Compact and Manufacturable Ultrastable Optical Reference Cavities: 10^{-14} Stability in Less Than 10 mL Volume

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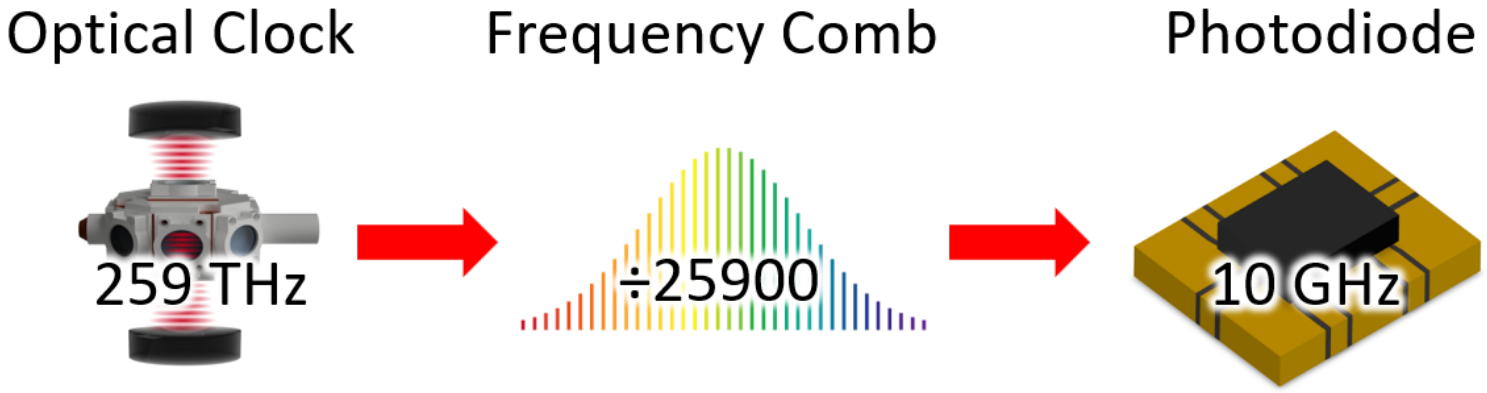
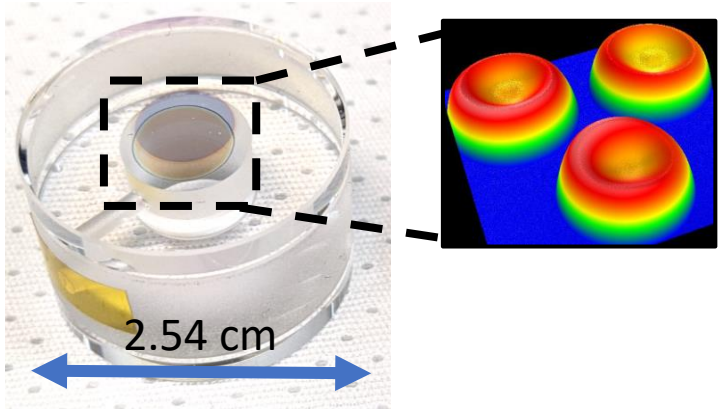
October 2023

Preview

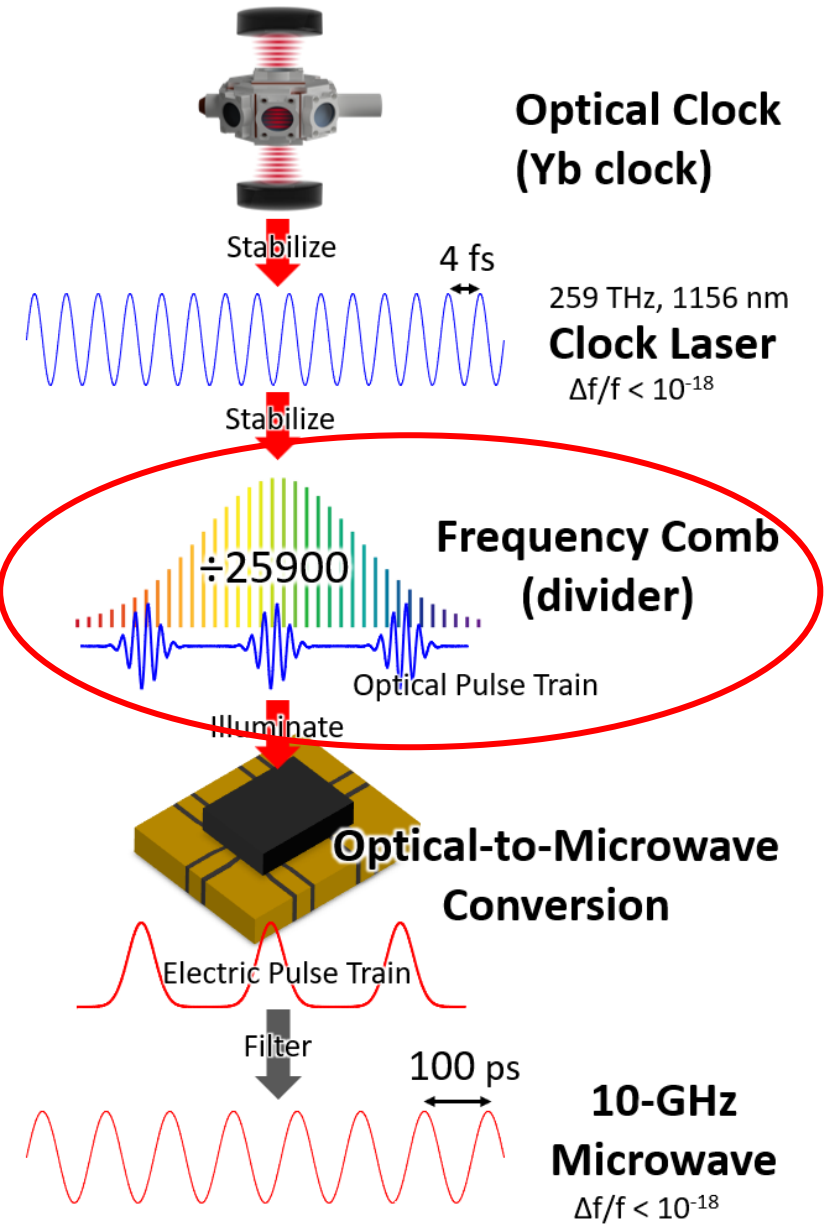
- Microwave signals with optical clock stability



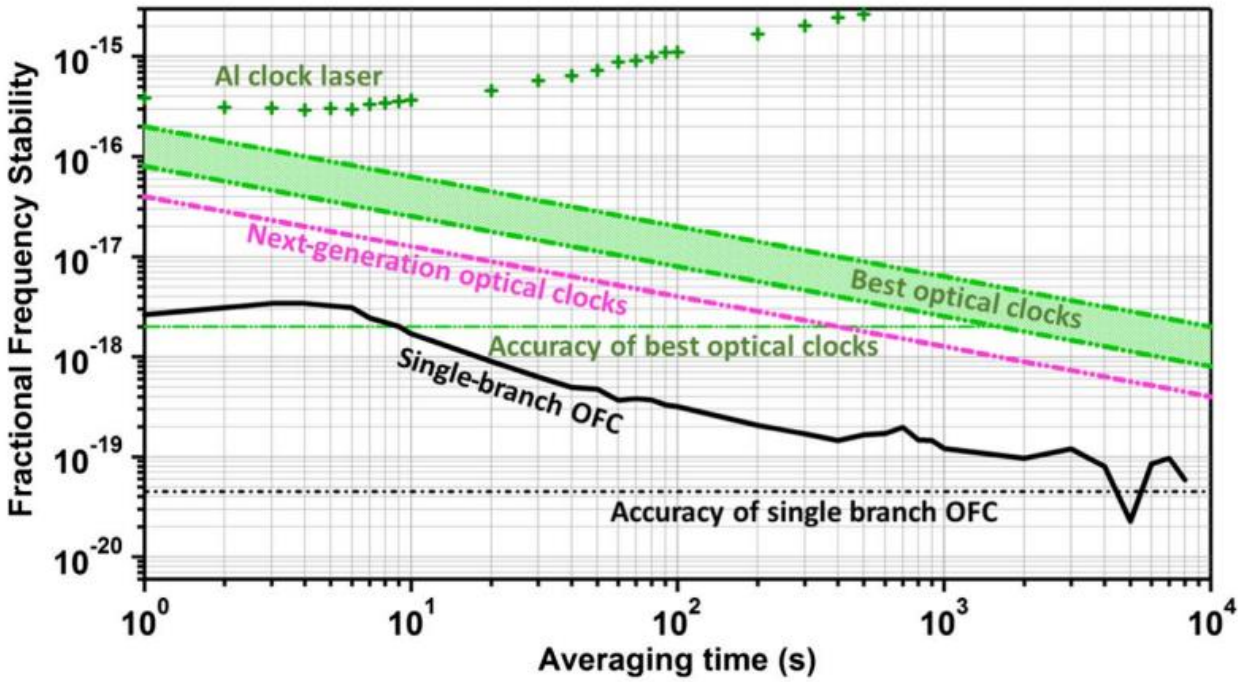
- Compact optical reference cavities



Optical clock frequency down conversion

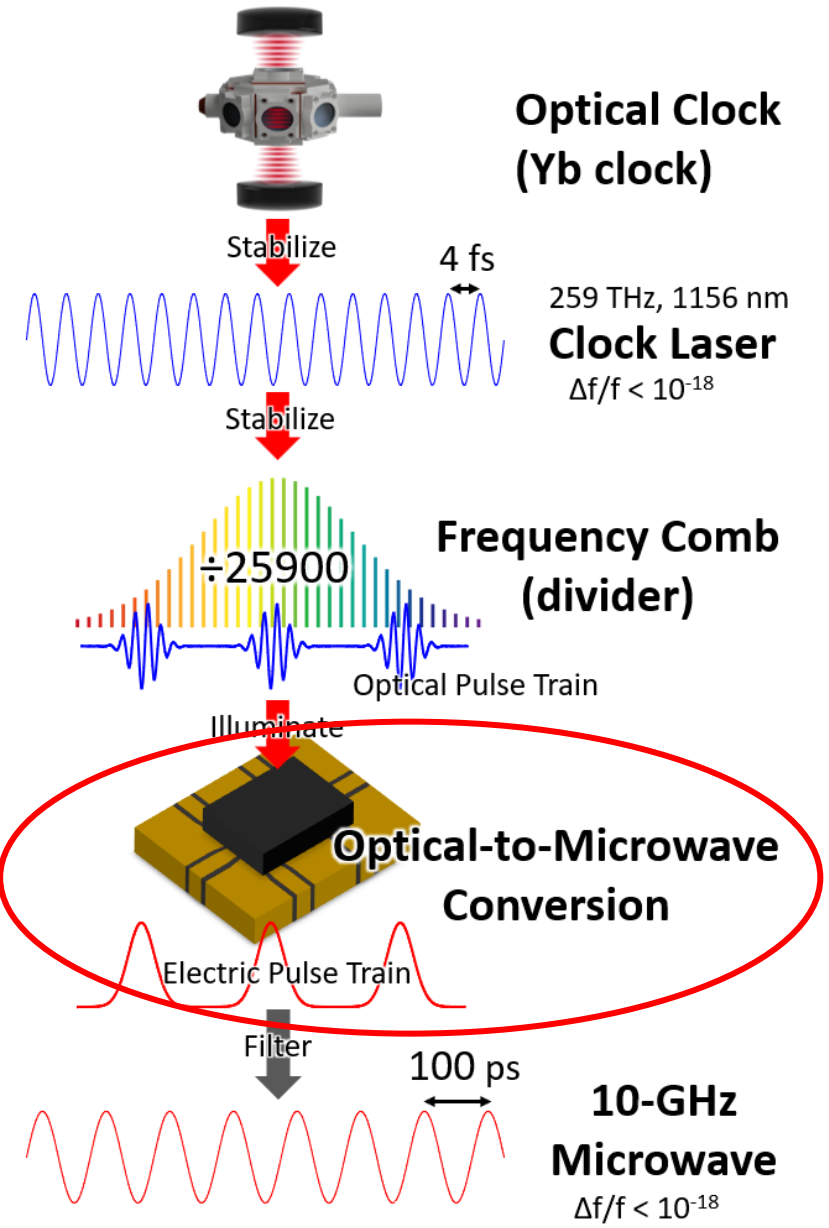


<u>Goal</u>: establish that an optical frequency comb and high-speed photodetector can support optical clock stability (10^{-18}) stability on a 10 GHz carrier



Leopardi et al, Optica **4** p. 879 (2017)

Optical clock frequency down conversion



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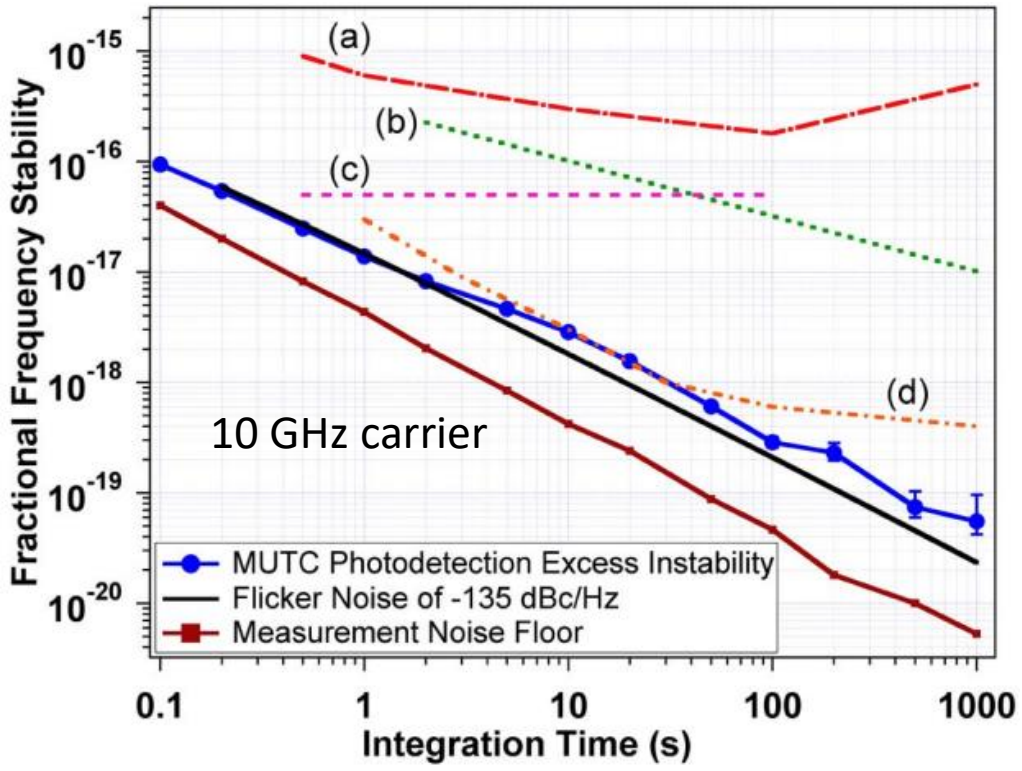
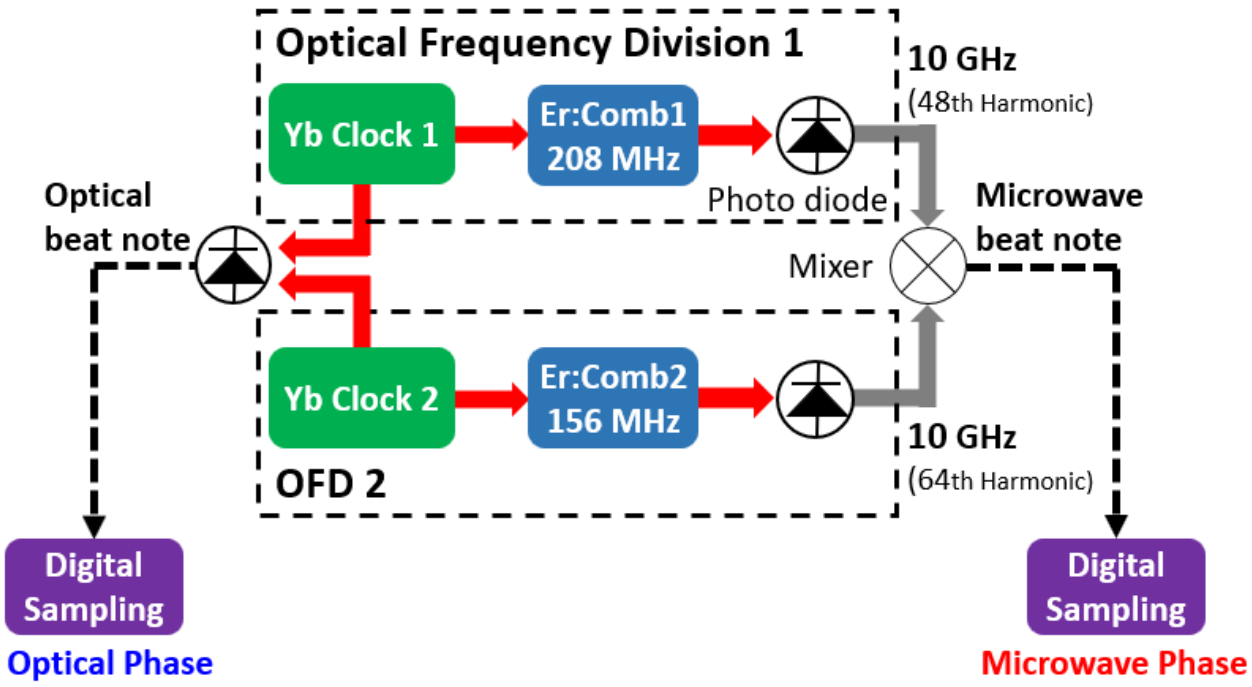
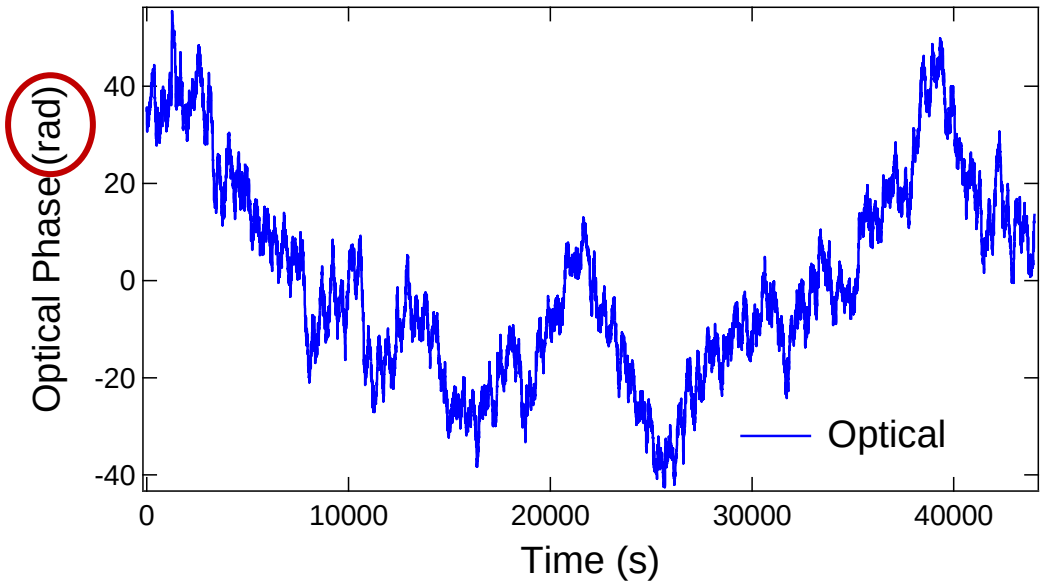


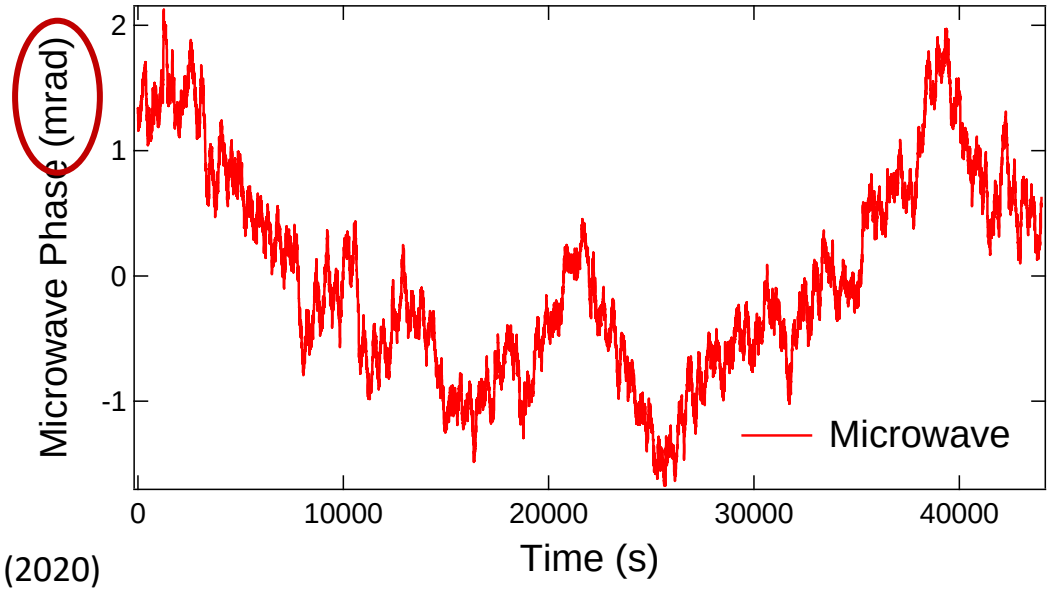
Baynes et al, Optica **2** p. 141 (2015)

Phase coherent down-conversion

Optical clock signals provided by A. Ludlow & team







Highly correlated phase records

Scaling should be given by (259 THz/10 GHz)

