Dual-Mode Frequency Stabilization of a Whispering Gallery Mode Optical Reference Cavity

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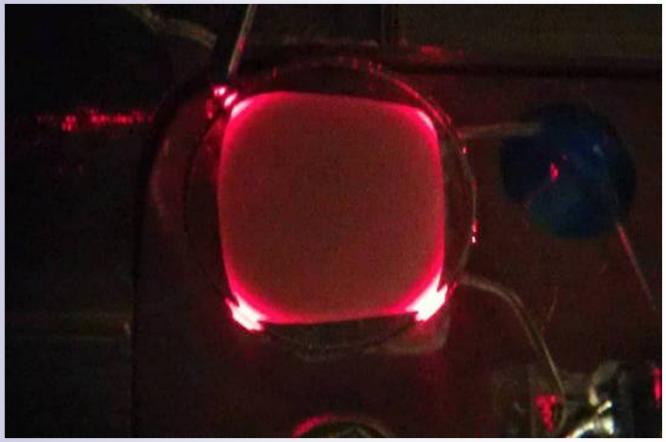
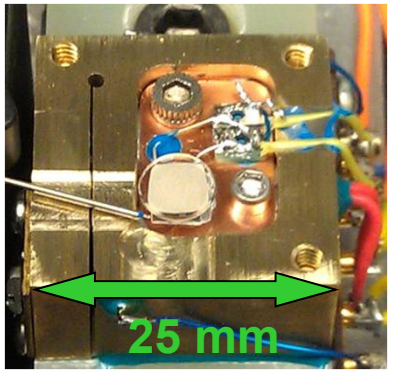


Jet Propulsion Laboratory
California Institute of Technology

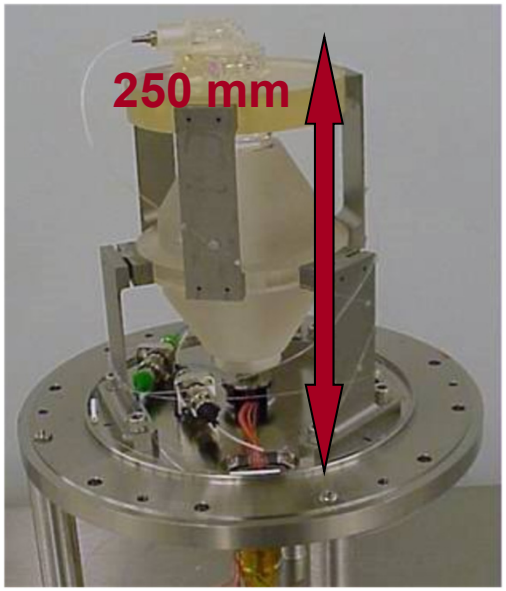
CLEO: May 10th 2012

WGMR as frequency reference cavities

- Motivation:
  - Very Compact
  - High Q over wide wavelength range
    - Eliminate expensive mirror coatings
  - Mechanically Robust
    - Vibrationally insensitive
    - Acoustically insensitive
- Challenges:
  - Light travels in solid media
    - Thermal noise (fundamental limits)
    - Technical noise



WGMR Cavity

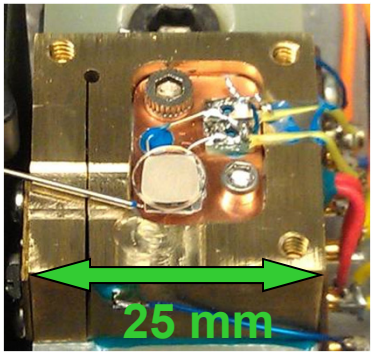


GRACE FO Fabry Perot Cavity

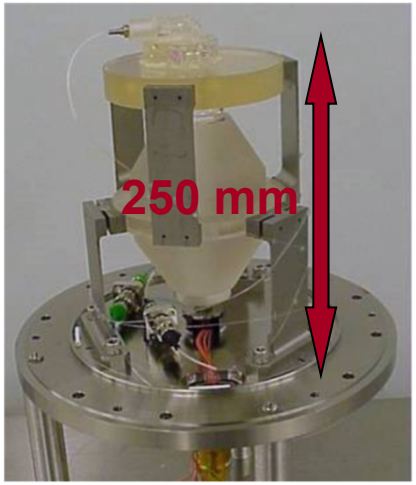
WGMR for Frequency Metrology

- Laser Stabilization:

