Testing athermal glass as laser frequency reference for interferometric sensors

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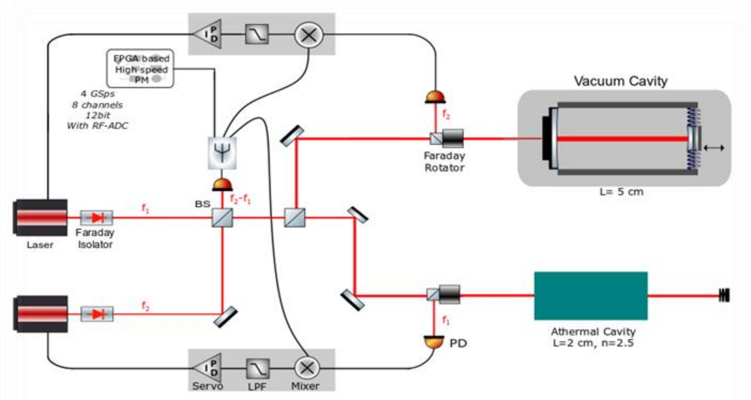
MOTIVATION

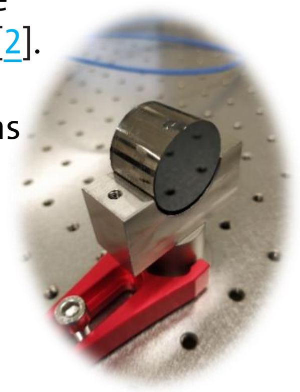
We work on developing an opto-mechanical inertial sensor that has a laser-interferometric readout. We plan to make use of the heterodyne stabilized cavity readout technique. The beat frequency carries the information about the accelerometer mirror movement and the reflected light from the cavity acts as an error signal and actuates the laser frequency [1].



For such a heterodyne technique, a highly-stable frequency reference cavity is of great importance, and we see that chalcogenide - 'Athermal' - glass material is one among the potential candidates.

ATHERMAL GLASS

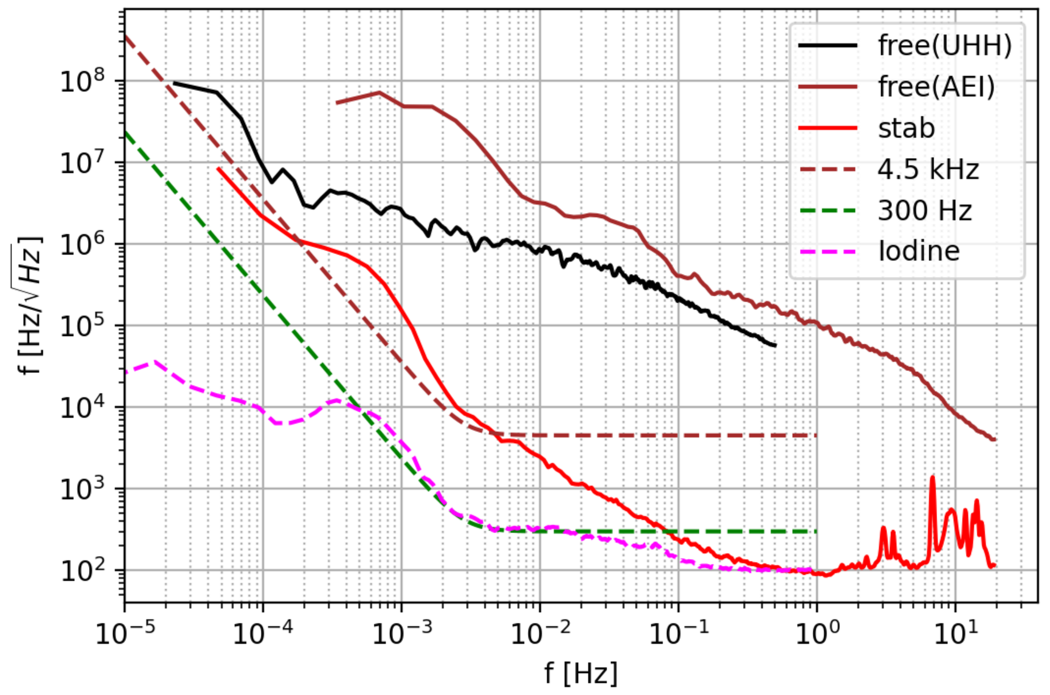
Athermal material can compensate for the effects of various noises on the frequency stability by maintaining a constant optical length of the cavity [2]. This eliminates the requirement of ultra-high temperature stability that often requires additional vacuum shielding. The ratio of As, Se, and S atoms on the substrate defines the Figures-Of-Merit (FOM) of the etalon. By tuning this ratio, it's possible to reach FOM equal to or very close to zero.