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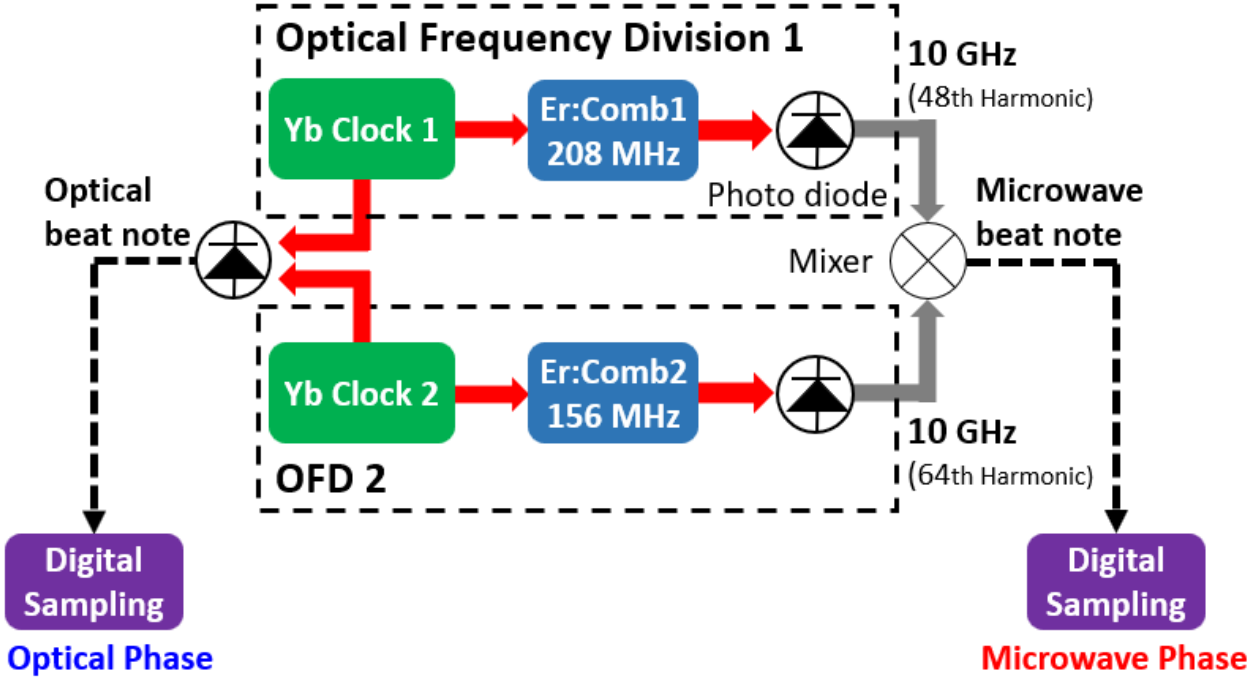
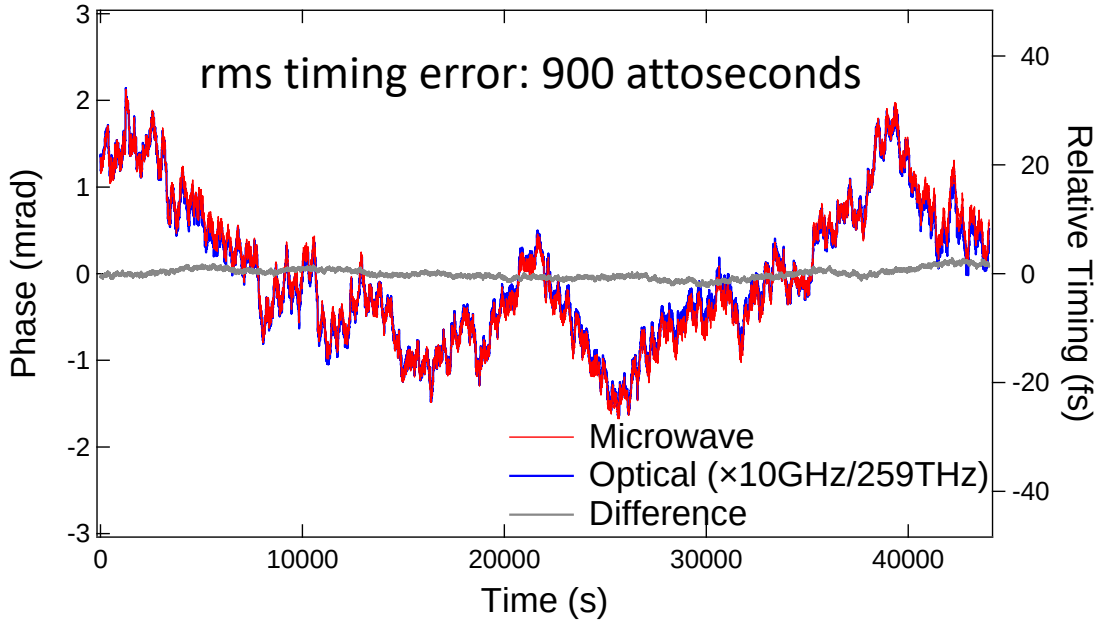
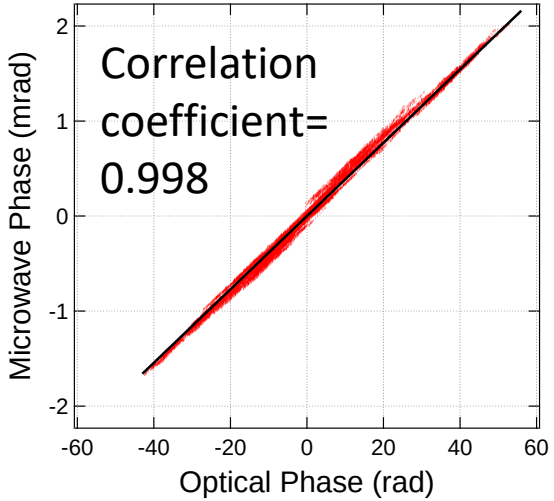
T. Nakamura et al, Science **368**, p. 889 (2020)

Phase coherent down-conversion







Highly correlated phase records

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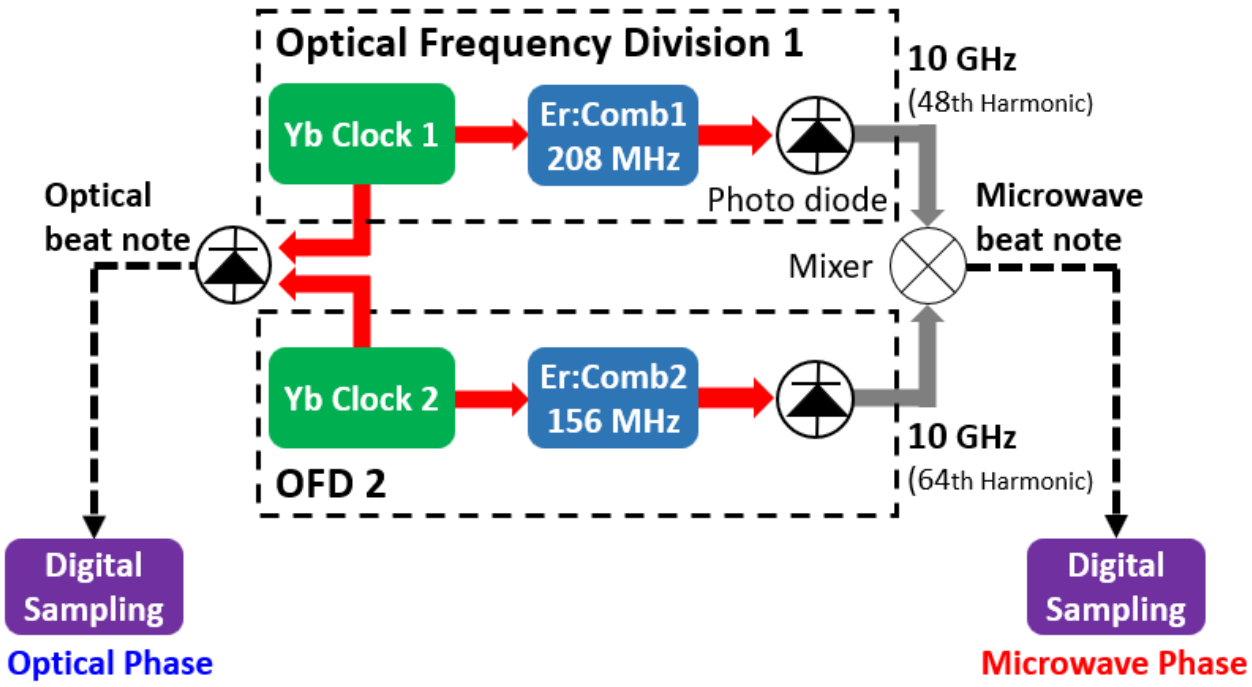
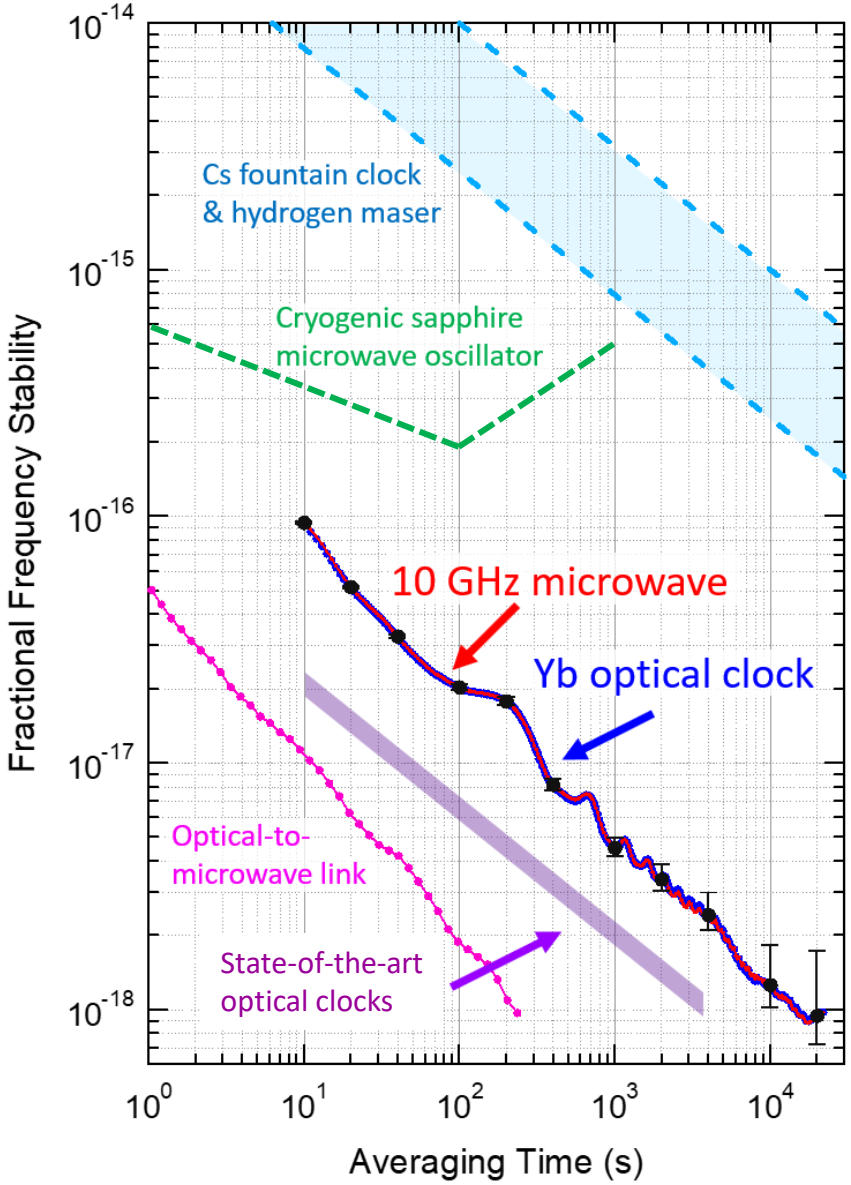
Frequency down-conversion





Optical-to-microwave frequency ratio:
OFD1: 25912.2626487667098(25)
OFD2: 25915.8720255287493985(25)

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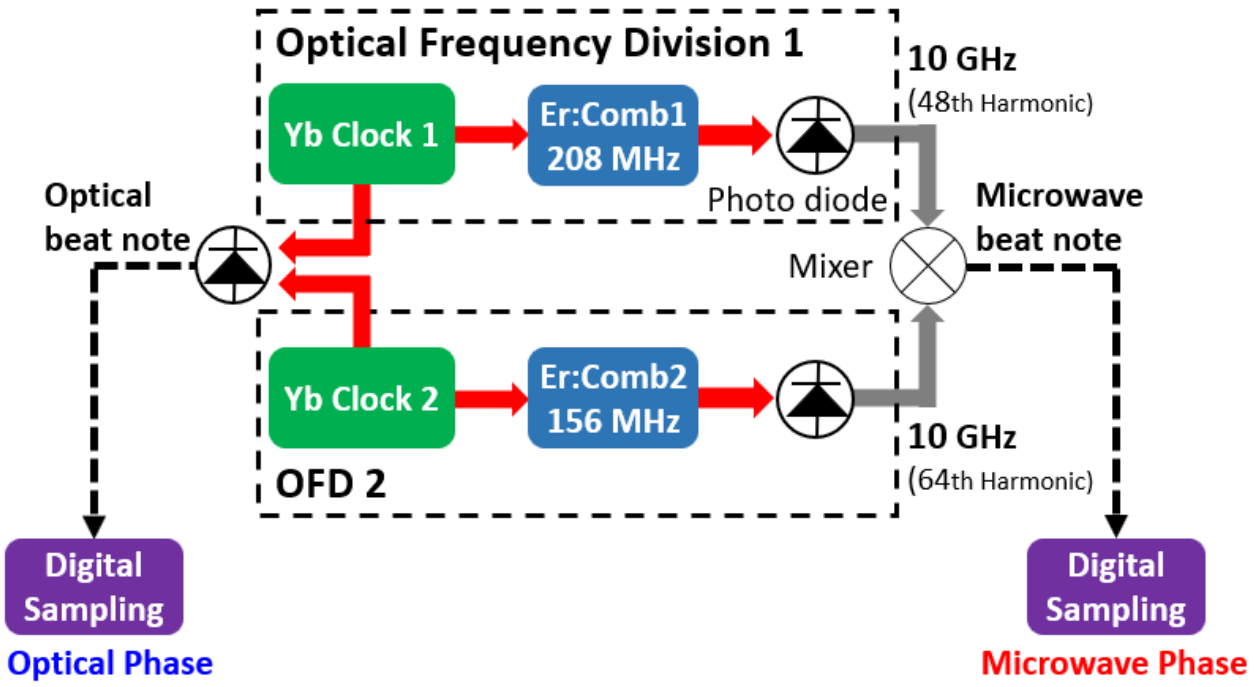
T. Nakamura et al, Science **368**, p. 889 (2020)

Accuracy of optical-to-microwave conversion



Parameters	Values
Absolute frequency of Yb1 ν_{yb1} (including all AOM shifts)	259147886795431.25 Hz (±2.1×10^{-16})
f_{beat}	126.5 MHz
Hydrogen maser shift	1 – 6.46×10^{-13} (fractional)
Mode number of comb1 (n)	1243788
Mode number of comb2 (m)	1658615
Frequency tuning word of DDS (FTW_{DDS})	103069168
Frequency tuning word of SDR (FTW_{NCO})	59821114
difference frequency (f_m)	-12.694921924988 Hz
ν_{offset} (from Eq. 20)	-0.0152926 Hz

$$\mathrm{Yb1} - \mathrm{Yb2} = \mathrm{AOMshift} - \frac{m}{64} \times f_m \times \frac{FTW_{DDS}}{2^{32}} \times 2 \times \left(\frac{\nu_{yb1} - f_{beat}}{n}\right) \times \frac{1}{10\ MHz} - \frac{m}{64} \times \left(\left(\frac{48}{n} - \frac{64}{m}\right) - 10 \times \frac{FTW_{NCO}}{2^{32}} \times \frac{FTW_{DDS}}{2^{32}} \times \frac{2}{n}\right) \times \left(\nu_{yb} + f_{beat}\right)$$

	Optical Frequency (Yb1-Yb2)	**fractional**
Optical beat note	-0.0152862 Hz	(-5.8986±0.095)×10^{-17}
Microwave + calculation	**-0.0152926 Hz**	**(-5.9011±0.096)×10^{-17}**

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Preview

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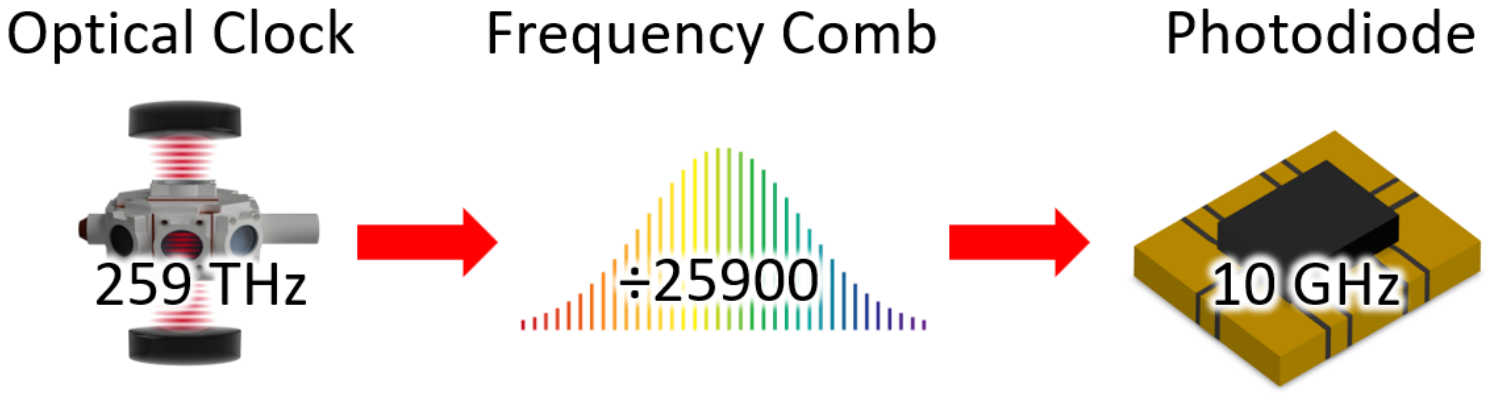
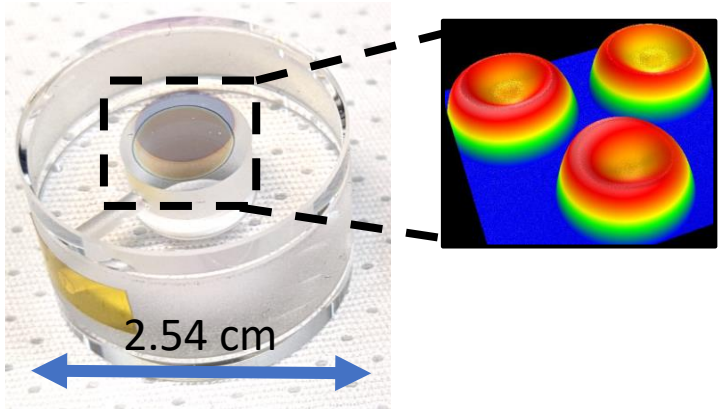
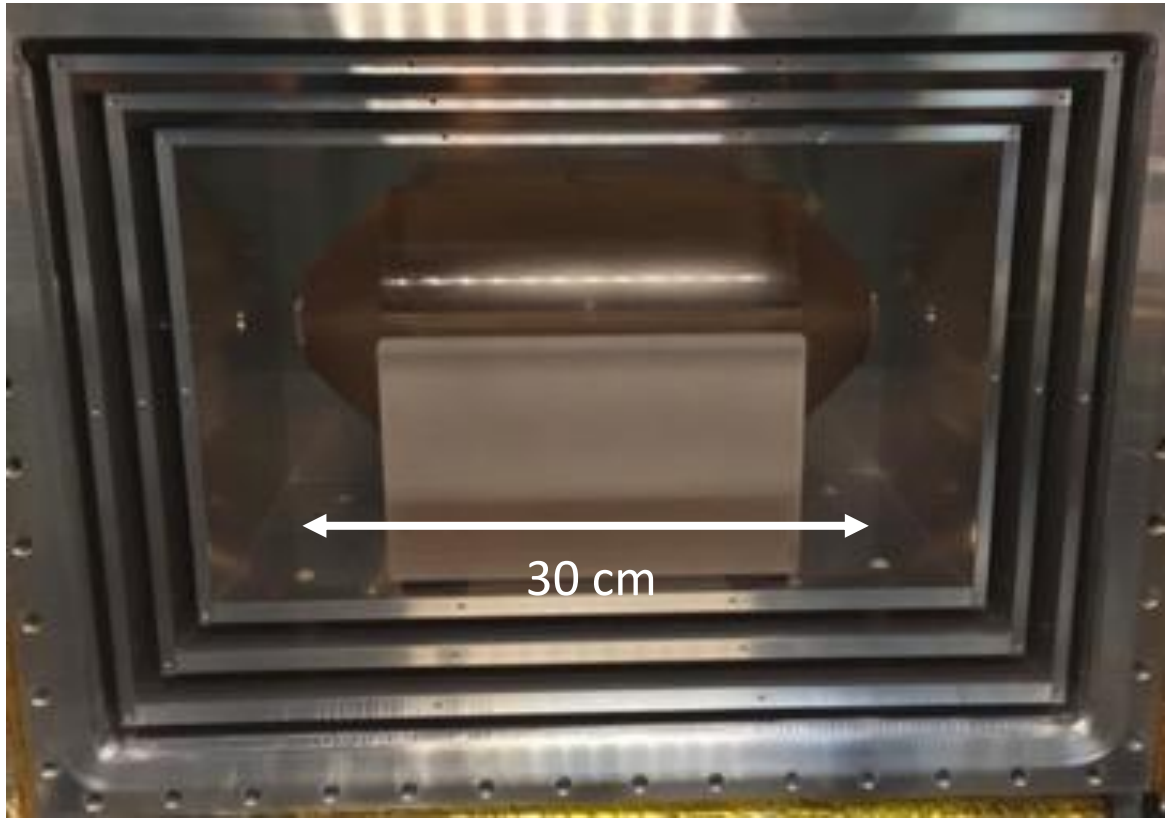


- Compact optical reference cavities



Compact optical reference cavities

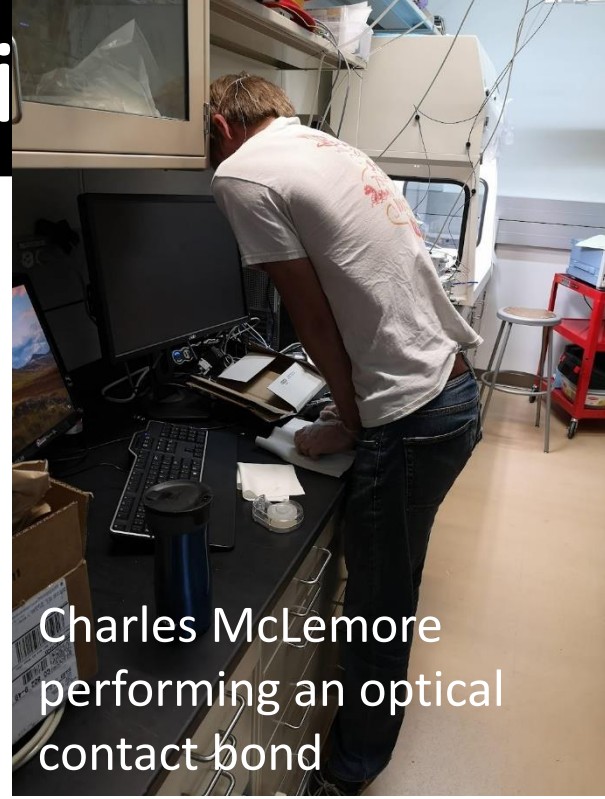
NIST Yb clock laser cavity



(to scale)

Stability ~1-2x10^{-16} at 1 second

Compact optical reference caviti



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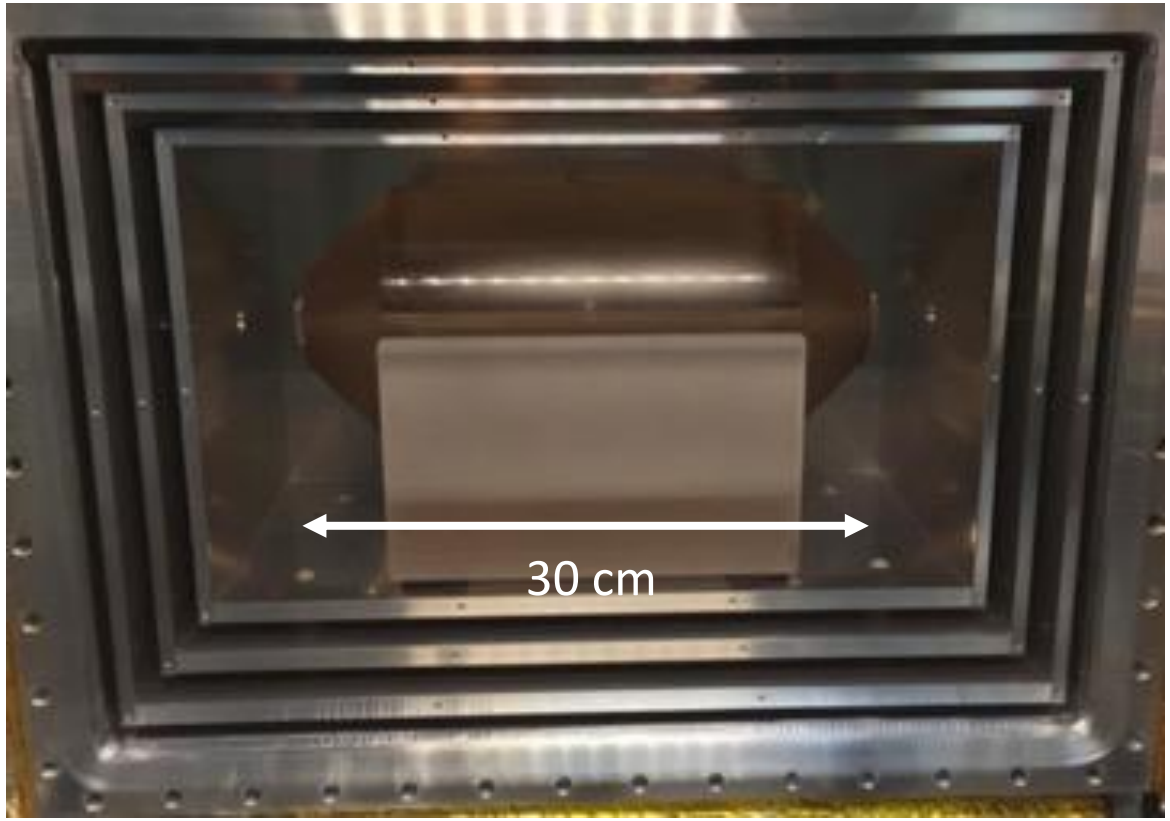
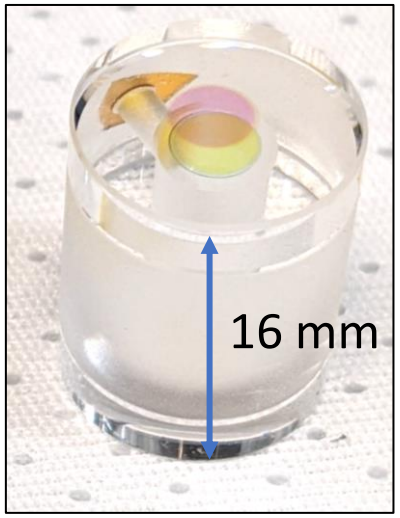