- **Highly Compact**
- **Robust to vibration, acceleration**
- **Wide transparency range in crystals**

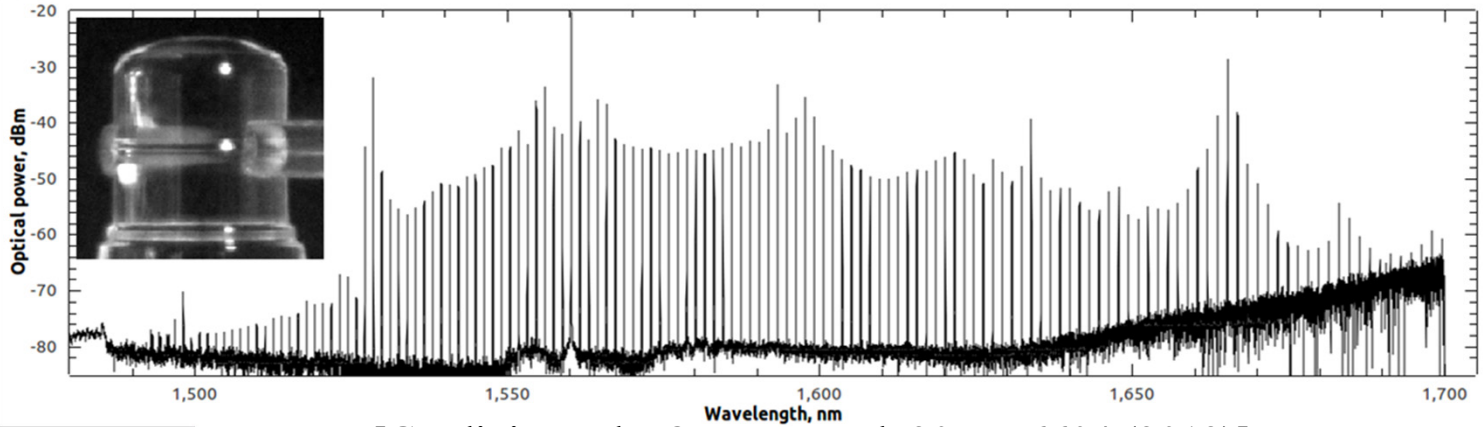


WGMR Cavity



GRACE FO Fabry Perot Cavity

- Frequency Combs:



[Grudinin et al., *Opt. Exp.* Vol. 20, pp 6604 (2012)]

Thermal Considerations

Temperature Noise → Frequency noise

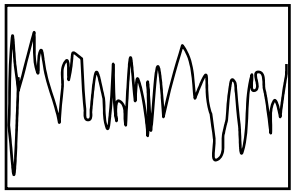
WGMR:

- Frequency: f
- Radius: R

$$\frac{1}{f}\frac{df}{dT}+\underbrace{\frac{1}{R}\frac{dR}{dT}}_{\text{Thermal-expansion}}+\underbrace{\frac{1}{n}\frac{dn}{dT}}_{\text{Thermo-refraction}}=0$$

Fundamental: $\left\langle (\Delta T)_m^2 \right\rangle = \frac{k_b T^2}{C_p V_m \rho}$