- Minimal achievable laser stability: $\frac{\tilde{\nu}}{\nu_0} = \frac{\tilde{l}}{L} = FOMetalon * \tilde{T}$
- $FOM_{etalon} = \frac{1}{nL}\frac{d(nL)}{dT}$, can be zero as well.

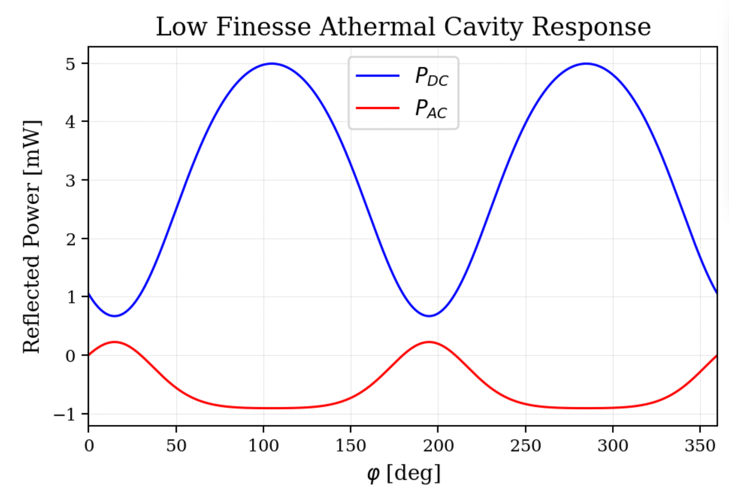
LASER FREQUENCY NOISE

The beat frequency between two free-running CTL lasers is measured for 12 hours using the frequency counter of Siglent SDG2122x Function Generator. The frequency spectral density is then compared with other references [4] as shown below. The used CTL lasers are External Cavity Diode Lasers (ECDL) that are tunable over a wide range (1510-1630nm).

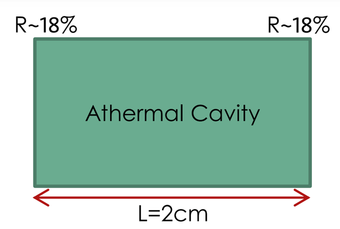


Finesse 2 — CAVITY SIMULATIONS

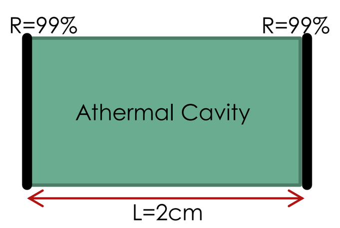
Before using the athermal samples as optical cavities, we have done few simulations on its performance using *'FINESSE'* [3]. The athermal substrate itself has a Refractive Index of ~2.5 and hence a reflectivity of ~18%. If a beat signal from two 10mW laser beams at 1550nm having an offset of 500MHz is coupled to such a cavity, then its response will be as shown in the figure. The shot noise induced displacement noise, in that case, is of the order of $4 \times 10^{-15}\ m/\sqrt{Hz}$.