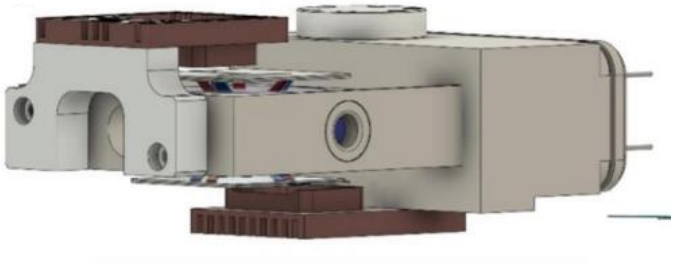


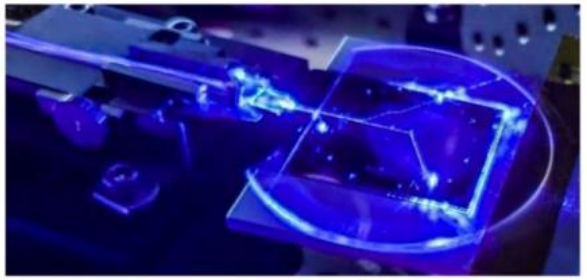
Wish list

- High finesse
- Mirrors with large radius of curvature
- Manufacturable – no more individual hand assembly
- Passive vacuum pumping – no more ion pumps
- Fractional frequency stability at 10^{-14} or better

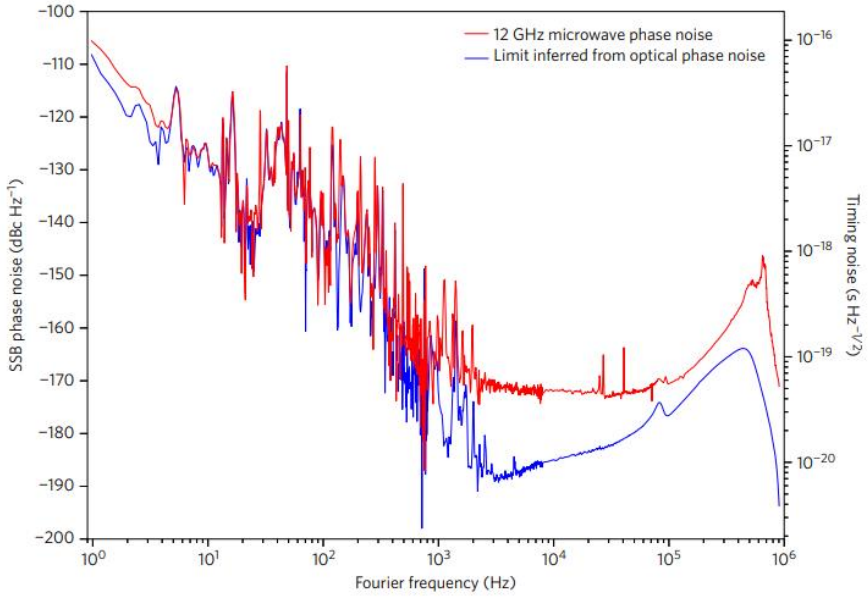
Applications of compact ultrastable cavities

Mobile optical clocks

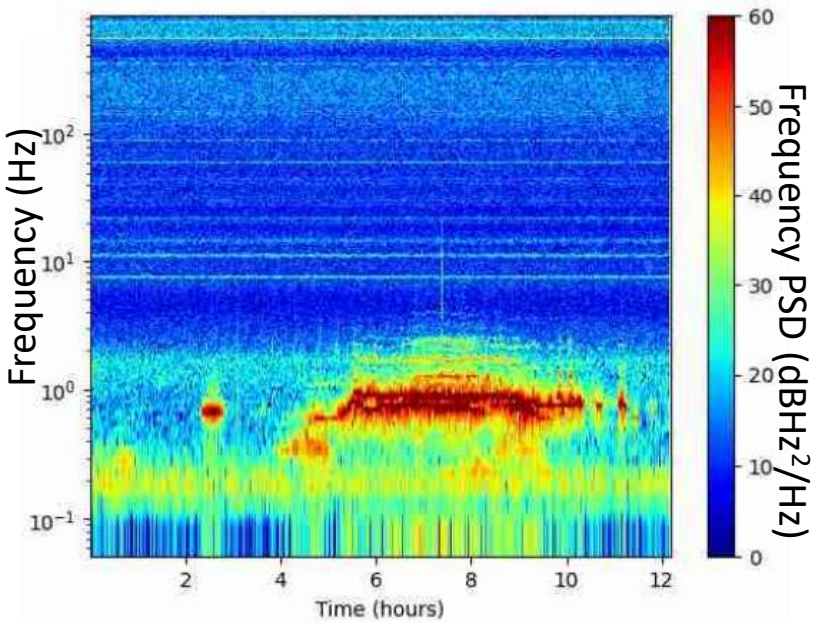




Low noise microwave generation



Environmental sensing



Jammi et al, CLEO 2022

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Fortier et al, Nat. Photon. **5** (2011)
Xie et al, Nat. Photon. **11** (2017)

Marra, et al. Science **361**, 6401 (2018)
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Mazur, et al. arXiv:2303.06528 (2023)

Applications of compact ultrastable cavities

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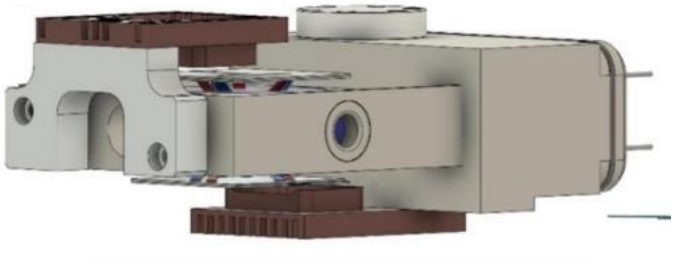

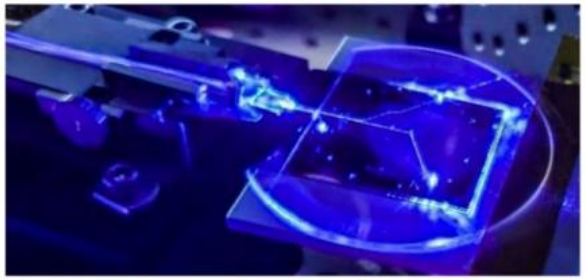

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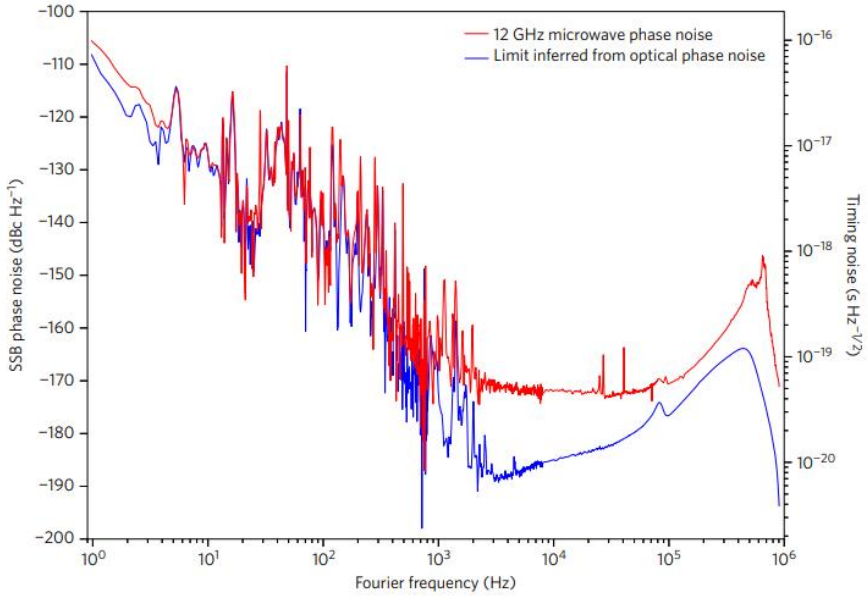

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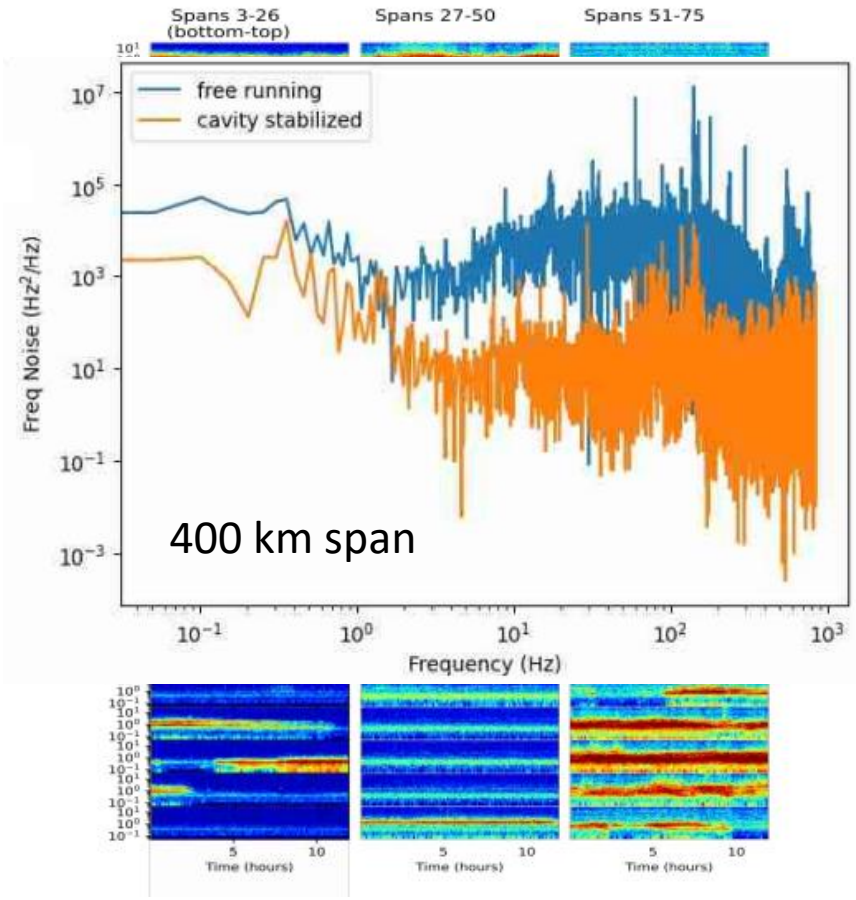

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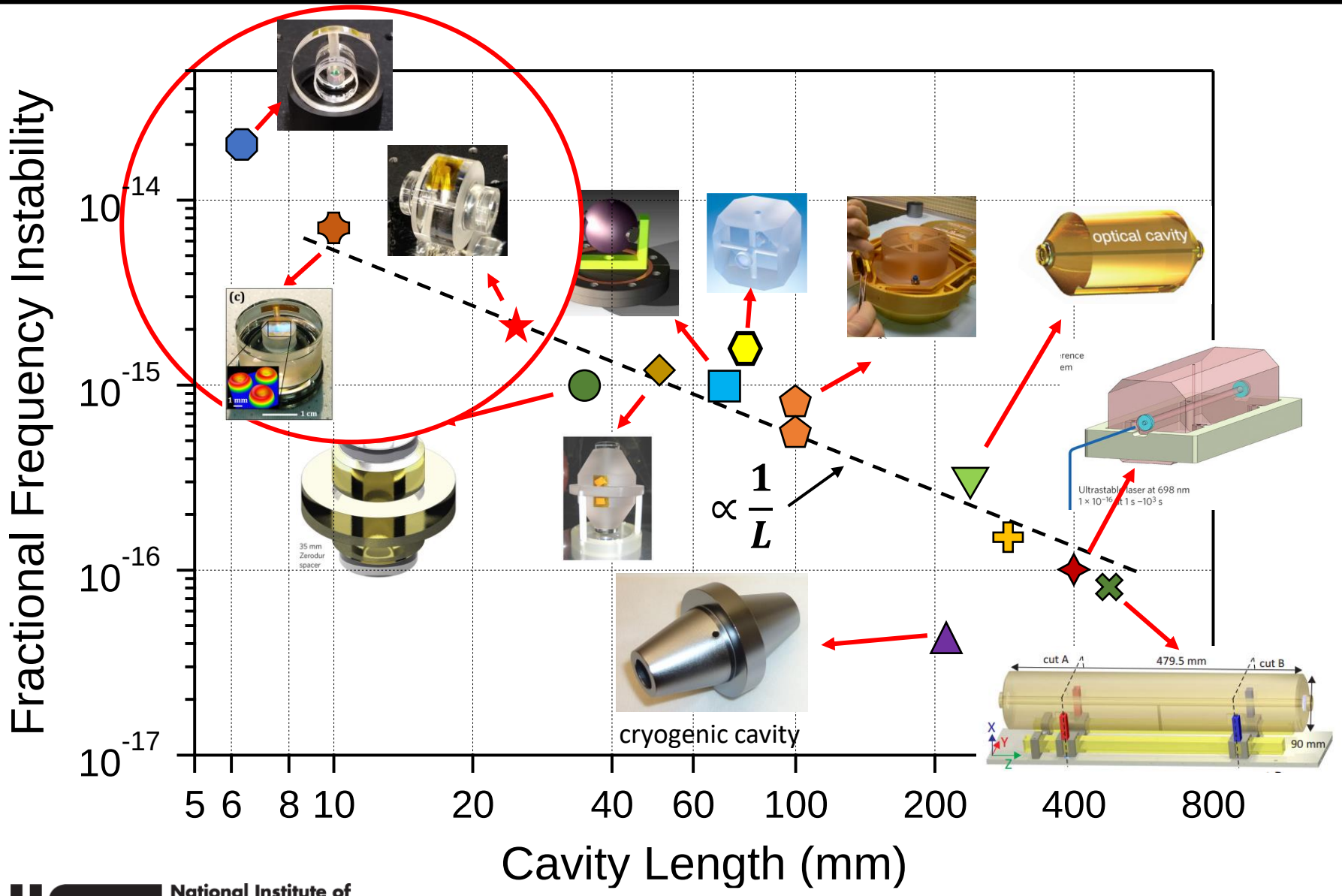
Survey of the state-of-the-art in FP stabilized lasers



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  M. Schioppo, et al., Nat. Photon. **11**, 48 (2017)
- Jun Ye's group at JILA
- S. Häfner, et al. Opt. Lett. **9**, 2112 (2015)

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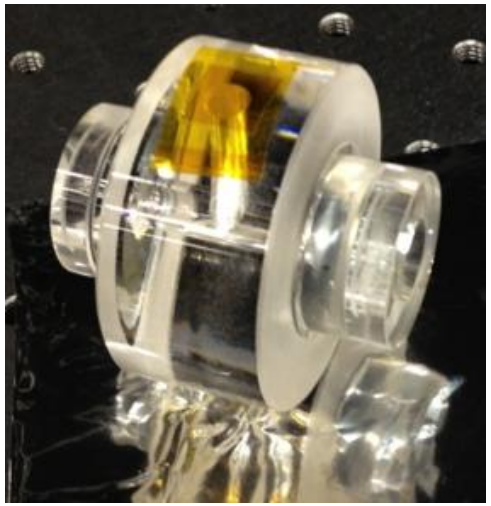
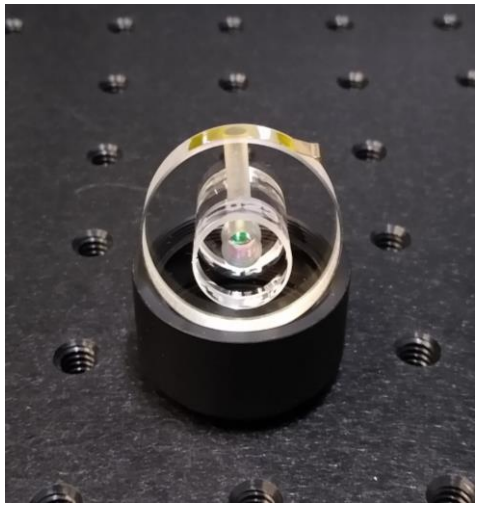
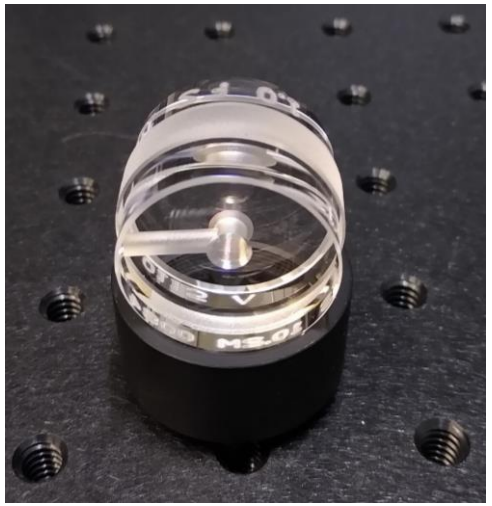
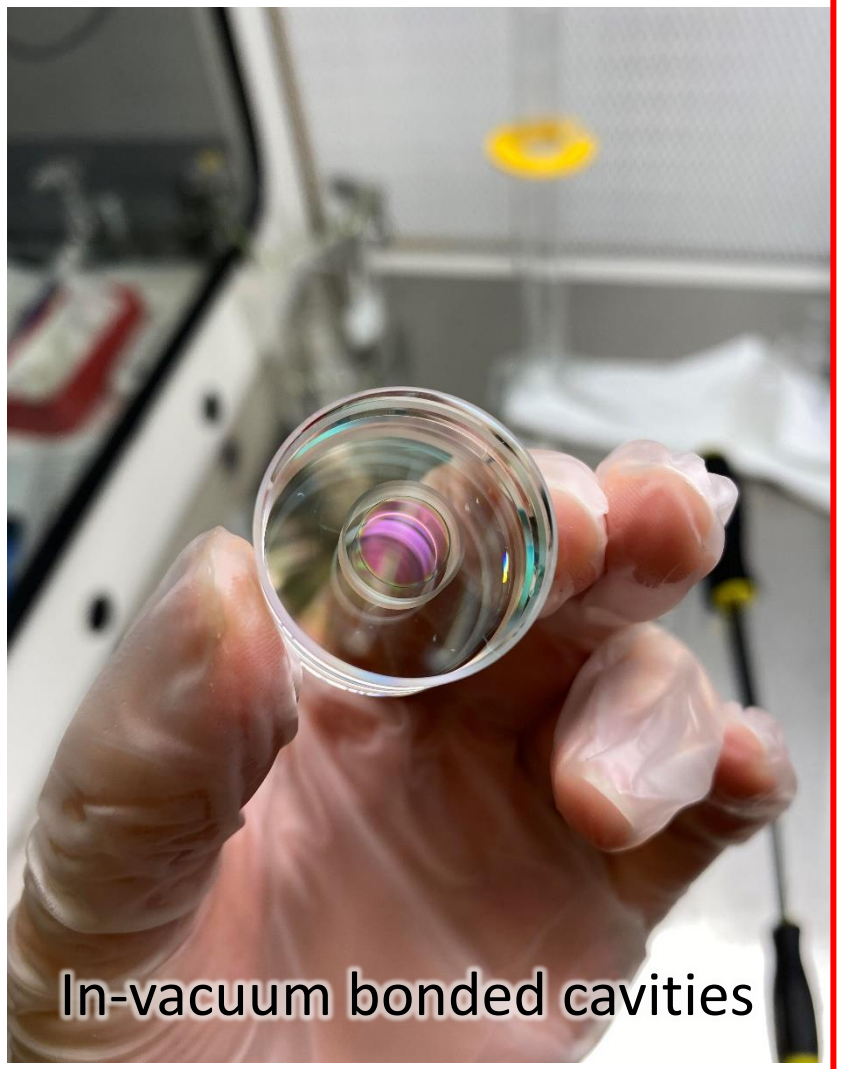
Original plot credit: J. Davila-Rodriguez

A glass menagerie



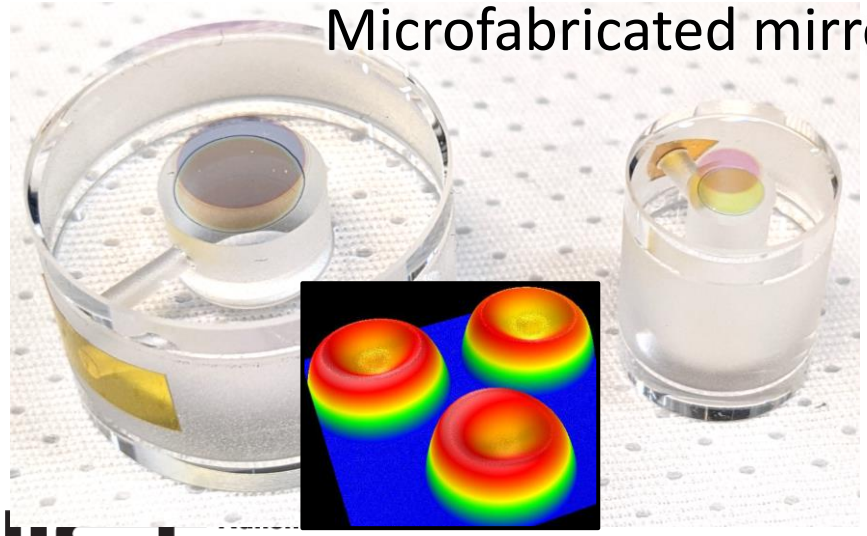


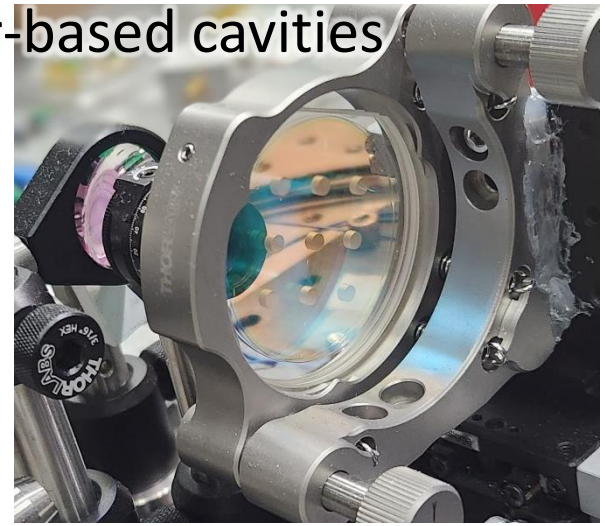




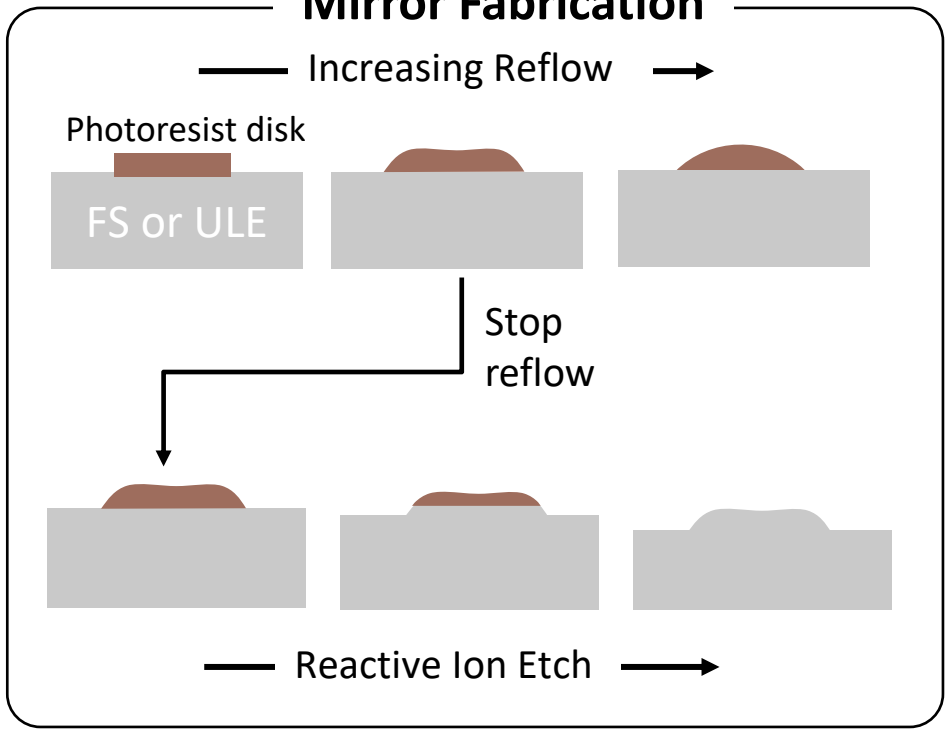
In-vacuum bonded cavities

Microfabricated mirror-based cavities



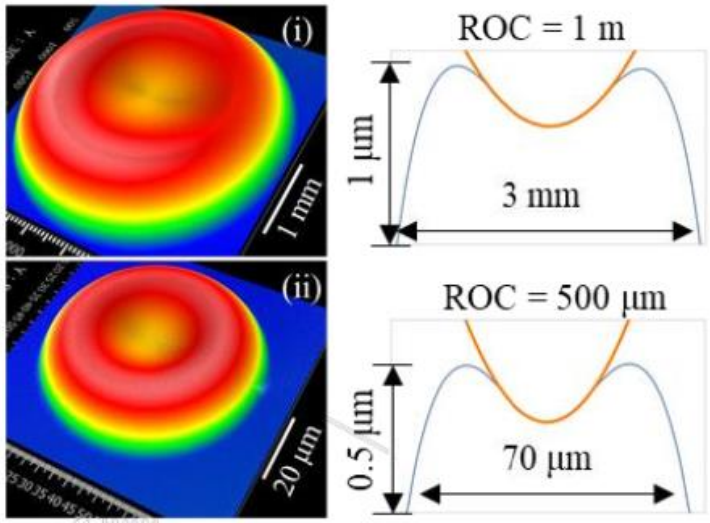


Microfabricating high finesse mirrors



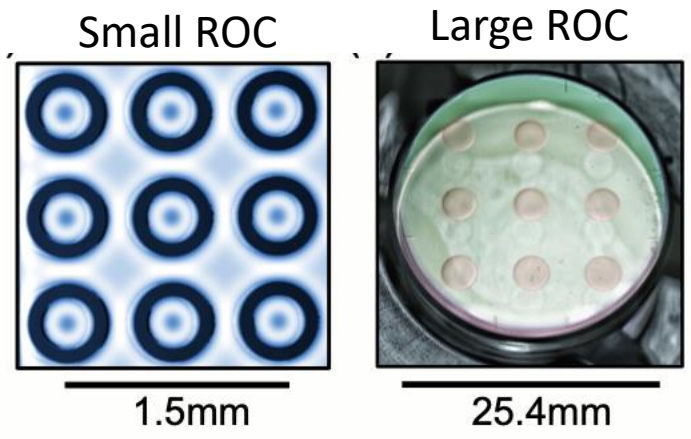
Photoresist pattern is transferred to substrate via RIE