Technical: Laser Intensity Noise



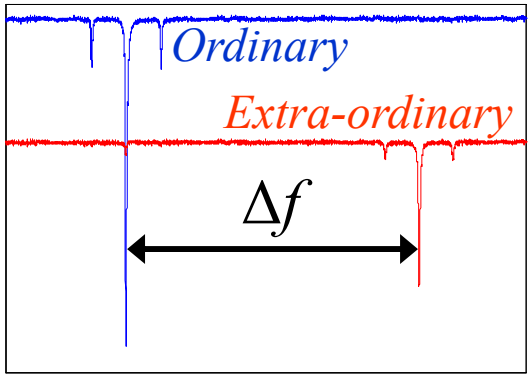
Dual-mode stabilization

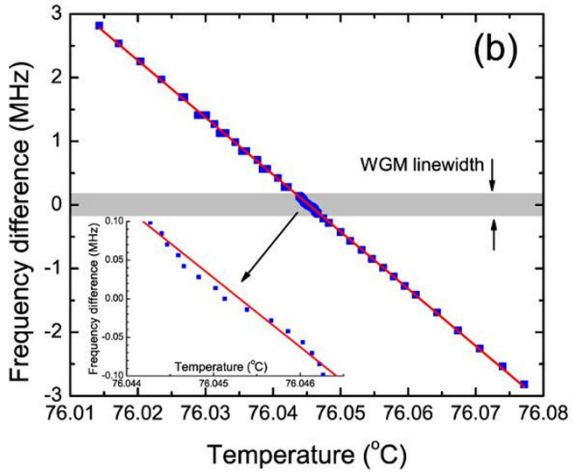
Thermo-refraction → Differential TempCo

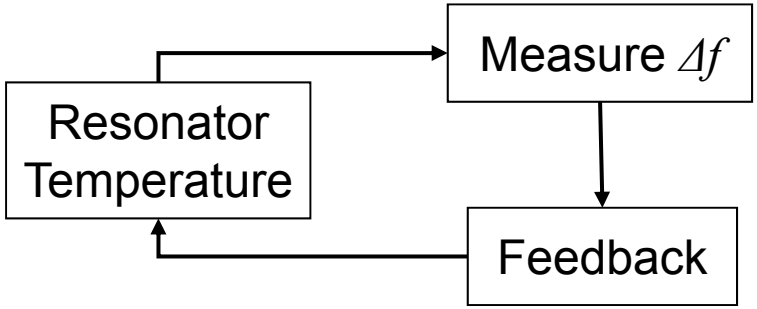
$$\frac{d}{dT}\Delta f = \pm\frac{c}{\lambda}\left[\alpha_n^{(o)} - \alpha_n^{(e)}\right] \approx \begin{cases} 79.8\ \text{MHz/K (literature values)} \\ 89.8\ \text{MHz/K (measured value)} \end{cases}$$

