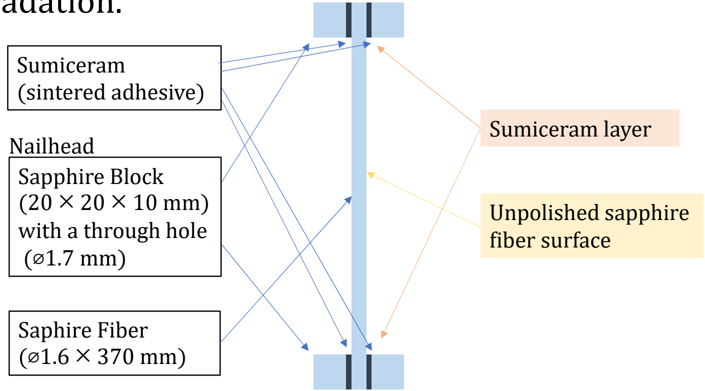


Possible Sources of Fiber Q degradation



Possible Sources of Fiber Q degradation

The Sumiceram layer and unpolished fiber surface may contribute to Q degradation.



Improve the Q Factor of the Fibers

- Reduction of Sumiceram layer loss
  - Monolithic sapphire fiber with nailheads → Crystal growth
  - Alternative fixing methods → Laser welding
  - Modification of Sumiceram → Heat treatment
  - Thinning of the Sumiceram layer → Changing through-hole size
- Reduction of surface loss
  - Polishing → Laser polishing

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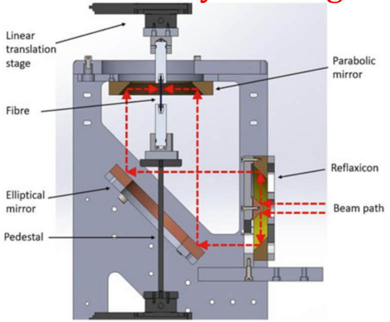
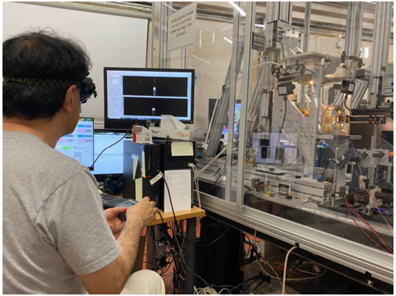
The highlighted items indicate the topics addressed in this study.
Details of these topics will be presented in the following section.

Current Status of This Research

Laser Welding

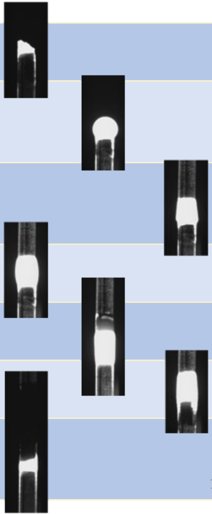
- The University of Glasgow has developed a sapphire fiber welding system using a CO_2 laser.
- In collaboration with the University of Glasgow, application to KAGRA fibers is currently under investigation.
- Welding between a sapphire rod and a nail head was attempted, but was found to be challenging.
- Instead, welding between sapphire fibers used in KAGRA has been carried out, and evaluation of the fabricated samples is ongoing.





Welding Sequence

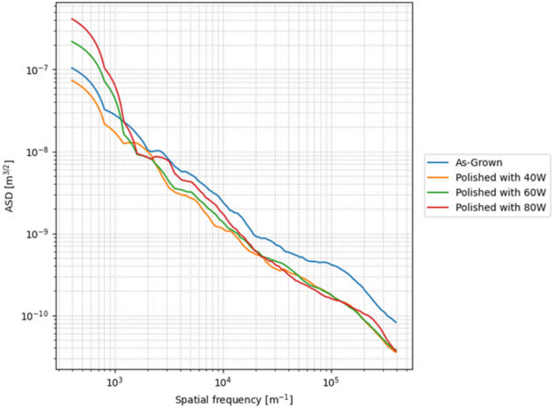
Heat the tip of the lower fiber
Increase the laser power to melt the tip and form a spherical end
Lower the upper fiber and make contact with the molten end
Increase the laser power
Slowly move the heating spot downward
Slowly move the heating spot upward
While moving the heating spot downward, gradually decrease the laser power



Welded Sample

Laser Polishing

- Performed by slowly heating the entire fiber at low laser power using the sapphire-fiber welding setup.
- For KAGRA fibers, CO_2 laser polishing is effective in the spatial frequency range of 10^4–10^6 m^{-1}.
- Thermal phonon scattering at around 20 K : expected to be dominated by surface features in the 10^7–10^8 m^{-1} range



Q factor Measurement

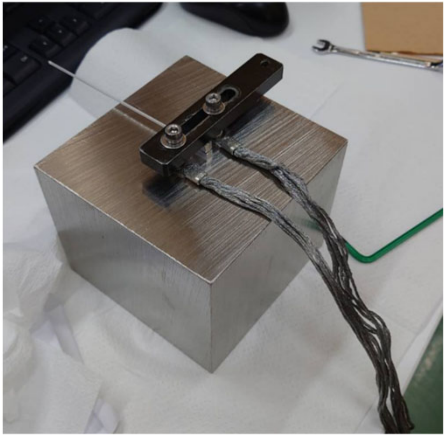
- Q factor measurements require extremely low-loss clamping.
- Possible strategies are:
  - Clamping at a nodal point

  - Perfectly Rigid support

  - Free support along the vibration direction

Rigid Support

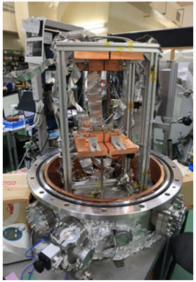
- The fiber is fixed to a large mass for measurement.
- However, high Q factors have not yet been obtained for KAGRA fibers with this method.



Suspended Measurement

		Pendulum Mode	Violin Mode
Fiber with nailhead bonded by Sumiceram	Shishido et al.	2.8×10^5	1.08×10^5
	SBF-1	1.15×10^5	$5.6 - 8.2 \times 10^4$
	SBF-2	7.9×10^4	$3 – 5.6 \times 10^4$
	SBF-3	1.3×10^5	$0.8 – 1.5 \times 10^5$
Φ1.6 rod	L370 mm	6.9×10^4	1.8×10^5
	L120 mm	5.1×10^5	2.1×10^6
L100 monolithic nail-head		$2.7 – 4.08 \times 10^6$	-
Impex's plasma welded No.6		5.4×10^4	-

Consistent with on-site measurement



Next Steps

- Improve the clamping method for high-precision Q-factor measurements of long/short fibers with/without nail heads.
- Experimentally evaluate methods for improving Q factors
- Improve the KAGRA suspension for O5

Summary

- KAGRA sensitivity around 100 Hz is limited by suspension thermal noise from sapphire blade springs and fibers.
- Strategies for reducing this thermal noise were introduced.
- Ongoing efforts and challenges in improving sapphire-fiber Q factors were discussed.