Mirror profiles

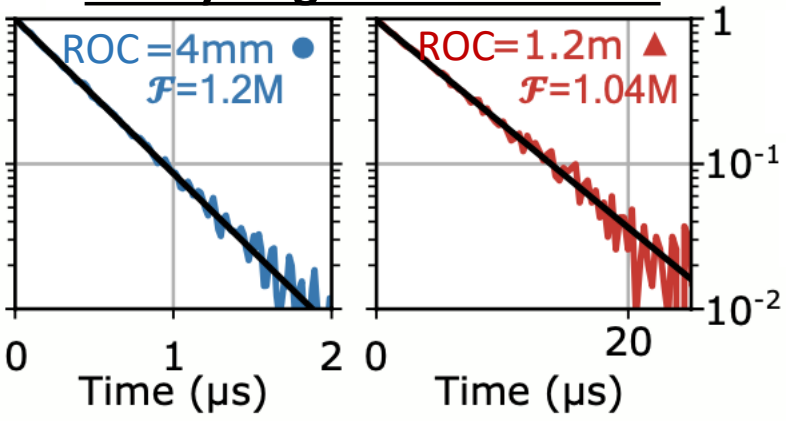


Tailorable mirror ROC and size

Mirror layout



Cavity ringdown & finesse



Mirror reflectivity > 99.9996%

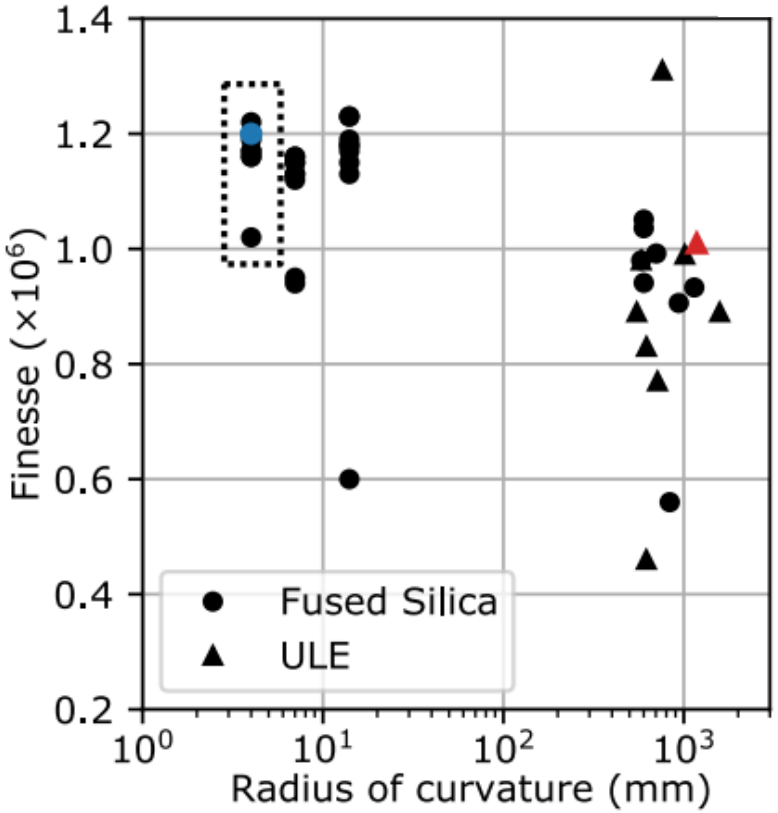
Yale

Kharel, et al., *APL Photonics*, **3**, 066101 (2018).

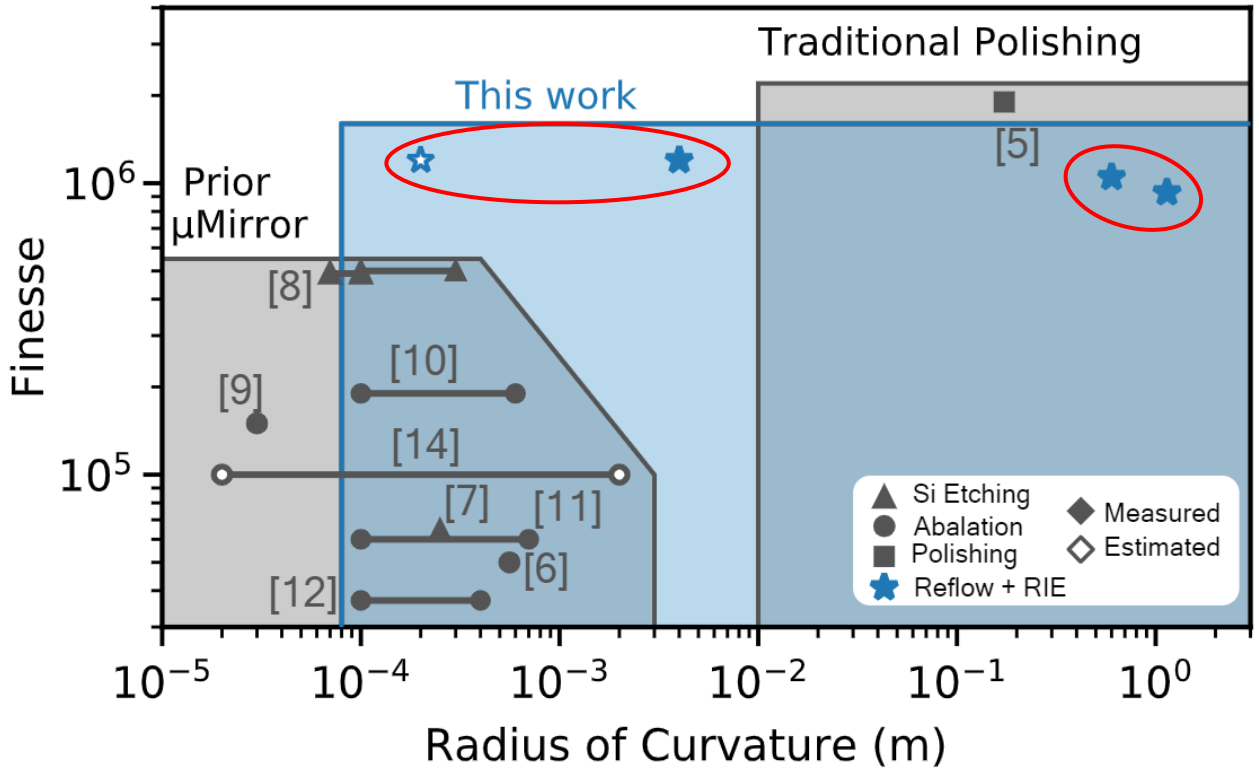
N. Jin, et al., Optica **9**, 965-970 (2022)

Million finesse micromirrors

Finesse compendium



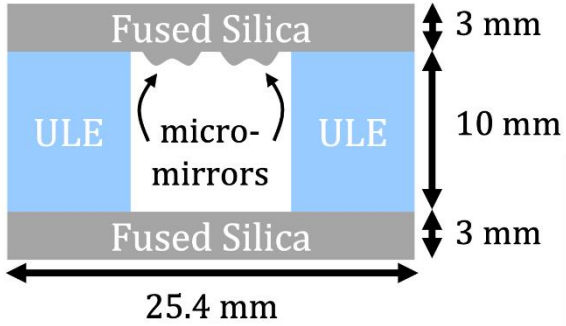
Survey of state-of-the-art mirror finesse

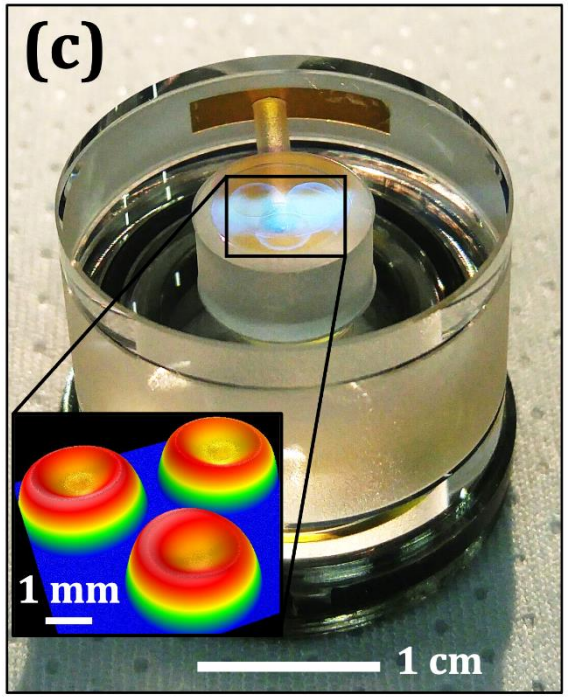


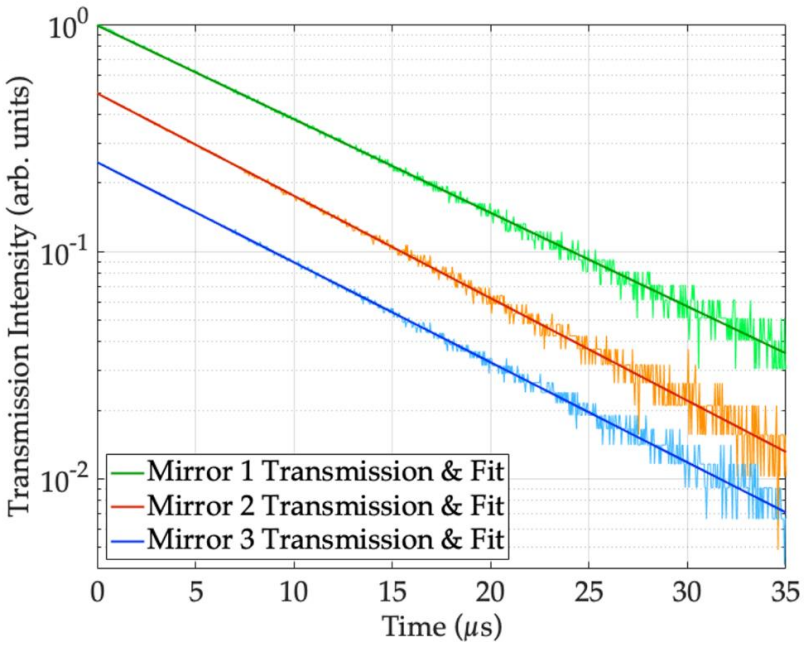
- **Demonstrated ROC covers ~4 orders of magnitude**
- **Applications range from cavity QED (small ROC) to optical clocks (large ROC)**
- **1 million-level finesse produced with high yield**

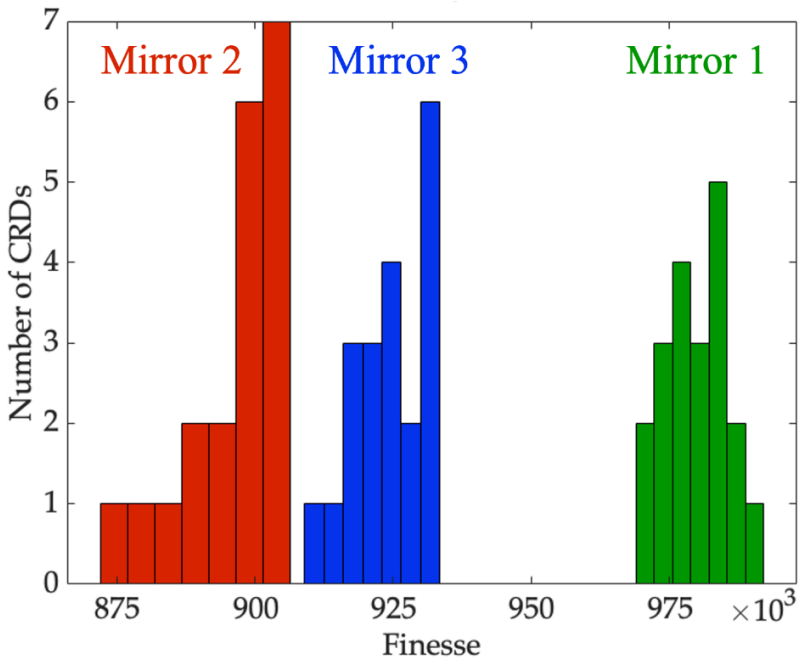
Naijun Jin, et al., Optica **9**, 965-970 (2022)

Micromirror cavities









- **Micromirrors are paired with a single flat mirror**
- **Three independent cavities in a single 8 mL volume structure**
- **Each cavity has a finesse ≥ 0.9 million**

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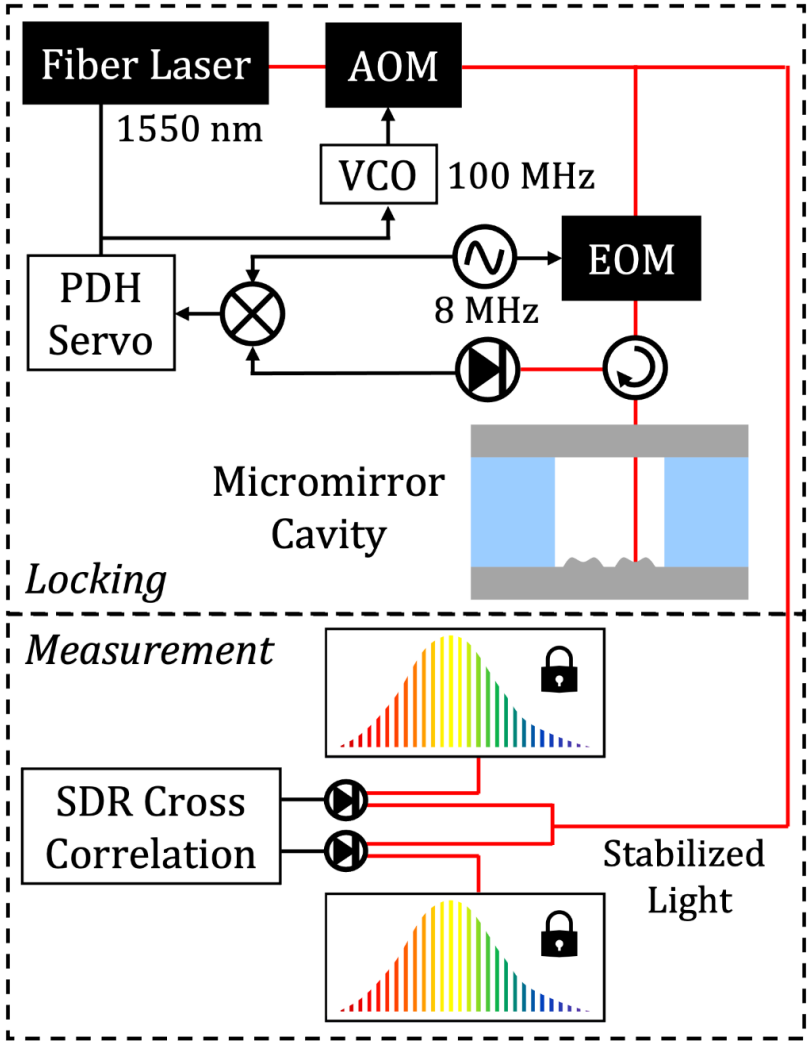
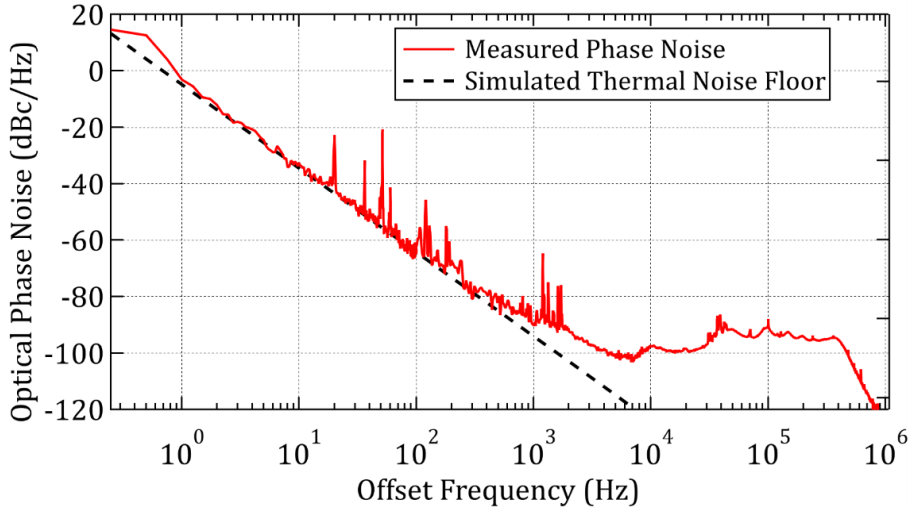
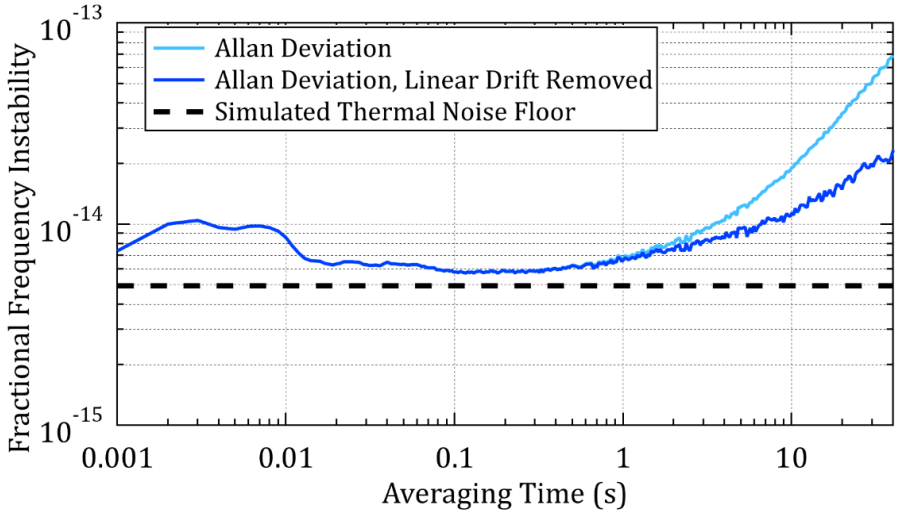
C. A. McLemore, *et al.*, Phys. Rev. Appl. **18**, 1 (2022)

Micromirror cavity phase noise and stability

measurement setup





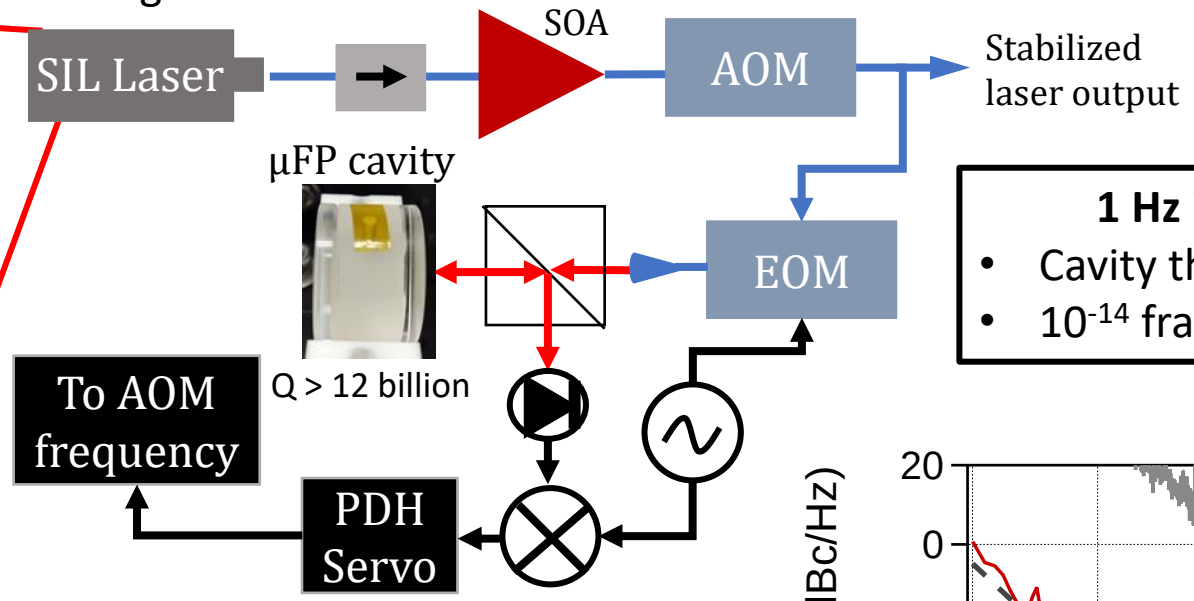


Thermal noise limited performance

Micromirror cavity + chip-scale laser

J. Guo et al, Sci. Adv. **8** (2022)

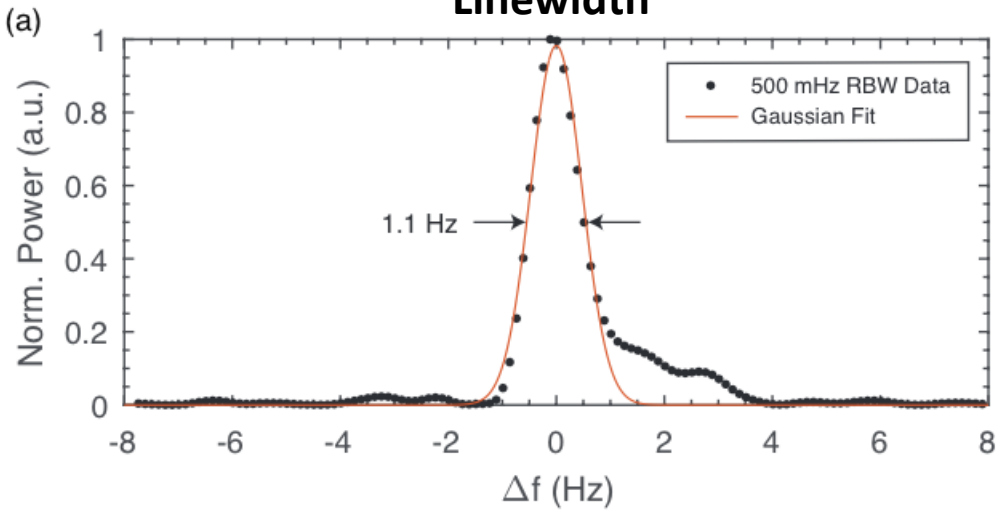
Diode laser injection-locked to SiN ring