MgF_2

Birefringent crystal

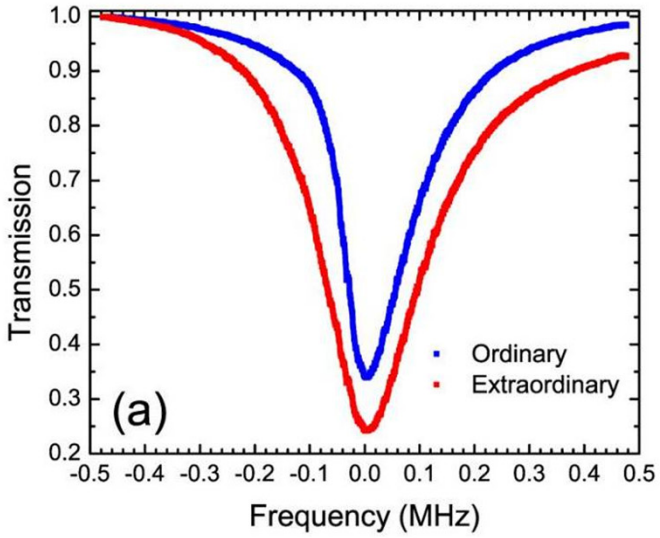




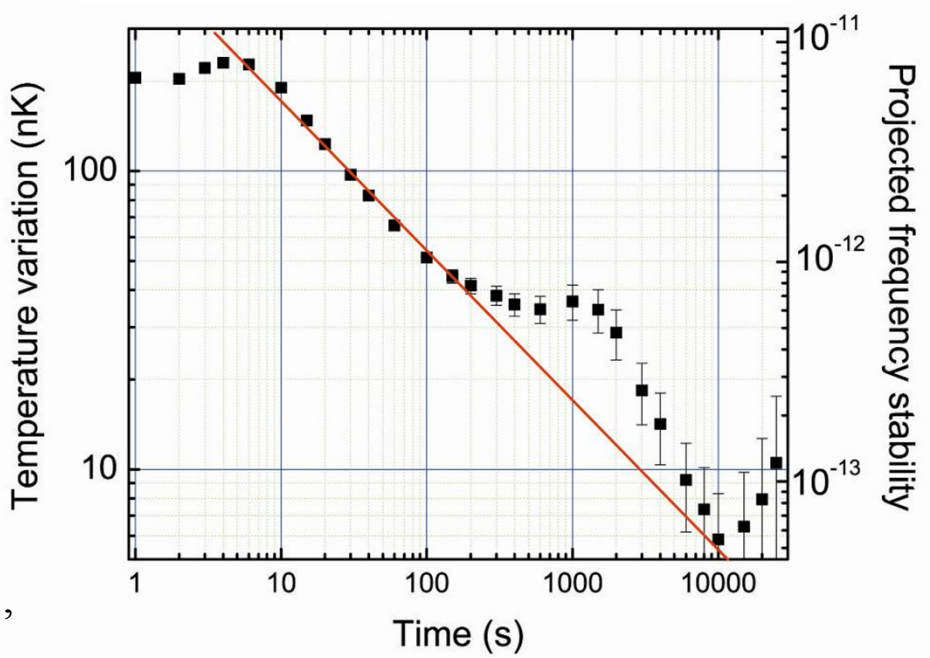


Demonstration

- Previously:
  - Swept Laser
  - Digital Feedback
  - Locked at $\Delta f=0$
  - Resistive Heater for Temp Control



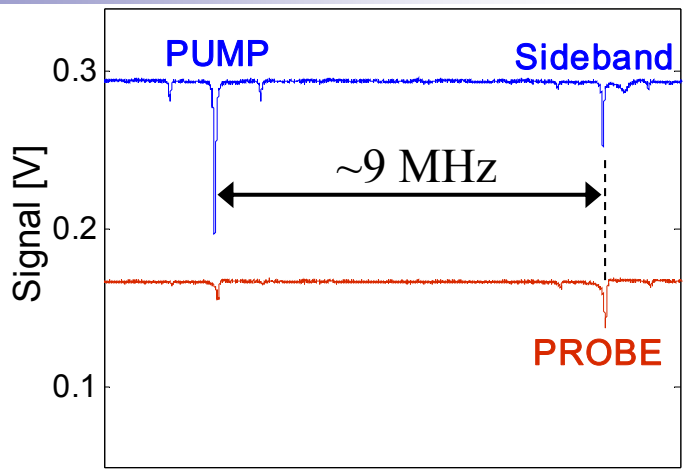
~ 6 nK temperature stability at 10,000 seconds