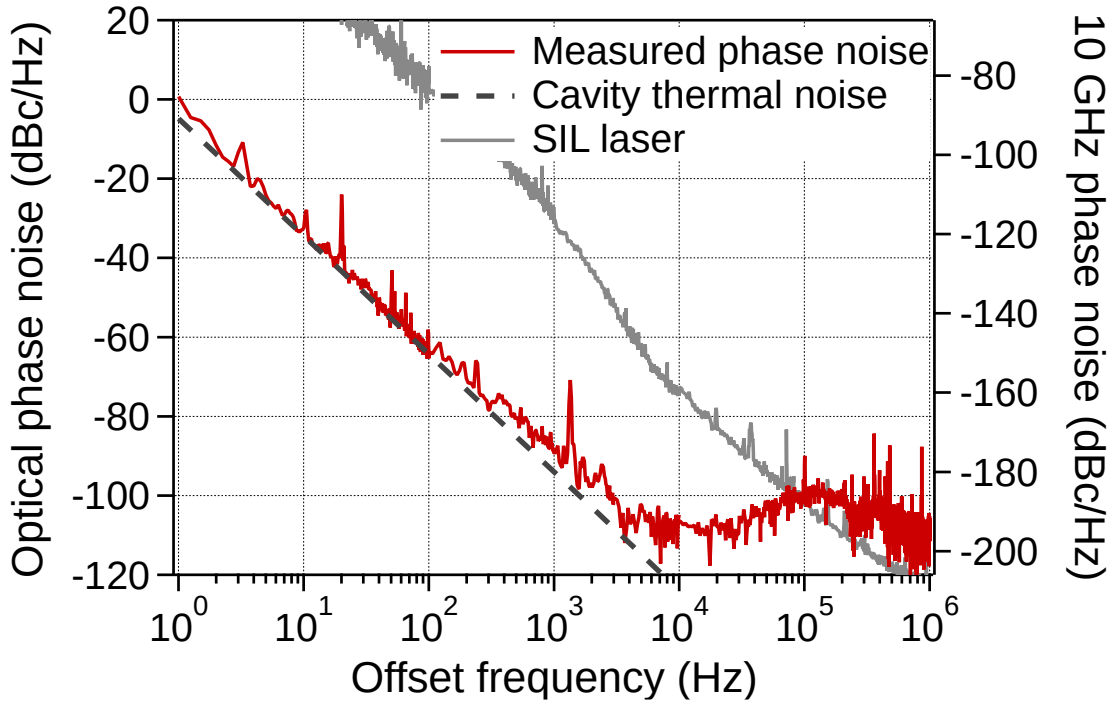
1 Hz integrated linewidth laser

- Cavity thermal noise limited to ~4 kHz
- 10^{-14} fractional frequency stability at 1 s

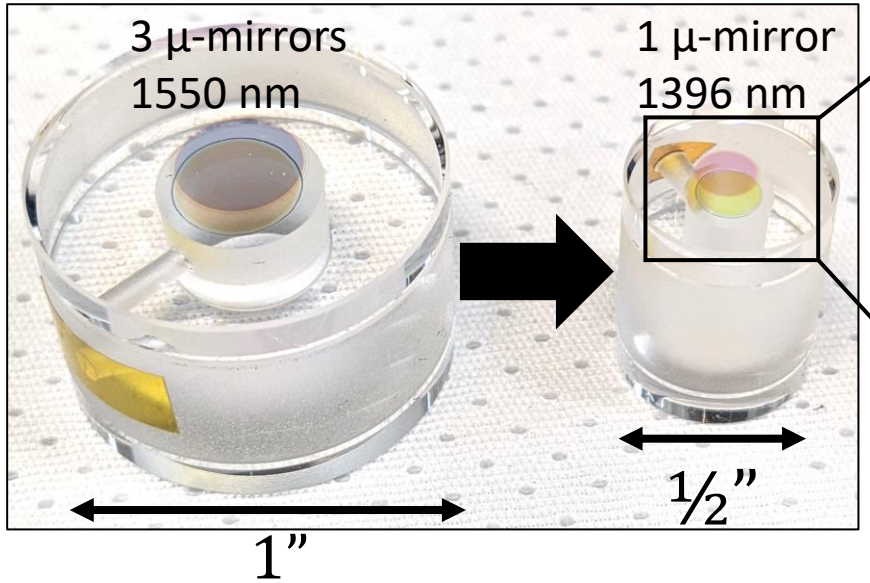
Linewidth



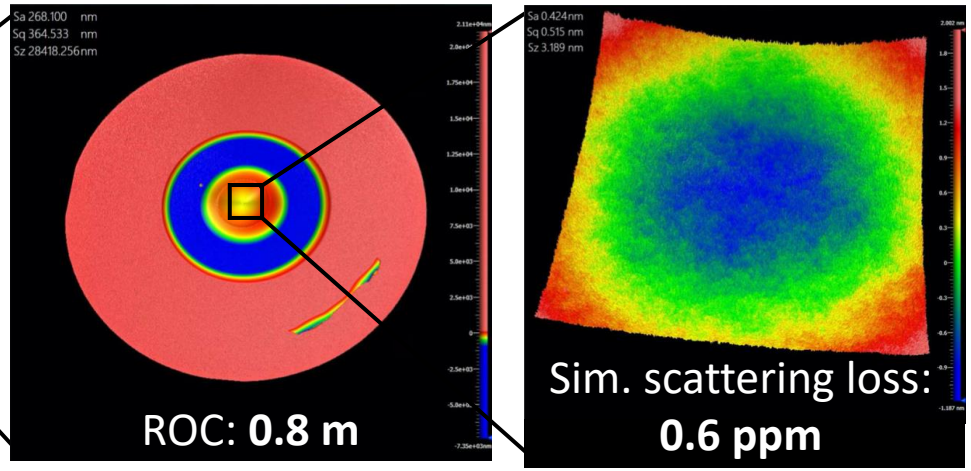
Phase noise



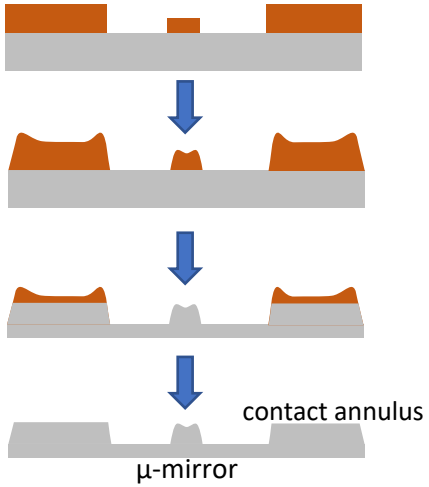
Micromirror cavities – reduction in size



Mirror profile

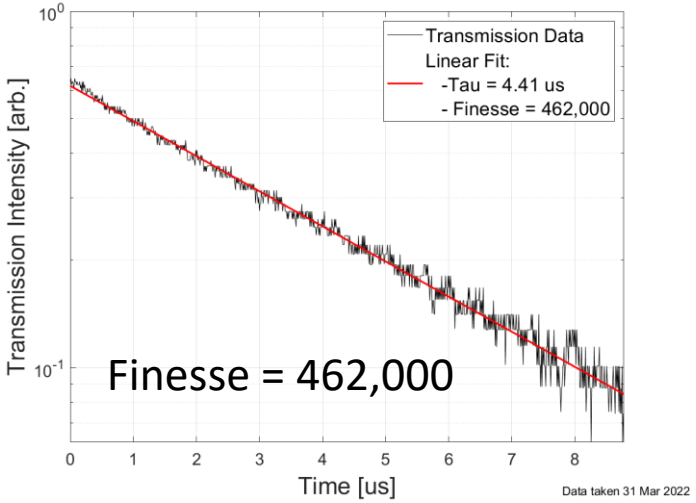


Mirror fab steps

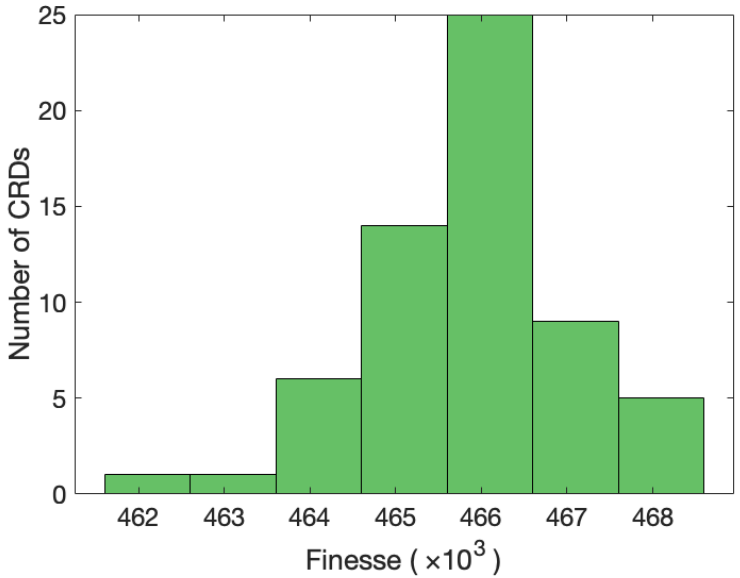


- Half-inch diameter decreases volume from 8 mL to **2 mL**
- Protected annulus on micromirror substrate guarantees reliable bond
- Finesse is sufficient to reach thermal noise limit