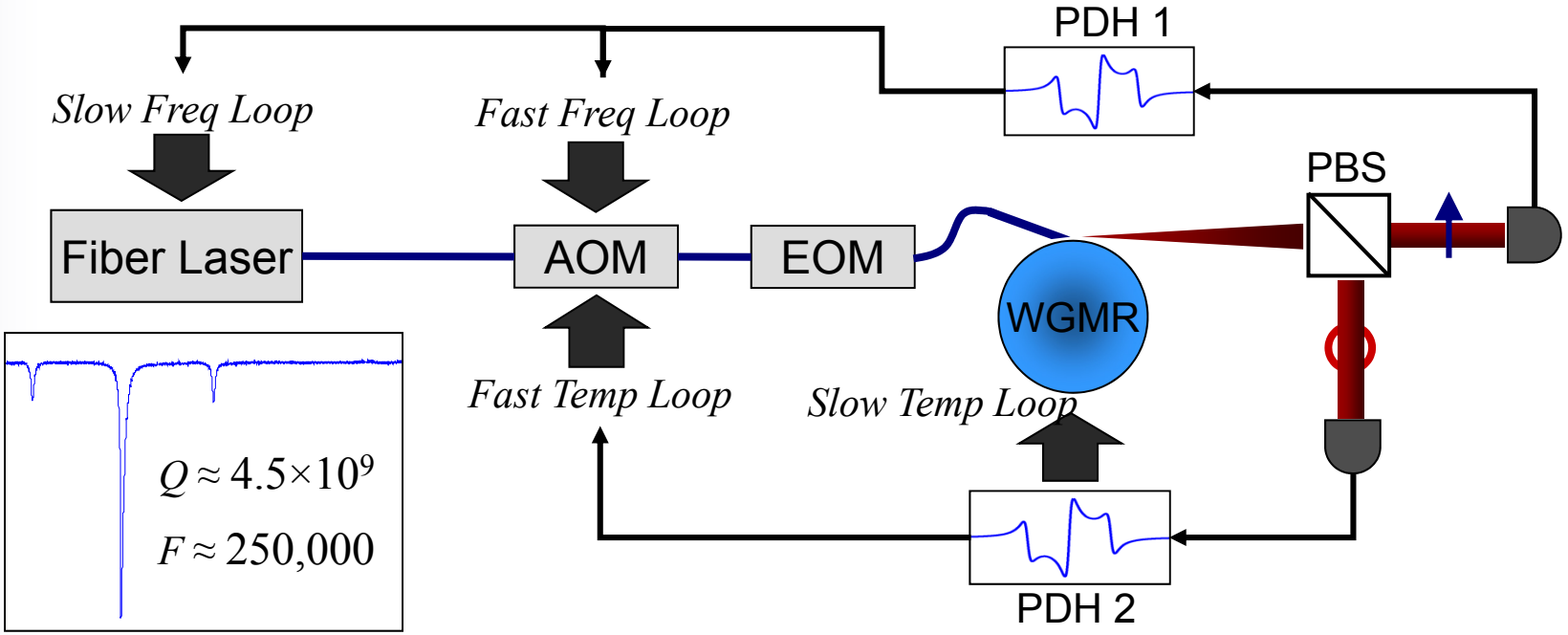


[Strekalov et al., *Opt. Exp.*, Vol. 19, pp 14495, 2011]

Current Scheme

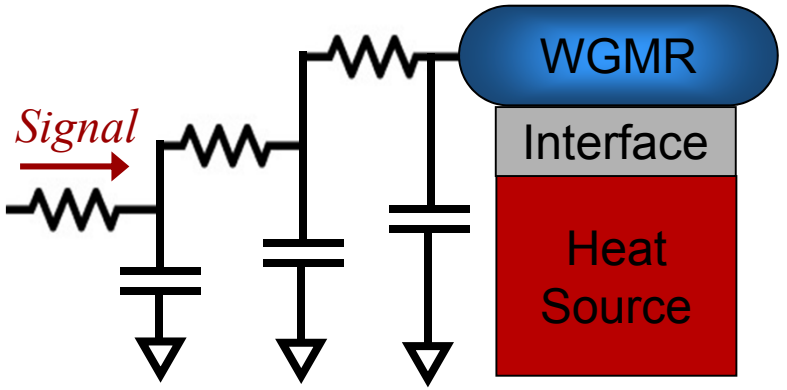
- Well-coupled “Pump” mode:
  - Laser Stabilization (Locking)
  - Amplitude modulation temp control
- Modulation sideband excites “probe” mode:
  - Lightly-coupled
  - Used for temp measurement