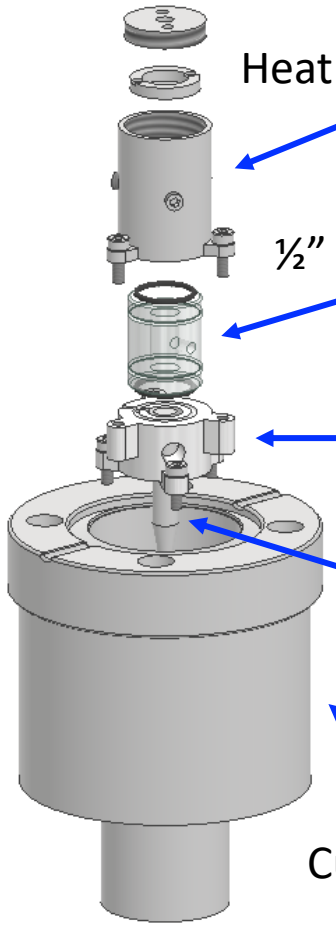
Example cavity ringdown



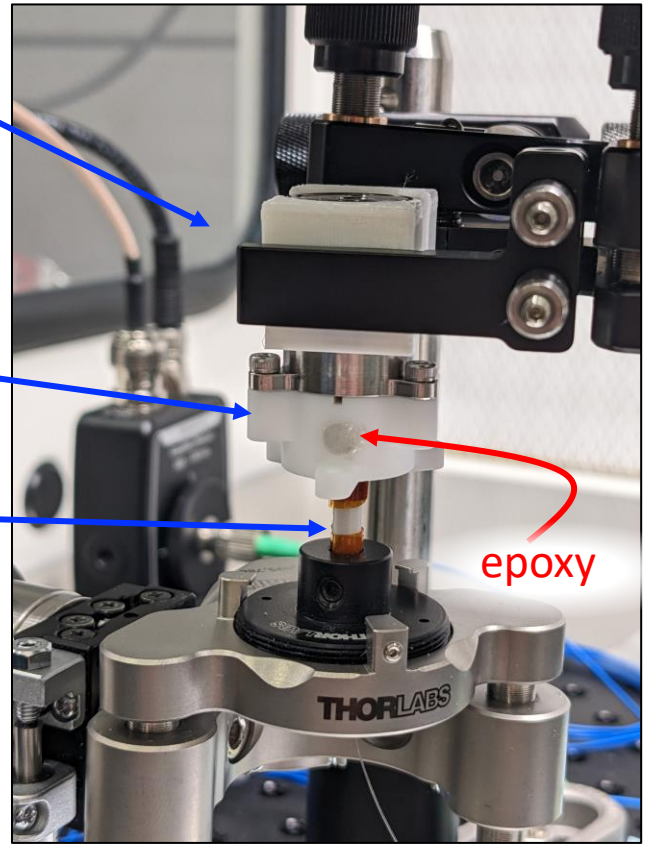
Cavity ringdown statistics



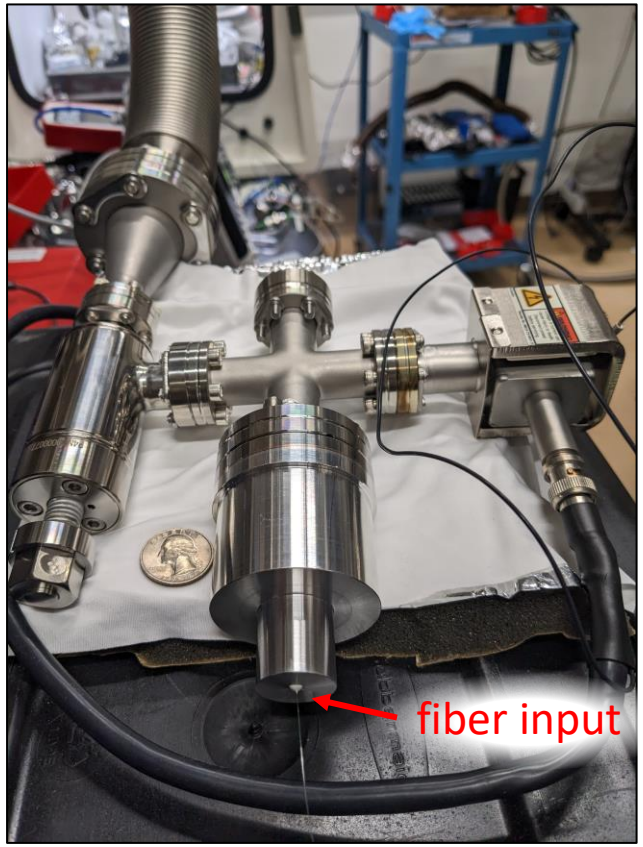
Cavity in a custom can



External Alignment Jig

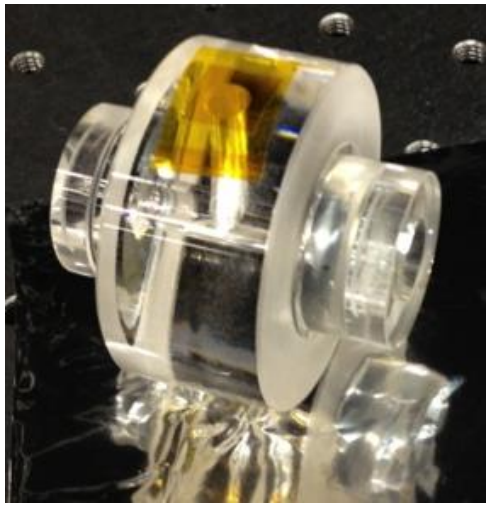


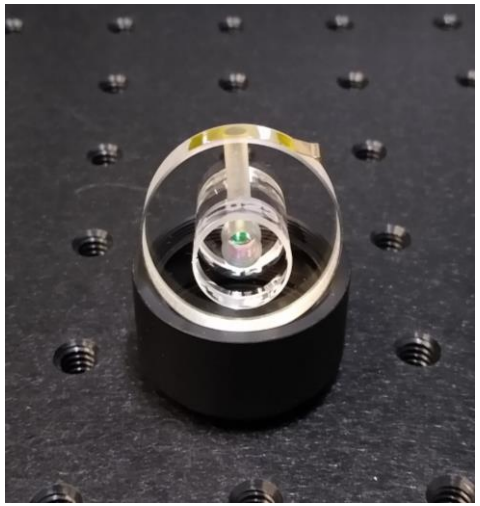
Assembled Vacuum System

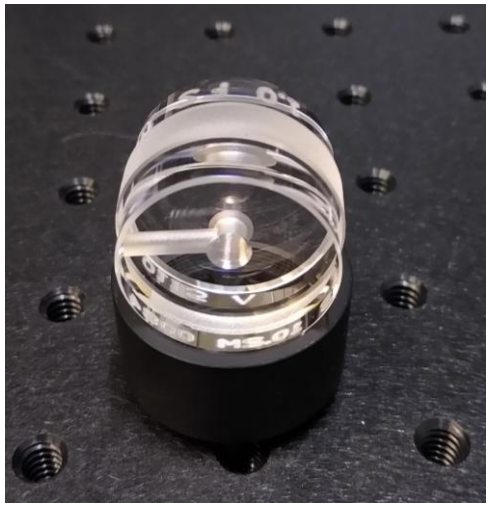


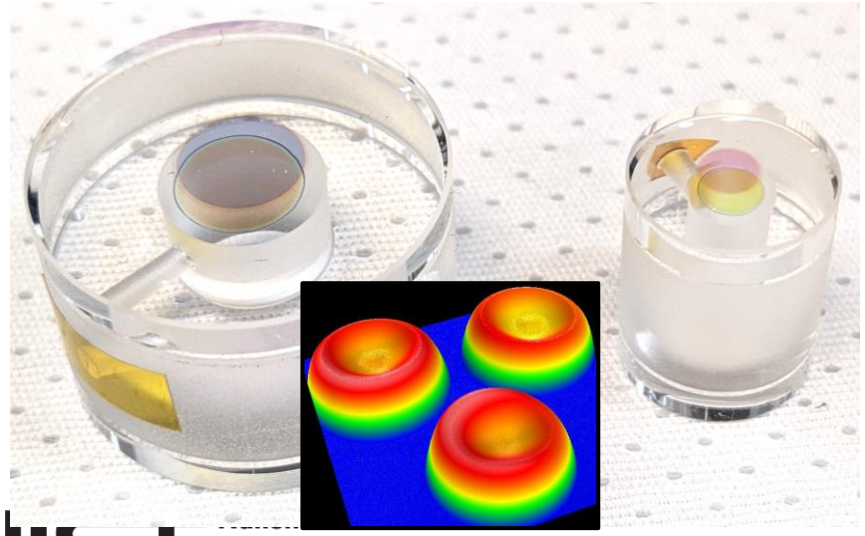
Performance currently under evaluation

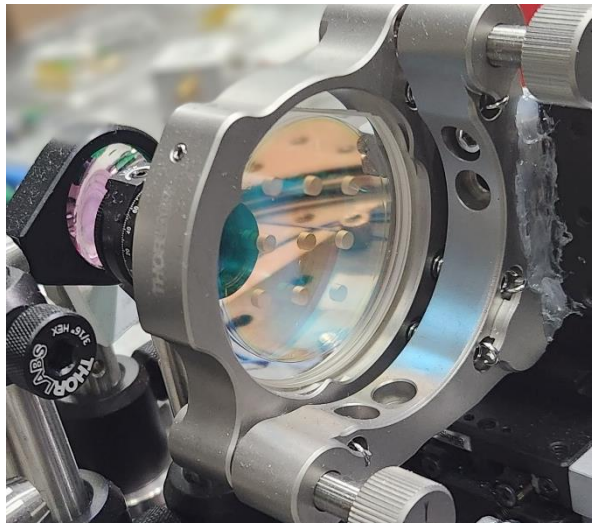
A glass menagerie

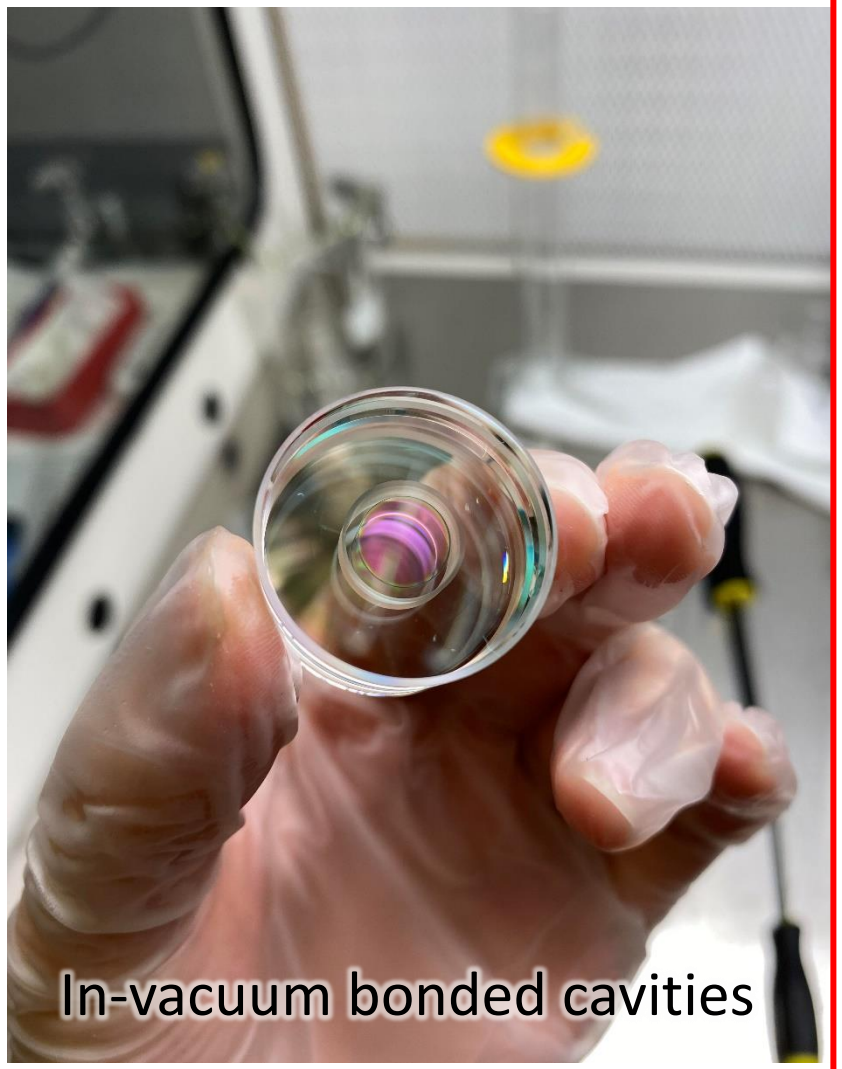






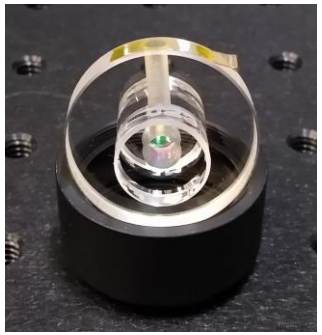






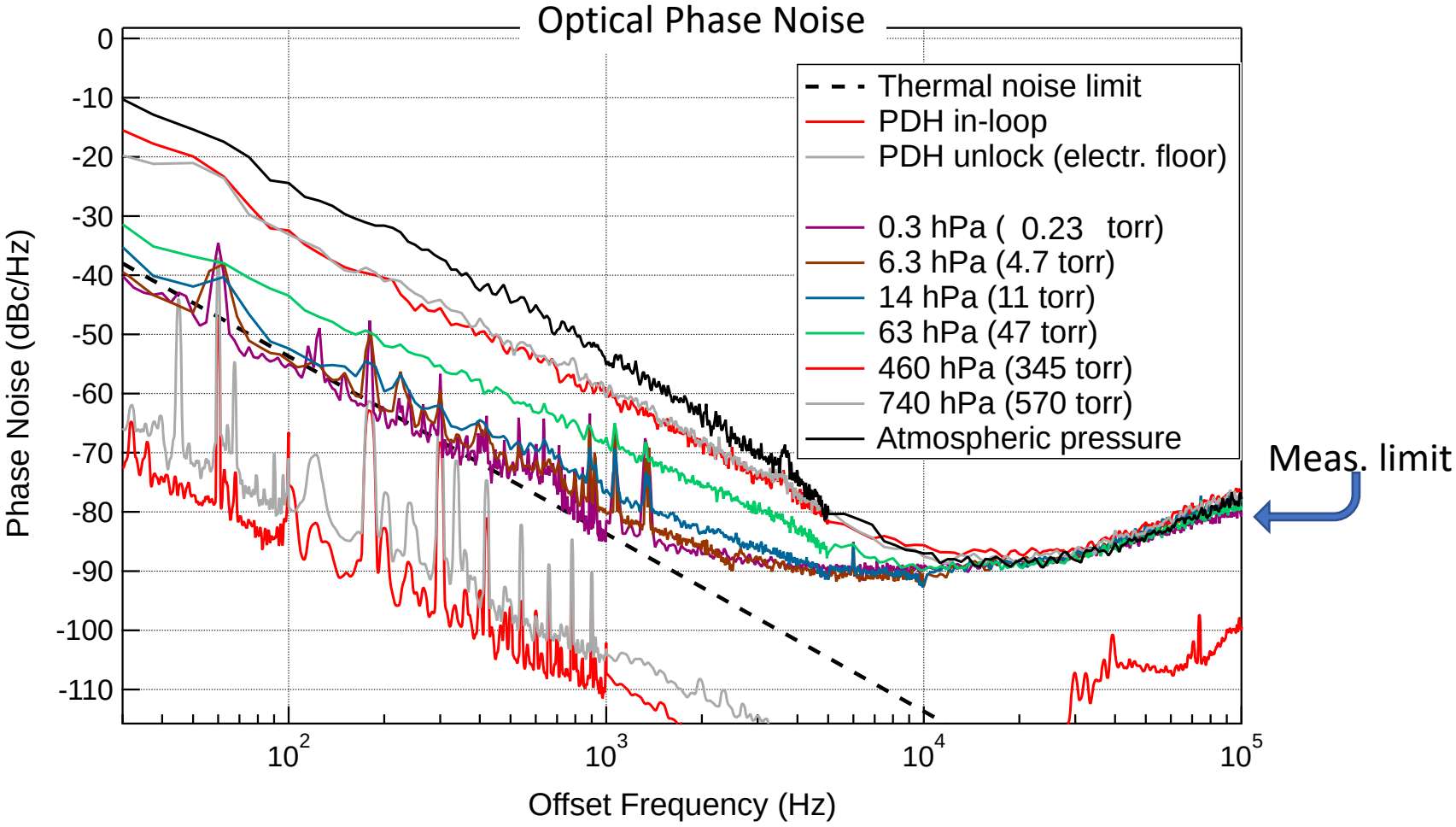
Phase noise vs. air pressure

Test cavity



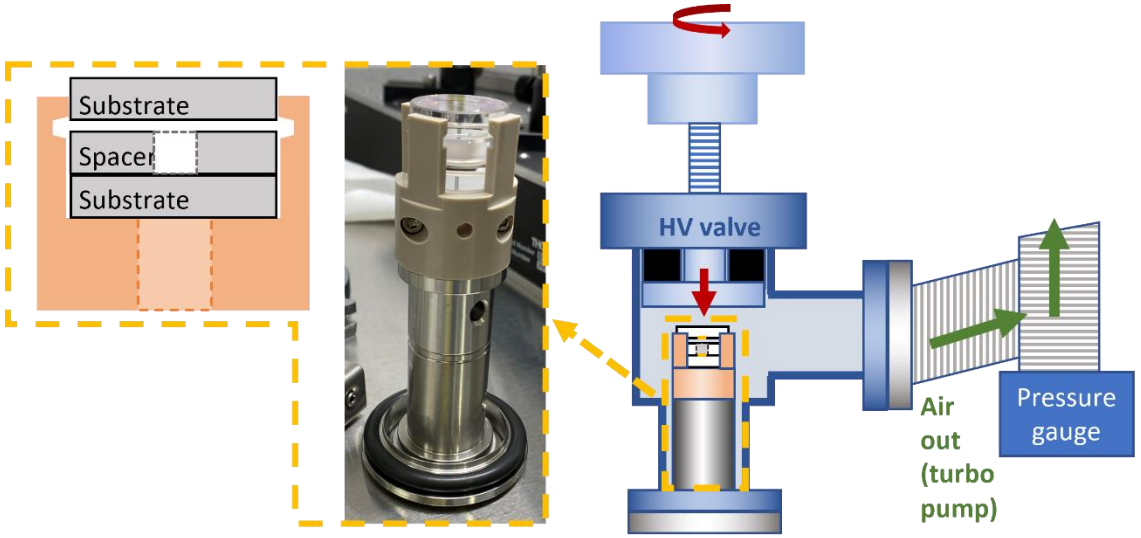
Spacer length: 6.3 mm
Spacer diameter: 27 mm
Mirror thickness: 6.35 mm

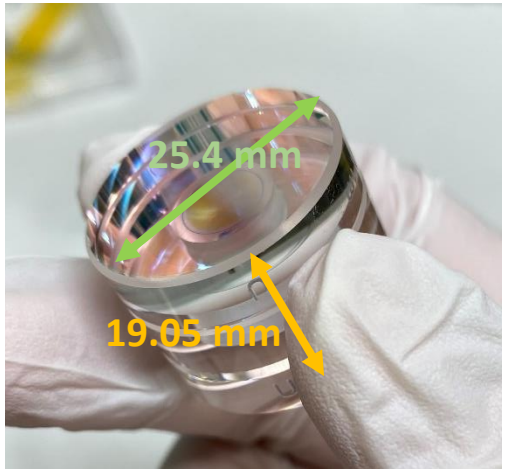
- Cavity is placed within a vacuum chamber with pressure monitoring
- Optical phase noise is measured at different pressure settings



Tests indicate only modest vacuum ~1 torr is required to reach thermal noise limit

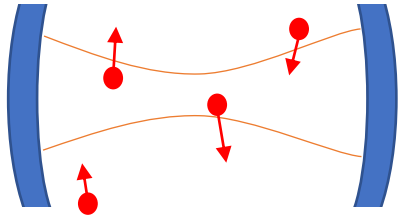
In-vacuum cavity bonding





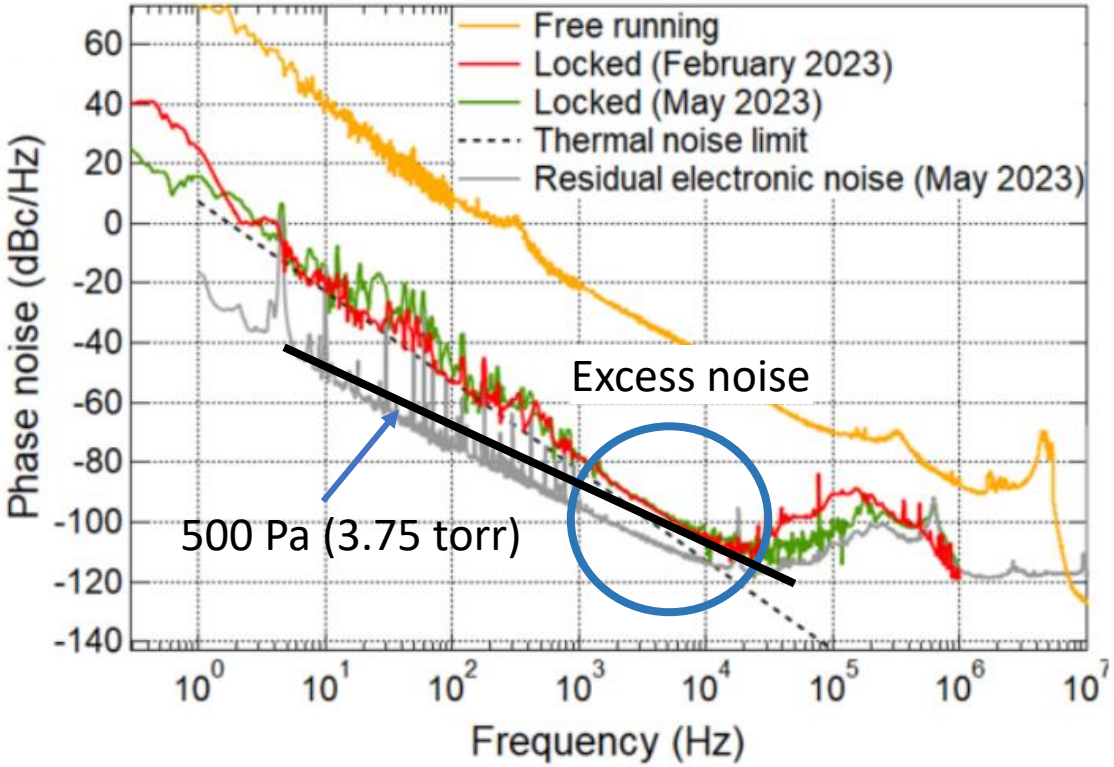
Residual gas noise

Gas molecules perturb the optical phase as they transit the beam



Noise model*:

$$S_\phi(f) = \frac{4\rho(2\pi\alpha)^2 f_c^2}{v_0 L^2 f^2} \int_0^L \frac{\exp[-2\pi f w(z)/v_0]}{w(z)} dz$$



- **Thermal noise limited phase noise**
- **Still holding vacuum and going strong!**

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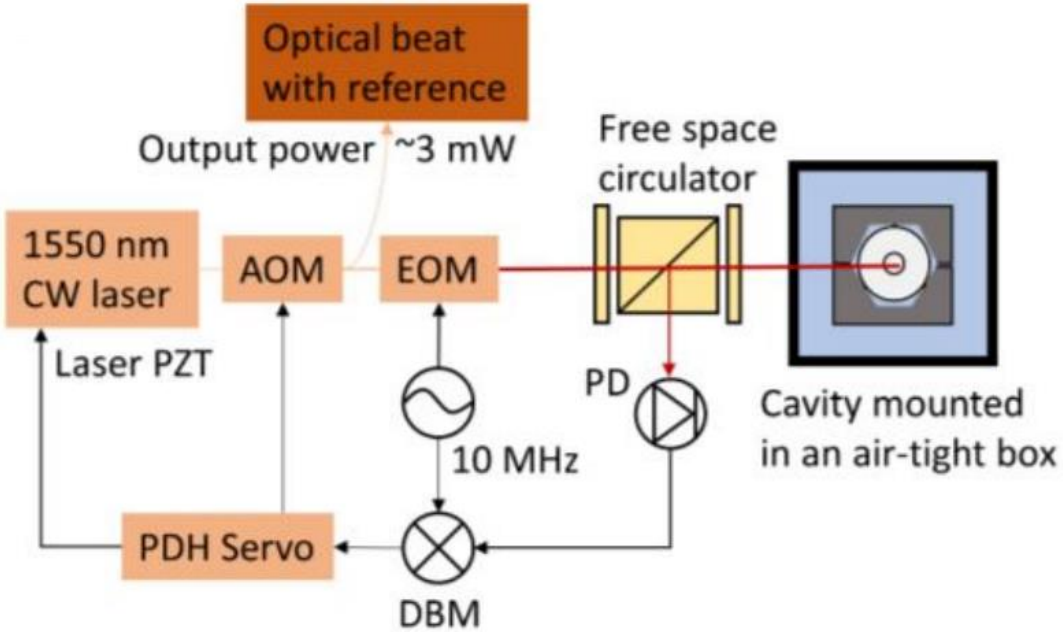
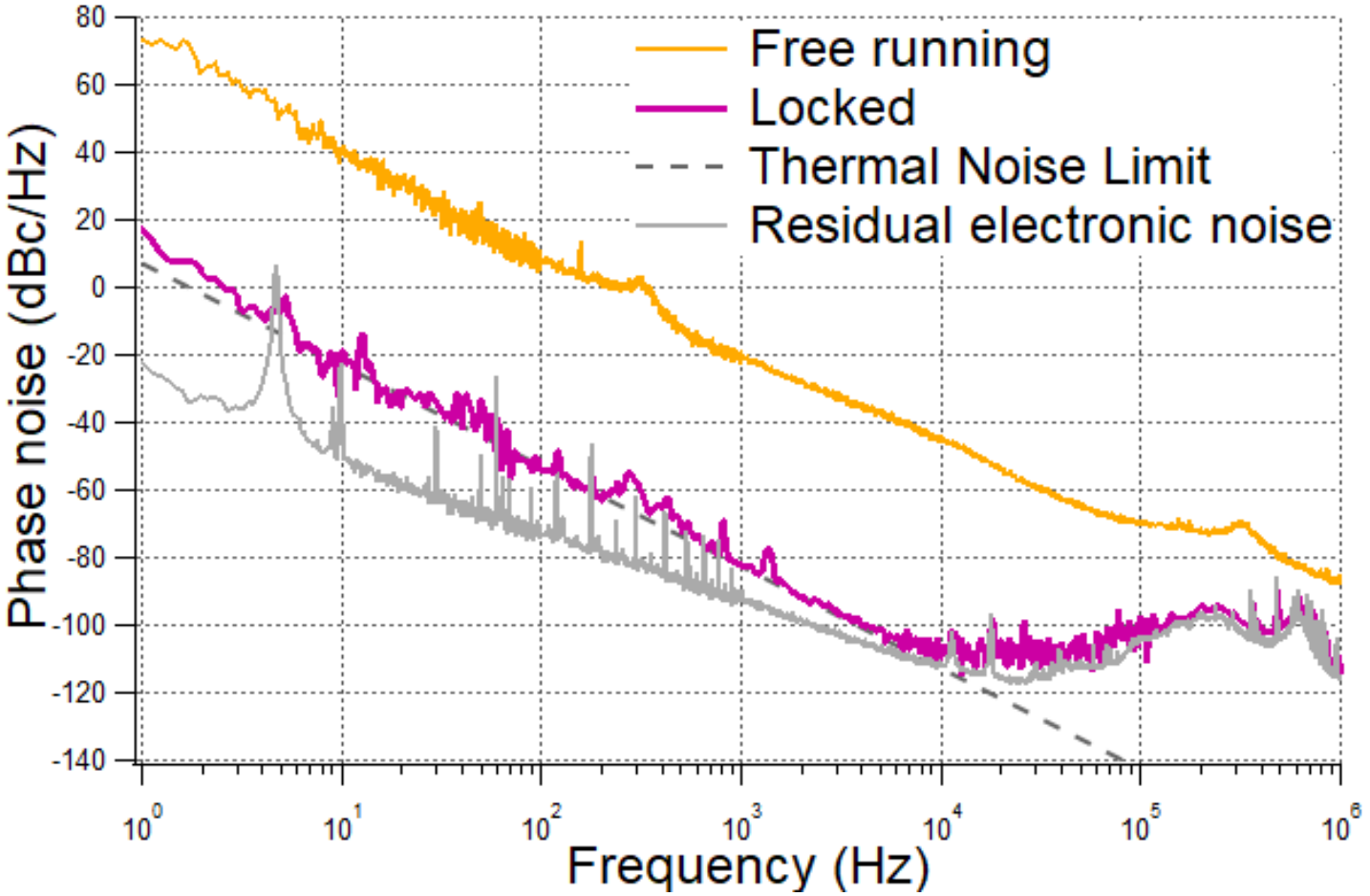
*Zucker & Whitcomb, LIGO (1994)

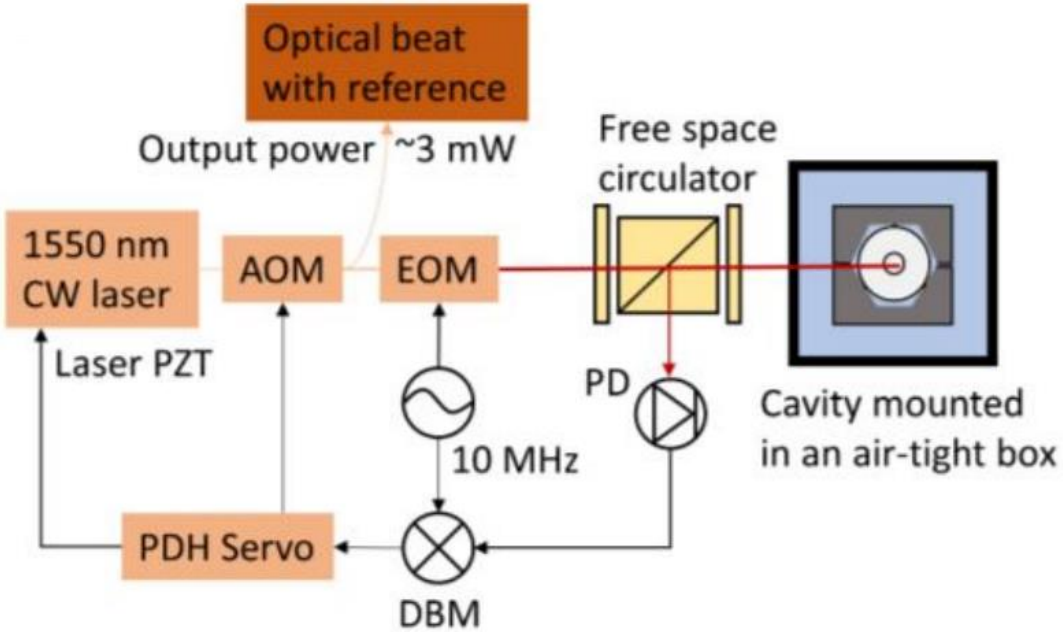
“Bake n’ bond” cavity

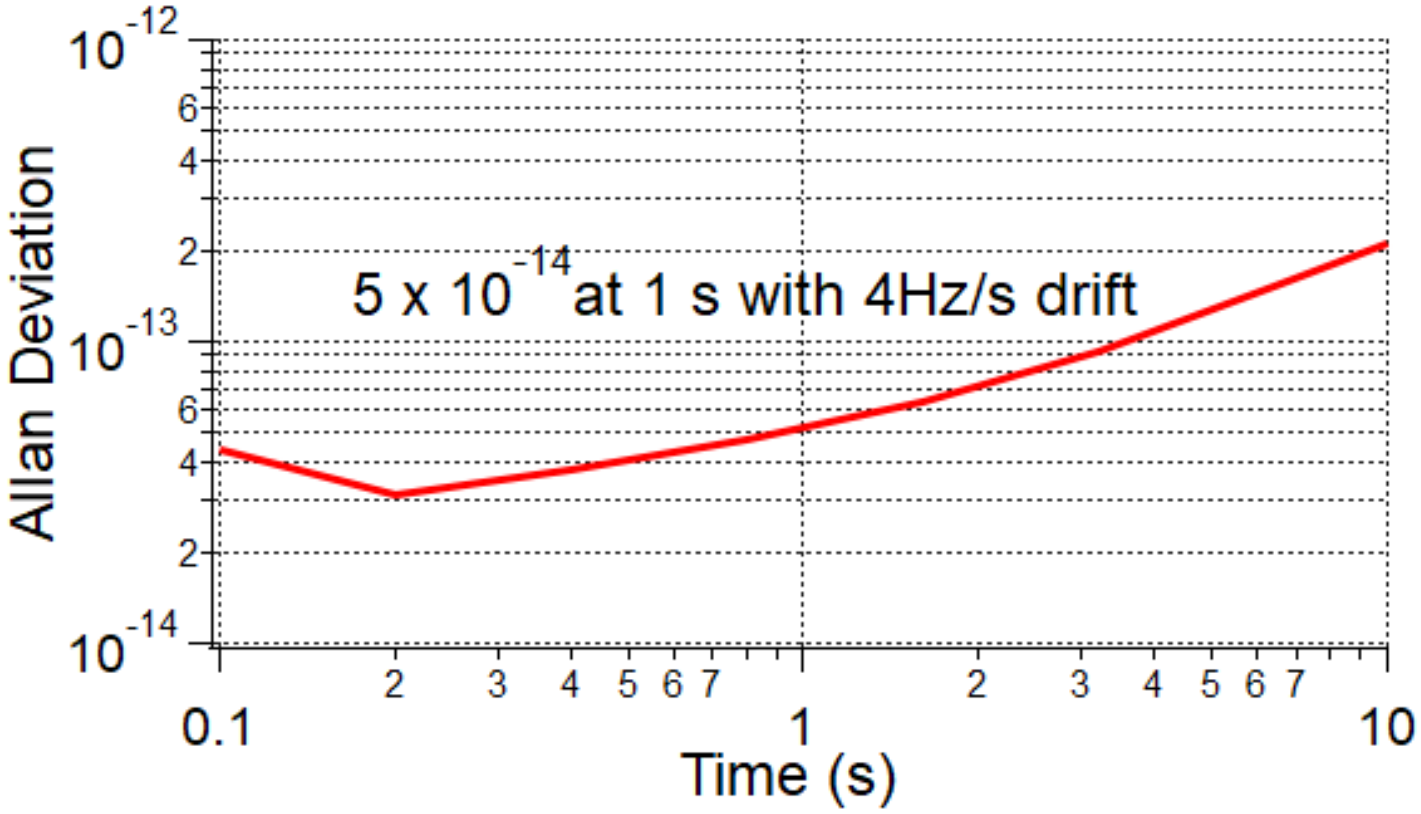




Thermal noise limited phase noise out to 10 kHz offset without a vacuum enclosure!

“Bake n’ bond” cavity

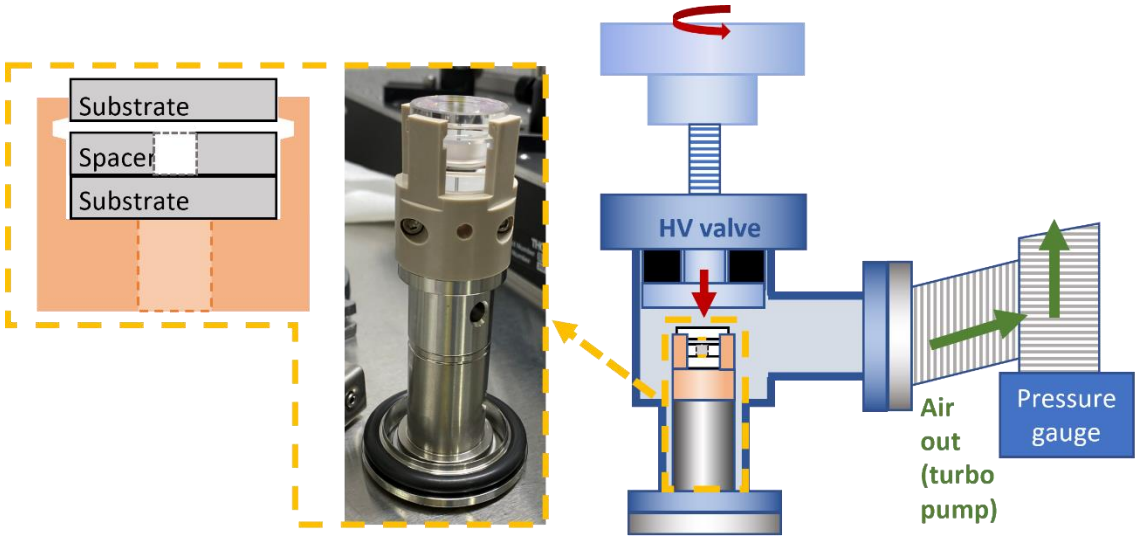




Thermal noise limited phase noise out to 10 kHz offset without a vacuum enclosure!

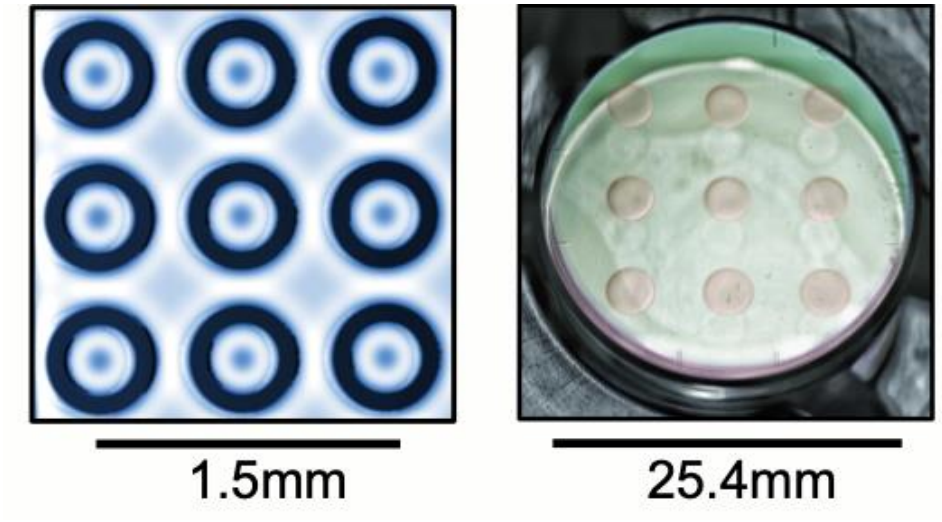
What's next?