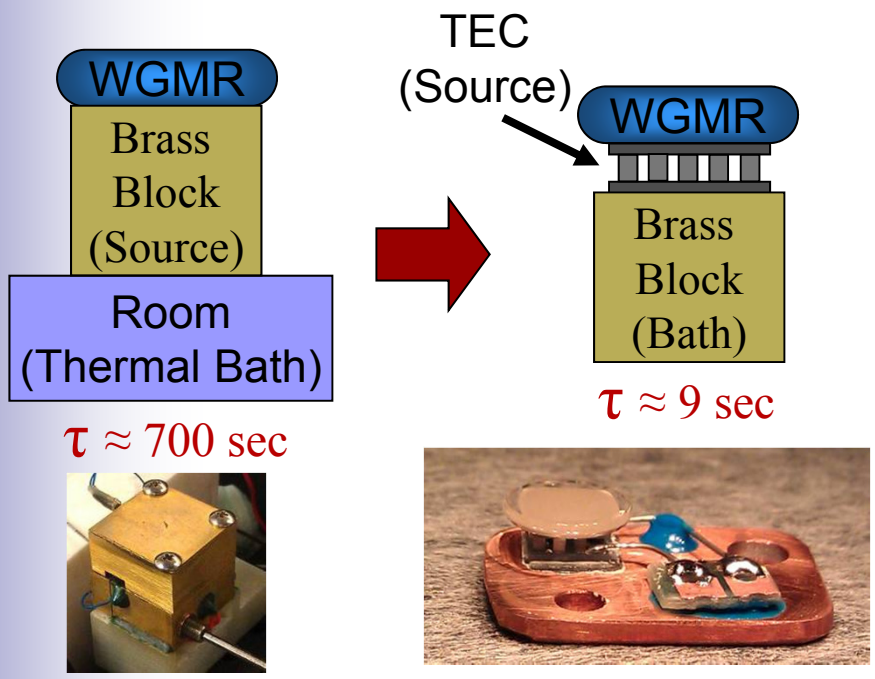


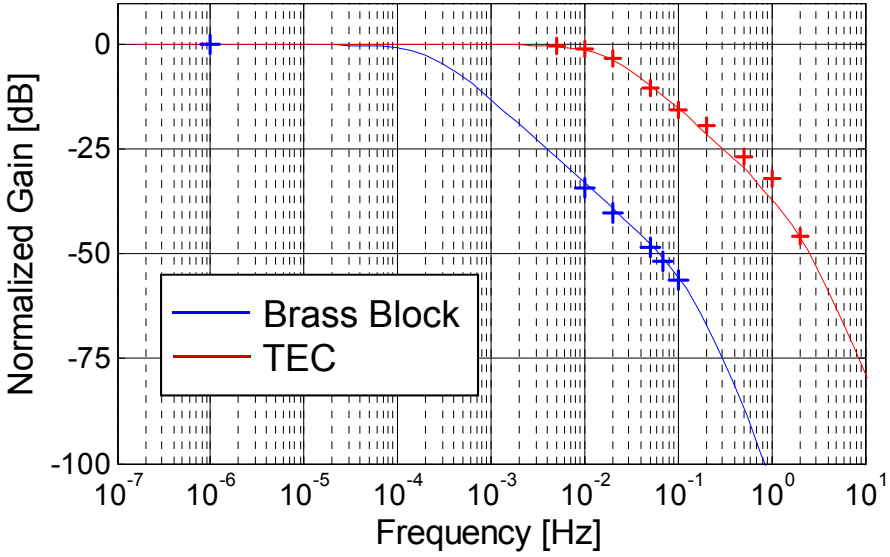


Controlling Cavity Temperature

- Third Order Systems
  - Thermal "RC" for each segment of temperature control
  - Long time constants a challenge for analog feedback electronics