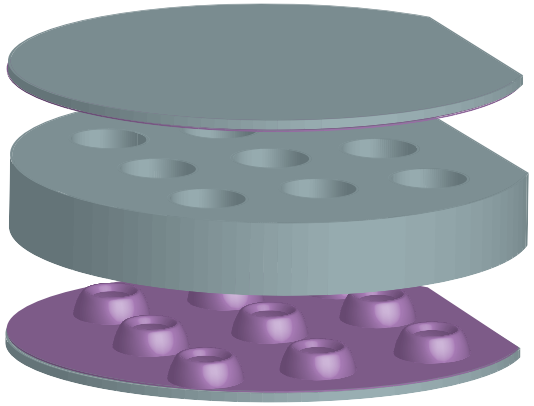
Vacuum bonding



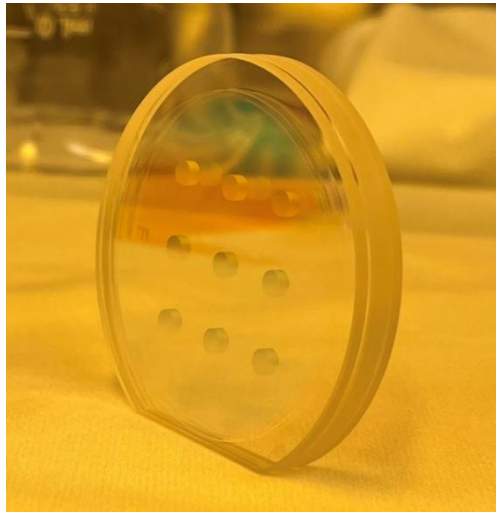
+

micromirrors

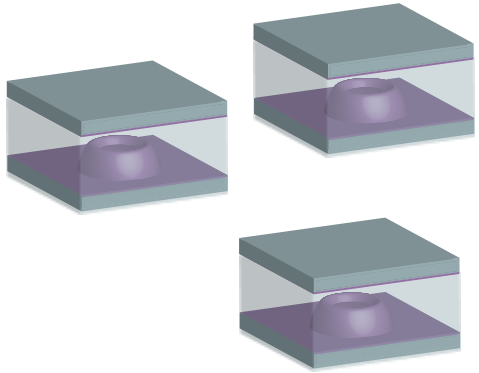




In-vacuum bond cavity arrays



Dice into individual cavities



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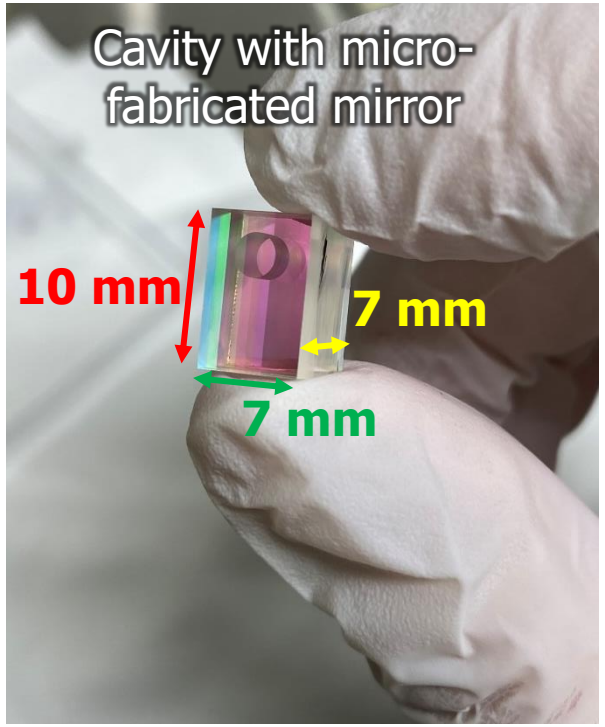
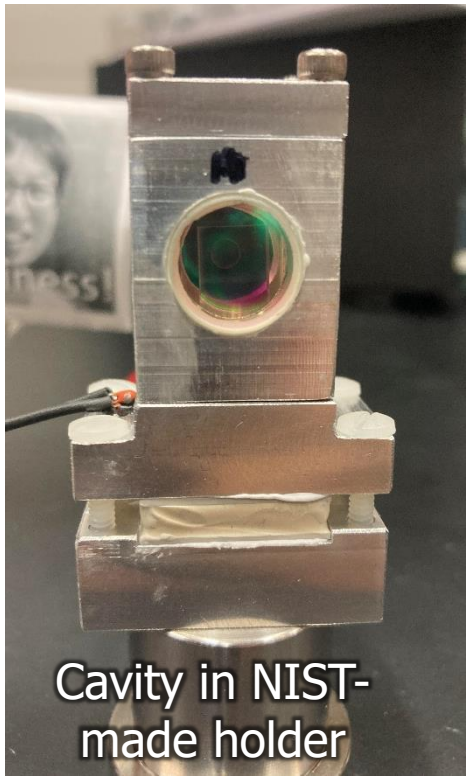
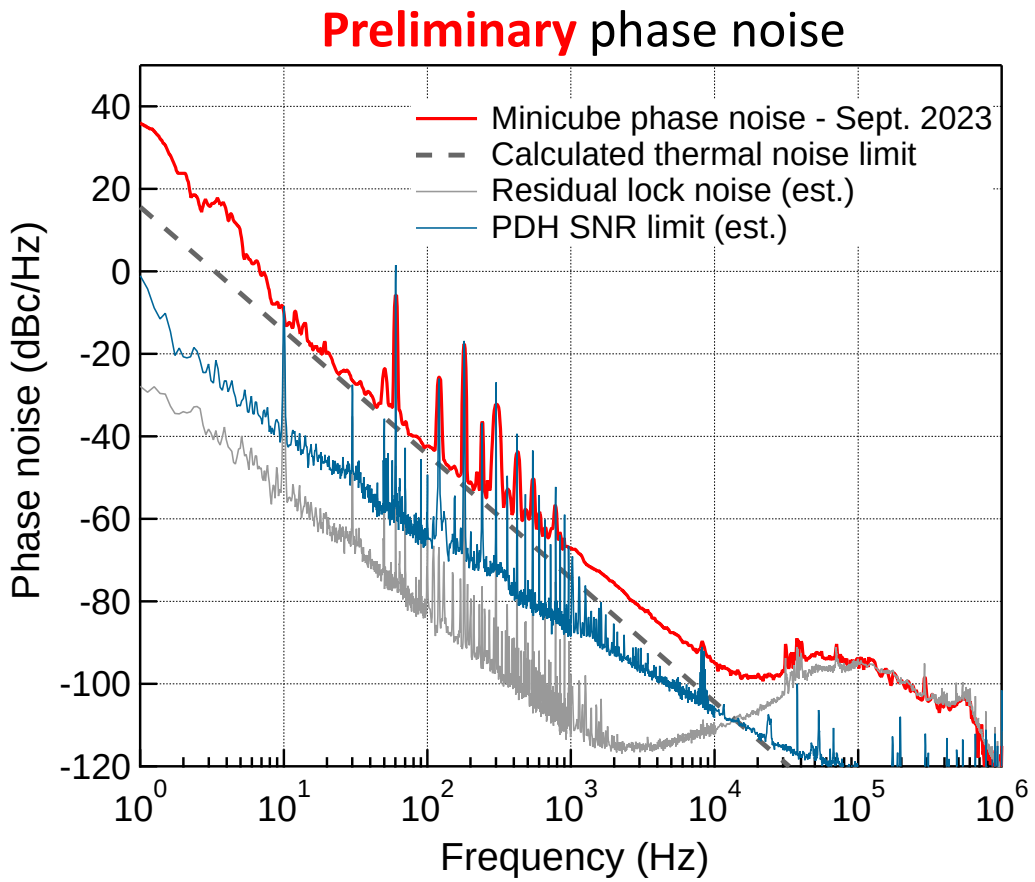
“minicube” cavity – preliminary results

In-vacuum micro-FP: bonded and diced at Yale





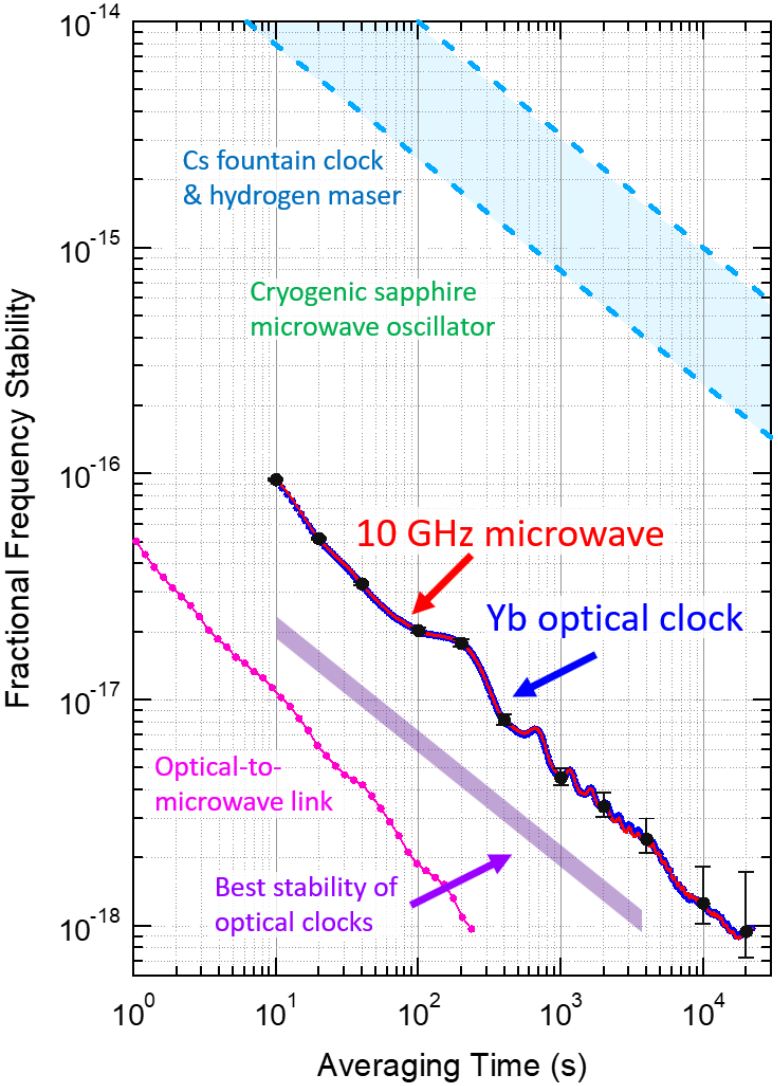


Noise matches thermal noise limit from ~10 Hz to ~200 Hz

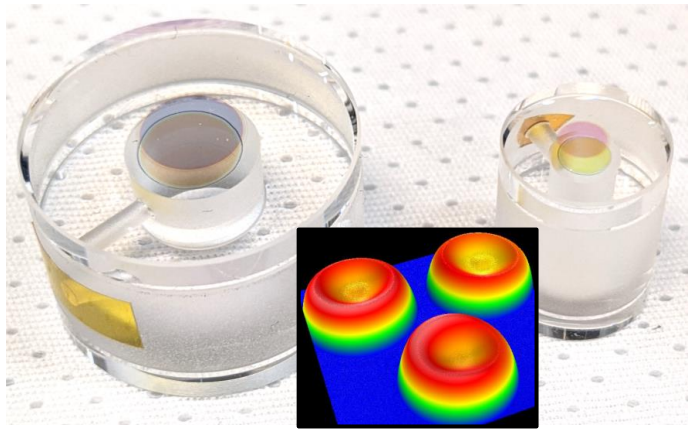
Bake n’ bond could improve noise from 200 Hz to 10 kHz

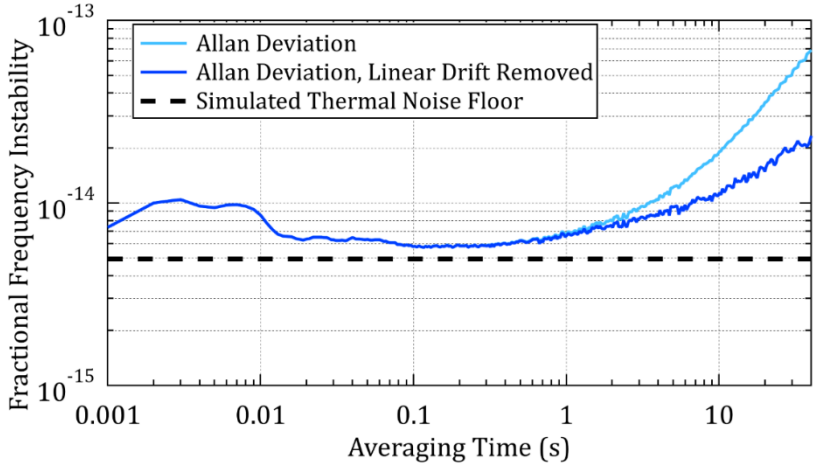
Summary

Microwave signals with optical clock stability

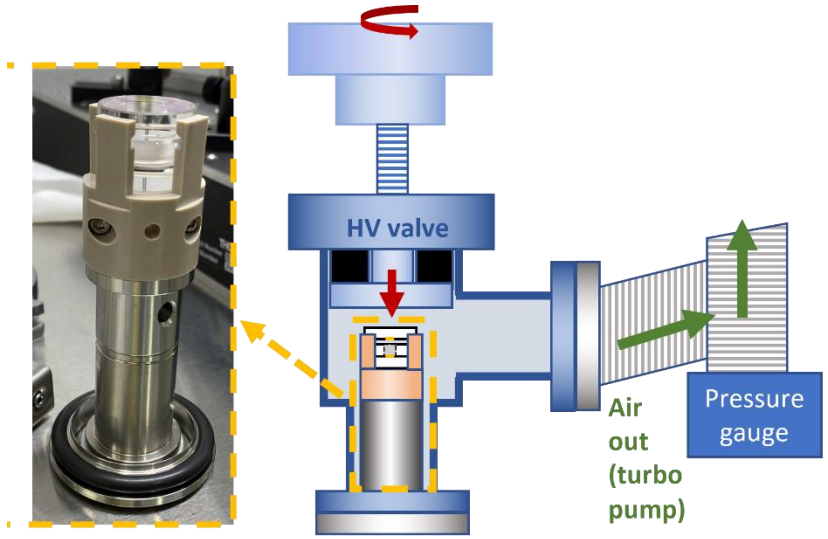


High finesse micro-mirror cavities





Low phase noise with in-vacuum bonding



"minicube" cavities

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UCSB

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University of Colorado Boulder

Scott Diddams

Caltech

Kerry Vahala

Funding

NIST

DARPA

Optical clock diagram

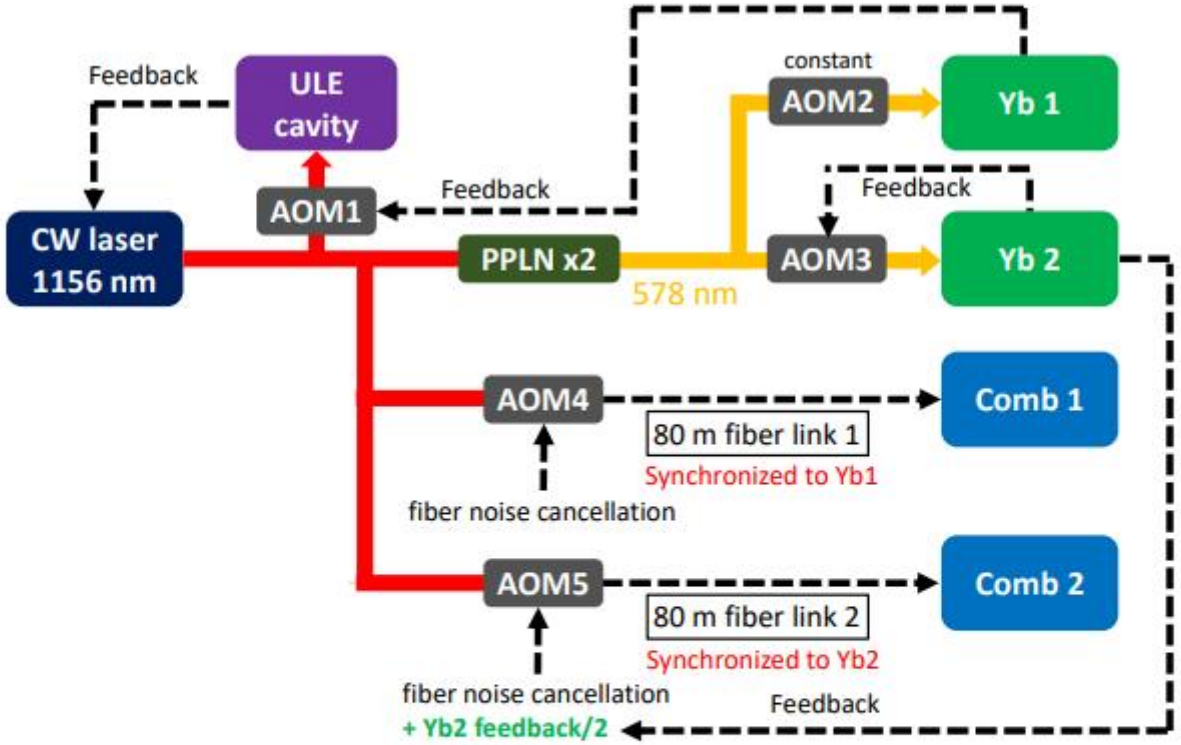


Fig. S1. Schematic diagram of Yb clocks and 80 m fiber links. A single CW laser operating at 1156 nm was pre-stabilized to a ULE cavity and used for probing two Yb systems. Feedback to AOM1 tuned the frequency of the CW laser to Yb1. AOM3 and AOM5 overwrote the feedback for Yb2. AOM4 and AOM5 are used for fiber noise cancellation over the 80 m link. AOM2 was only used to add a constant frequency offset. AOM, acousto-optic modulator; ULE, ultralow expansion; PPLN, periodically poled lithium niobate.

OFD frequency

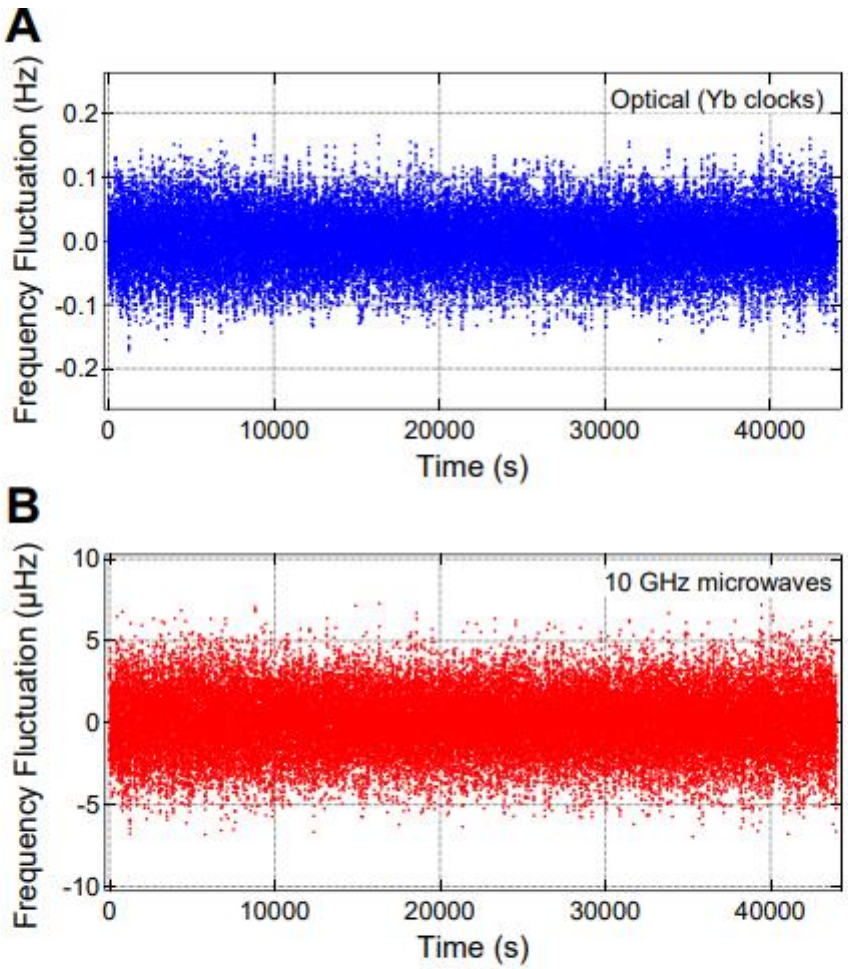
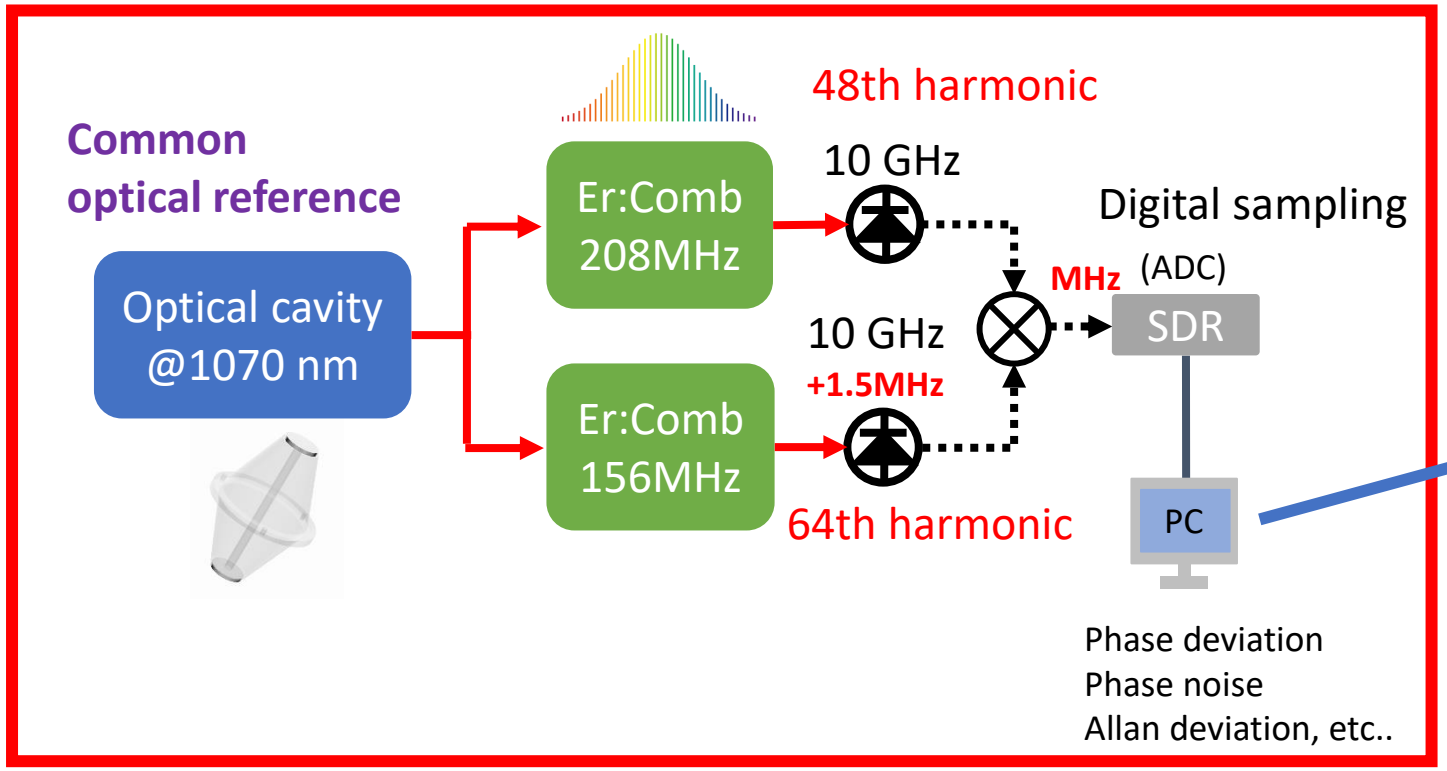


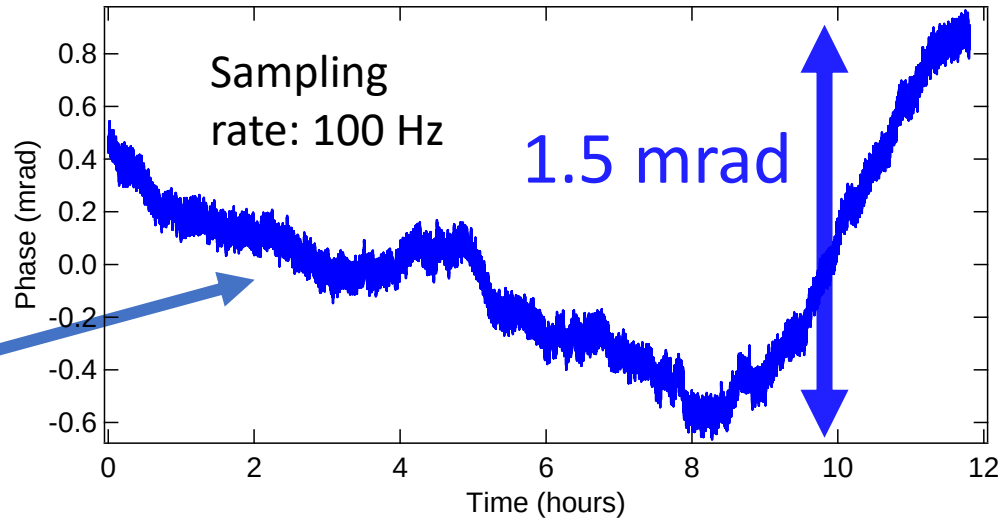
Fig. S6. Frequency fluctuations in optical and microwave domains. (**A**) The frequency difference between two Yb clocks, with rms fluctuations of 43 mHz. (**B**) The frequency difference between two 10 GHz microwaves, with rms fluctuations of 1.86 μHz. In both plots, the effective gate time was 1 s, and a carrier frequency around 1.5 MHz was subtracted.

OFD noise

Two independent OFD systems



Phase fluctuation



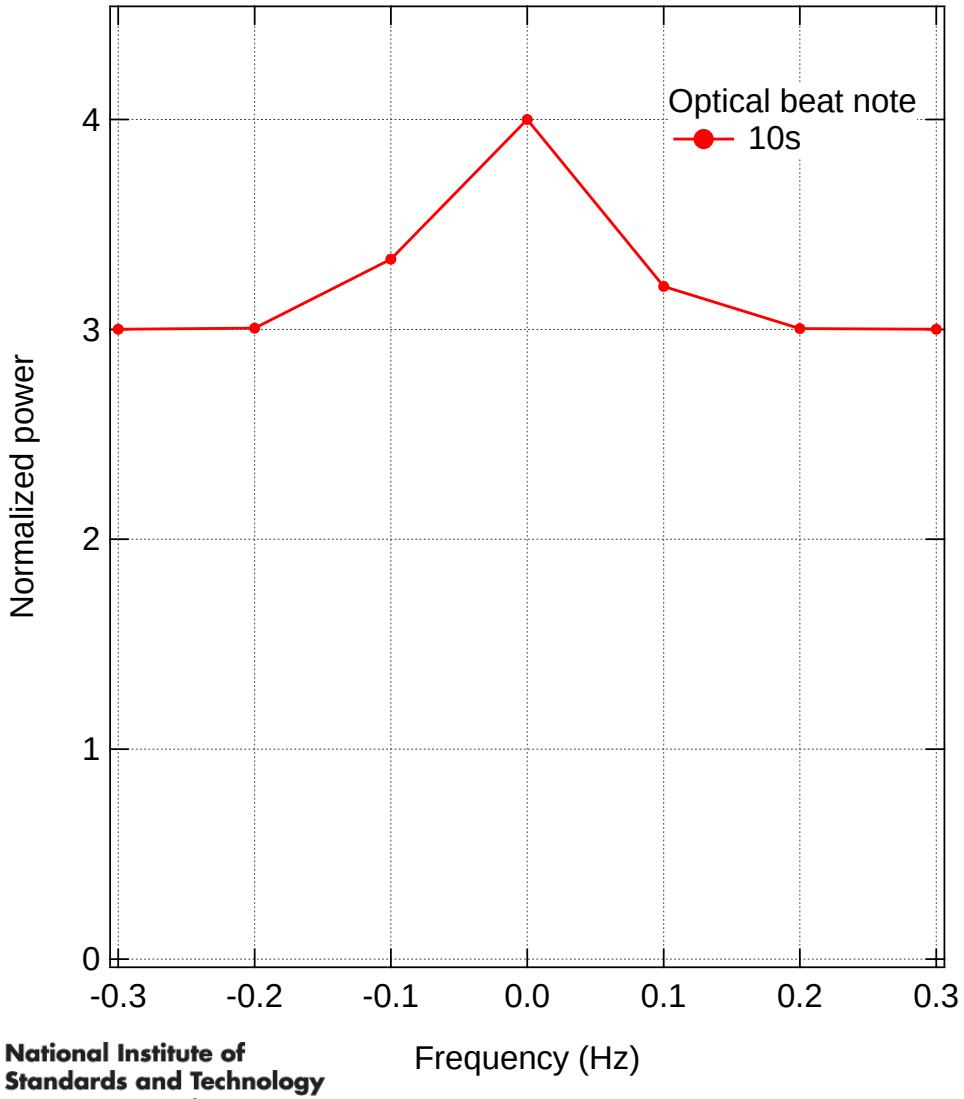
No cycle slip for 12 hours

Noise of reference was cancelled out

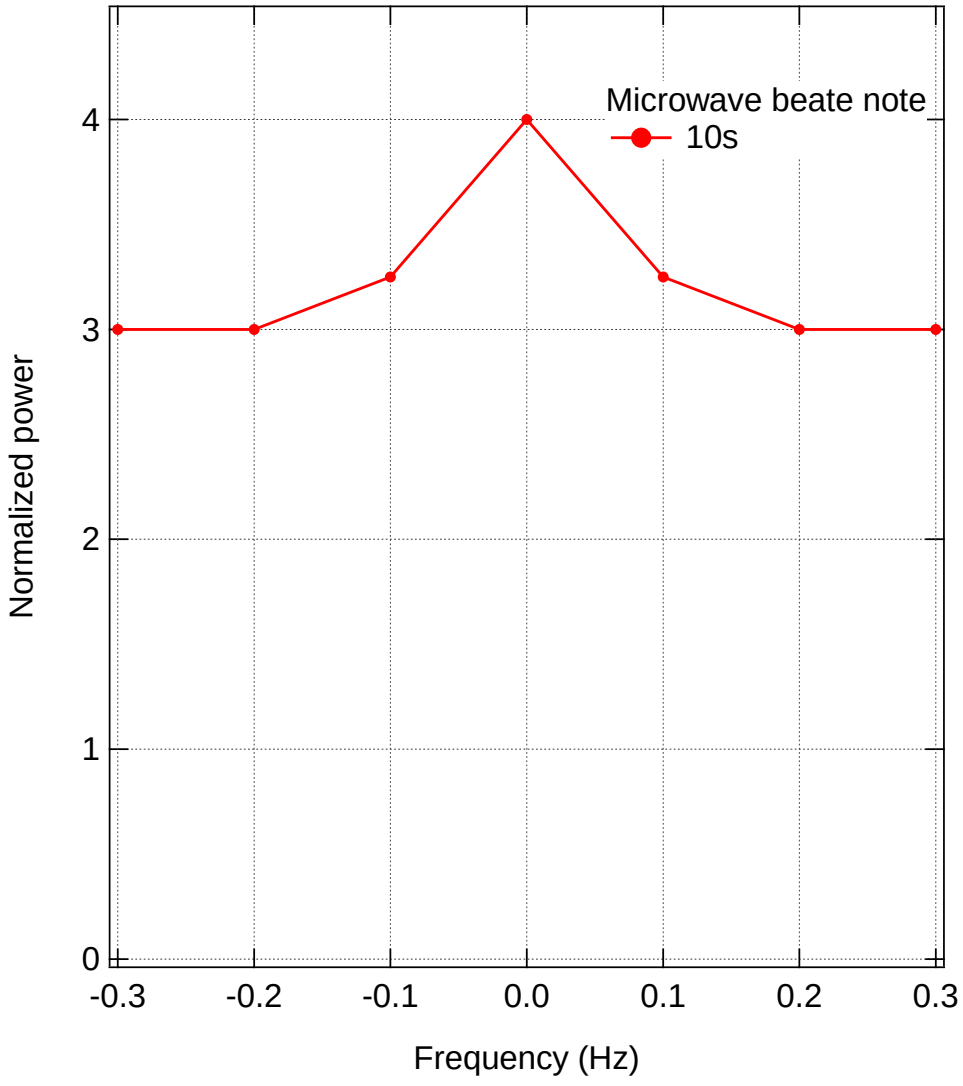
Estimate OFD system noise

Linewidth

Optical Clock

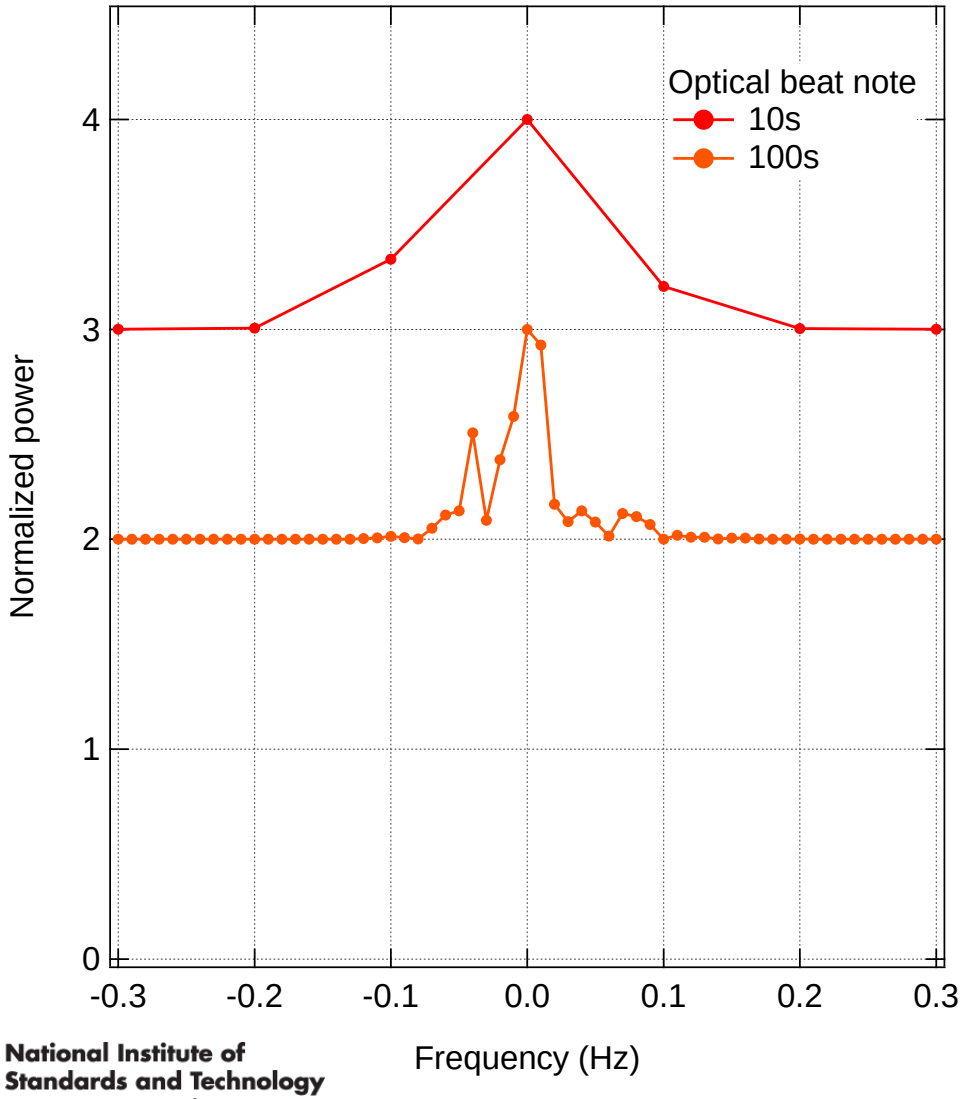


Microwave

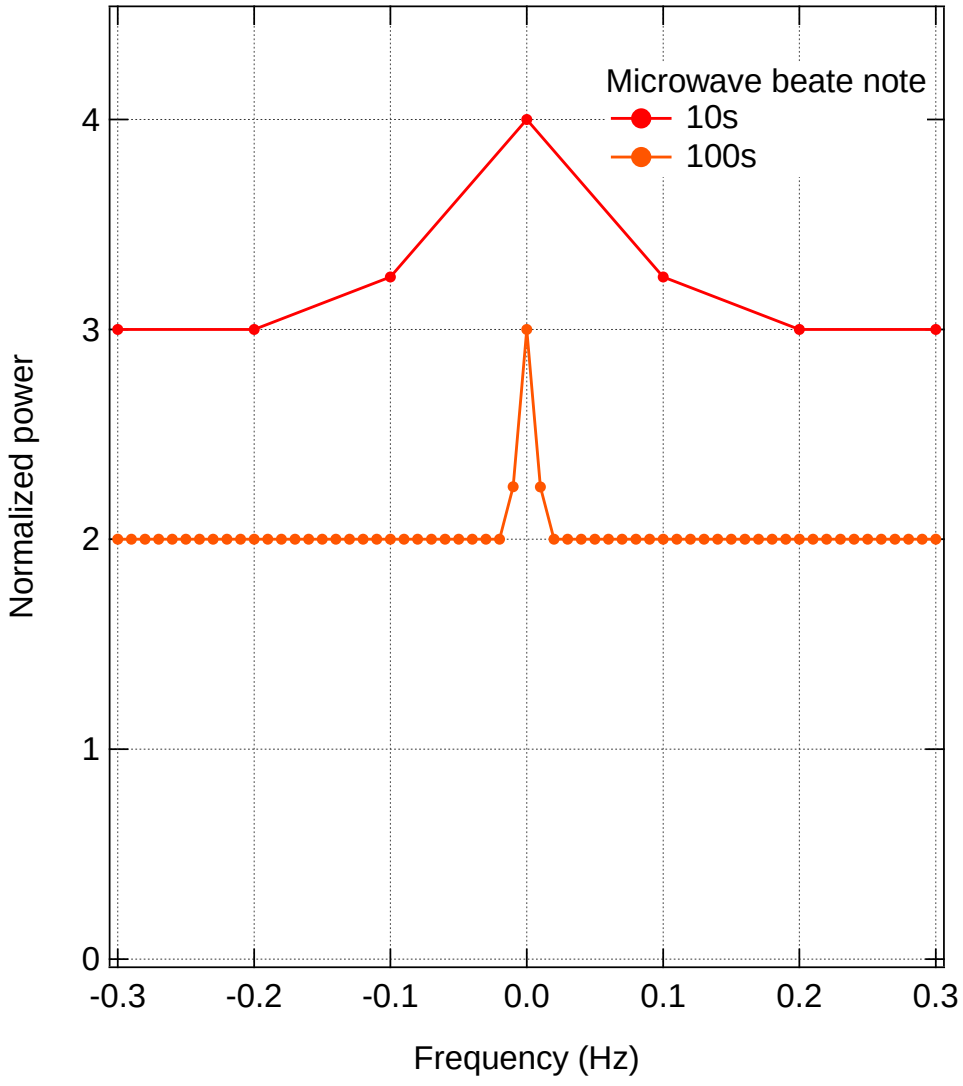


Linewidth

Optical Clock

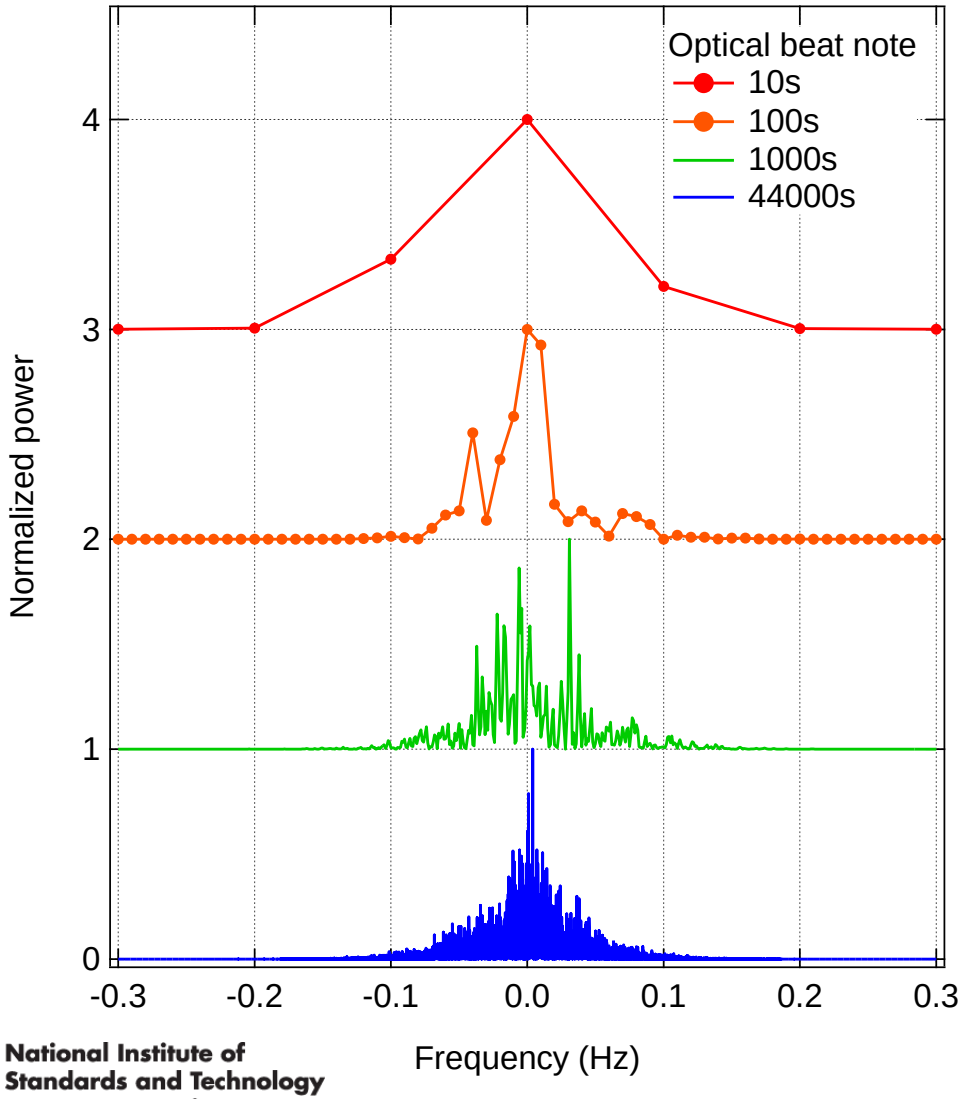


Microwave

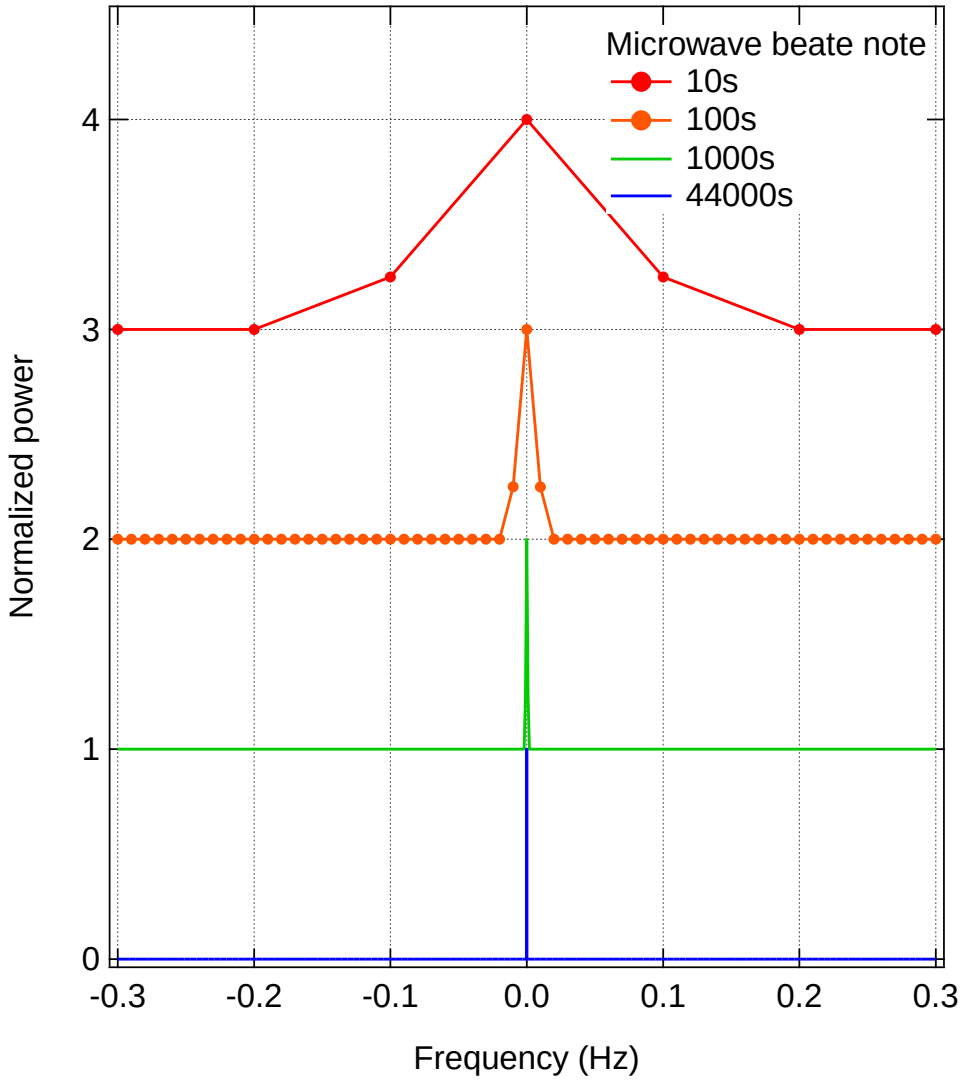


Linewidth

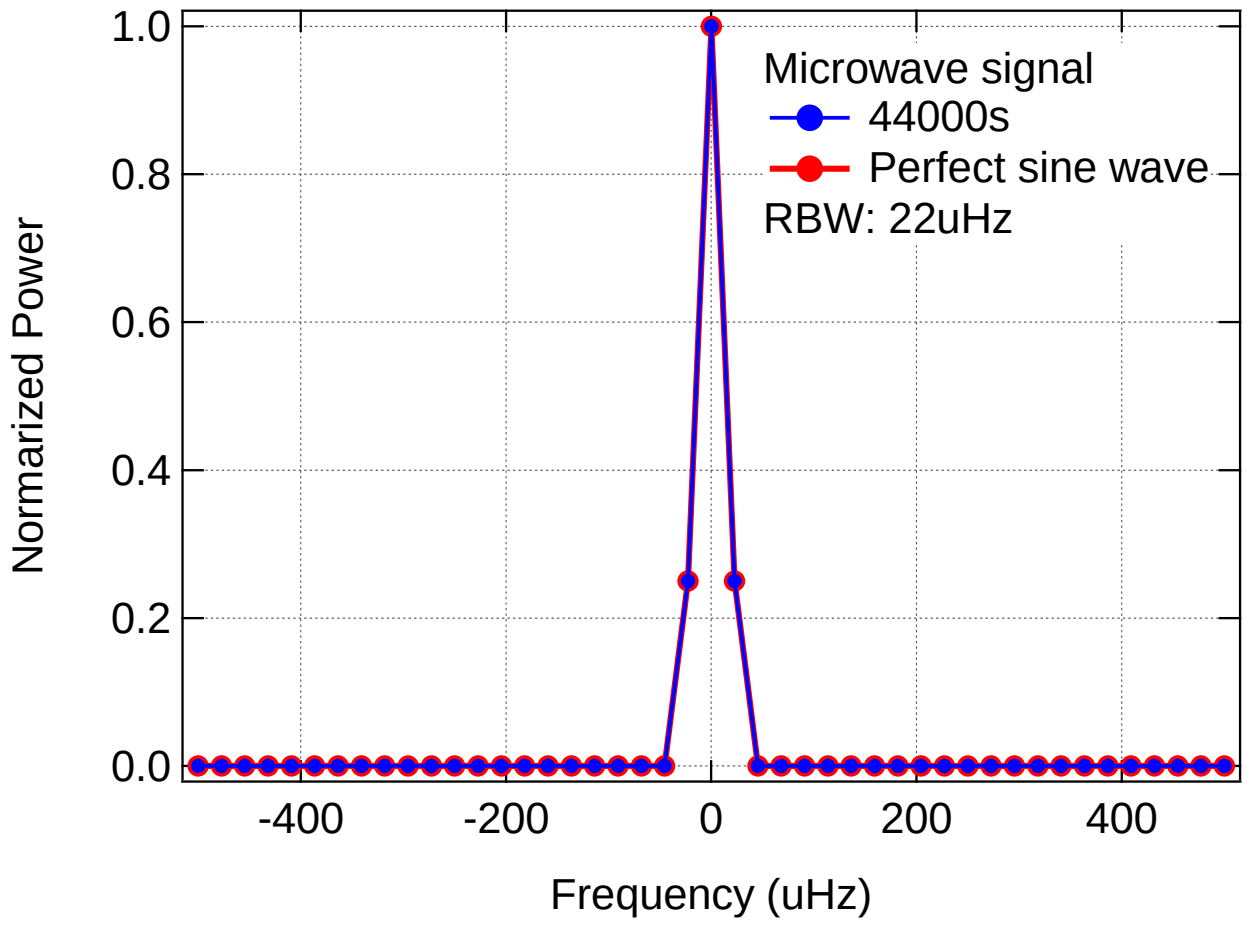
Optical Clock



Microwave



Linewidth



- Microwave is still transform-limited after 44000 seconds
- Difference between measured sinewave and “perfect” sinewave not visible on a linear scale