Two decades faster

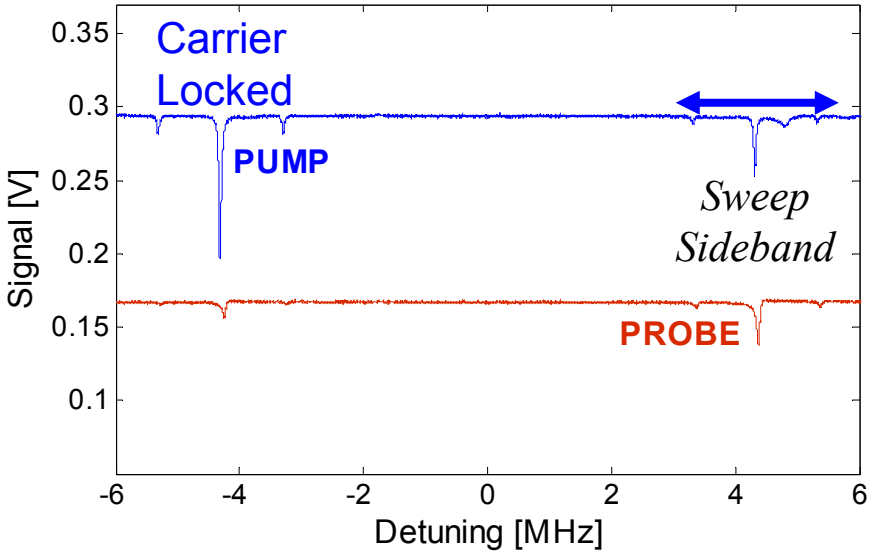
Measuring Cavity Temperature

- Precise measurements of temperature response

Open Thermal-Lock Loop:

Swept Sideband → Mode Location

Γ Resolution: 200 μK

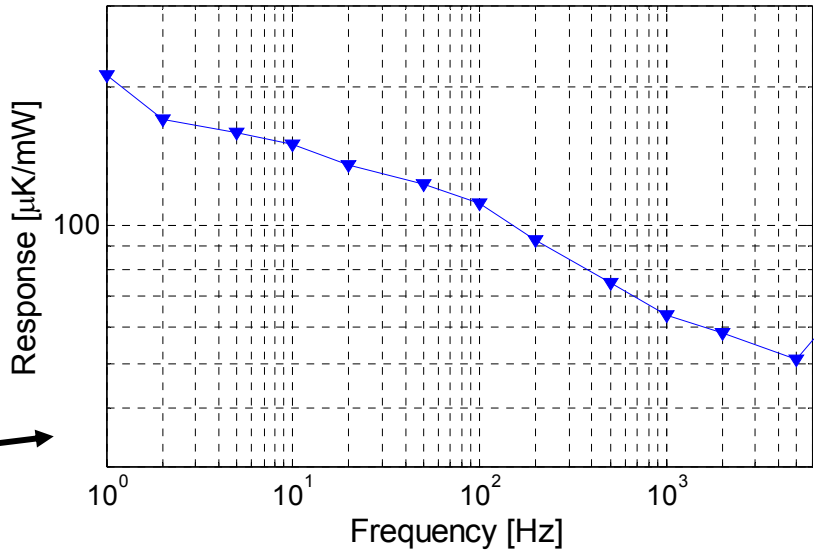


Closed Thermal-Lock Loop:

Out-of-Band Modulation → PDH Dispersion Slope

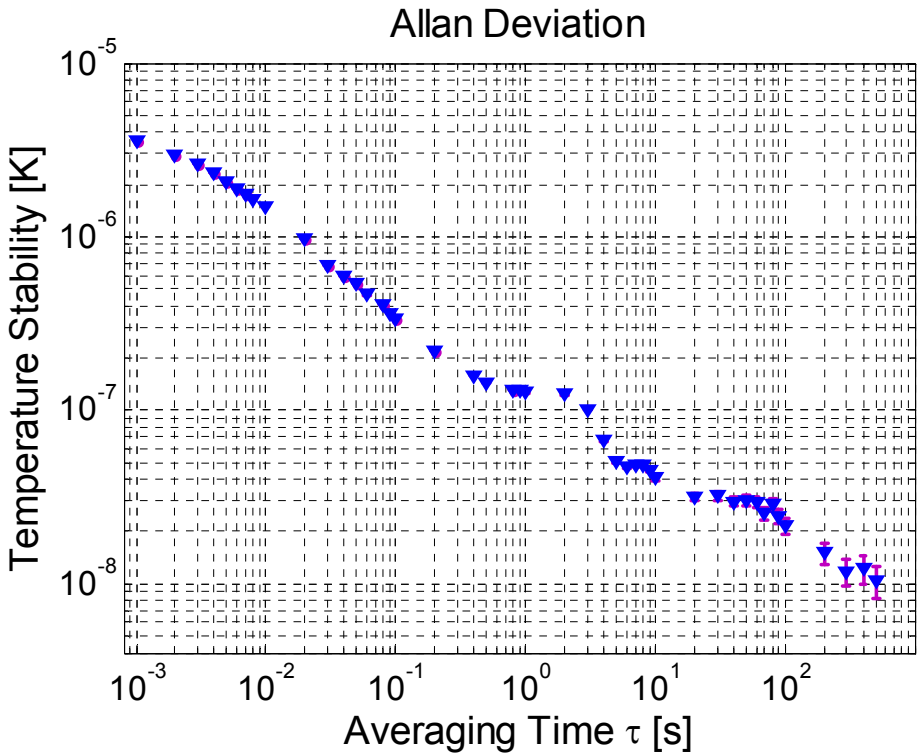
SNR Resolution: 4 μK

Example: Frequency response of pump amplitude modulation



Stabilization Result

- Stabilization of mode volume temperature down to nK range
- Laser simultaneously locked to cavity
- TEC ➔ Increased thermal BW means 2 decades faster averaging over heater alone



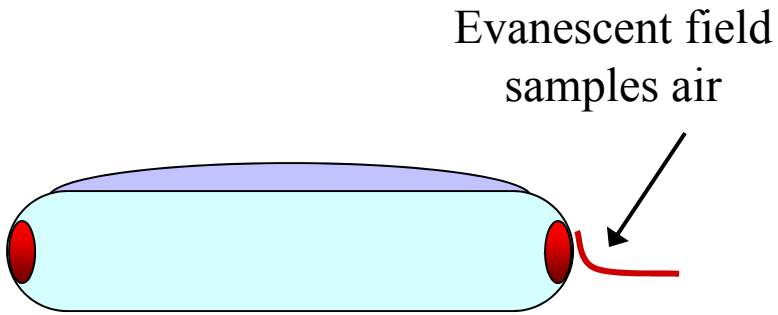
10 nK stability → ~8.7×10^{-14} optical frequency stability

Is the locked laser really this stable?

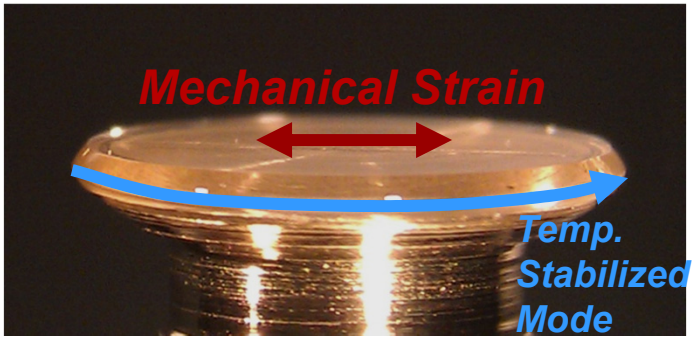
Optical Stability Error Sources

Common-mode Drifts are not Corrected

- Refrective index changes in the:
  - Host material
    - Non-linearities, photo-refraction
    - Interaction with other fields (magnetic, acoustic, e.g.)
  - Surrounding Gas



- Mechanical deformations from:
  - Temperature Gradients in disc
  - Strain in mounting structure
  - Aging



$$10^{-14} = \frac{\Delta f}{f} = \frac{\Delta R}{R}$$

Radial stability ~10^{-16} m needed!

Conclusions, Future Work

- Dual Mode Temperature stabilization:
  - Achieved tight laser lock with fast thermal feedback
  - High temperature stability of *Mode Volume*

- Investigate optical instability sources
  - Comparison to stable external reference
  - Vacuum enclosure of temperature stabilized WGMR