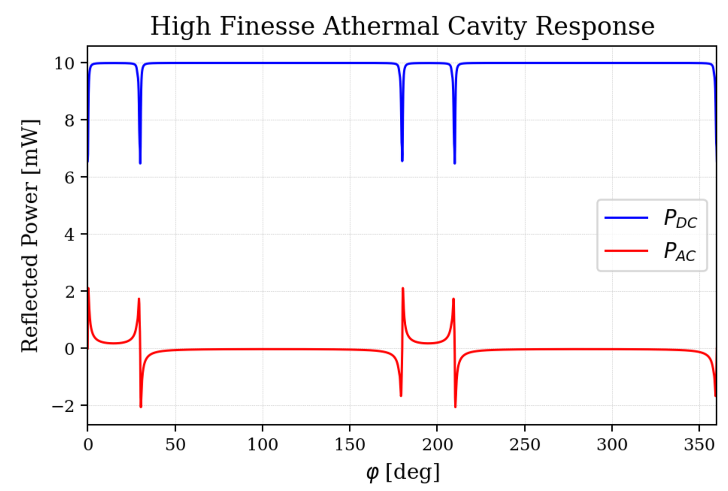


$$\tilde{\varphi}_{SN} = \sqrt{2}\cdot\frac{\tilde{i}_{SN}}{\frac{\partial i_{AC}}{\partial\varphi}} \quad [rad/\sqrt{Hz}]$$
$$= \sqrt{2}\cdot\sqrt{\frac{2q_e}{R_{PD}}}\cdot\frac{\sqrt{P_{DC}}}{\frac{\partial P_{AC}}{\partial\varphi}}$$



Coating the faces of such an etalon to 99% reflectivity improves the characteristics significantly and reduces the shot noise induced displacement noise by a factor of 100.



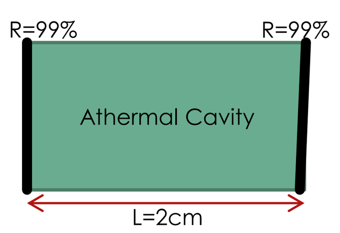


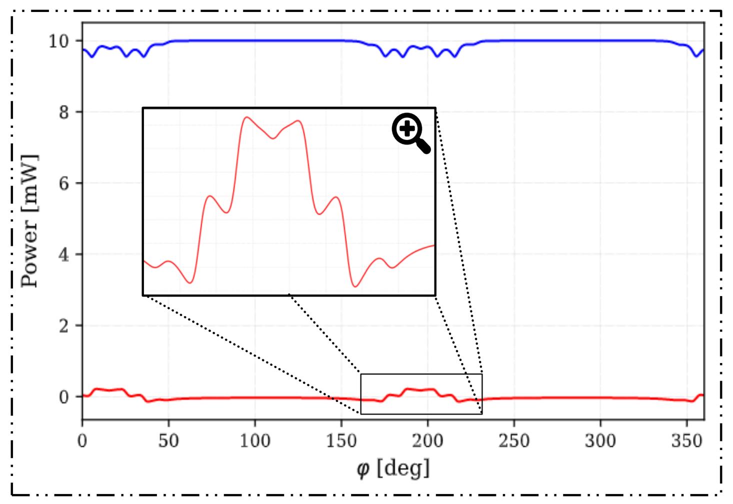
MIRROR MISALIGNMENT

The effect of tilting the end mirror of the flat-flat cavity on shot noise induced displacement noise under a heterodyne configuration is simulated. A few case studies considering only TEM_{00} modes are tabulated:

Waist size [mm]	Waist position [m]	Misalignment [µrad]	Displacement noise [m/√Hz]
5	0	0	1.54×10^{-17}
5	0	30	3.01×10^{-13}
1	0.5	100	5.37×10^{-14}

Including the higher-order modes affects the contrast significantly and one such response is shown below (here for a misalignment of 30µrad):

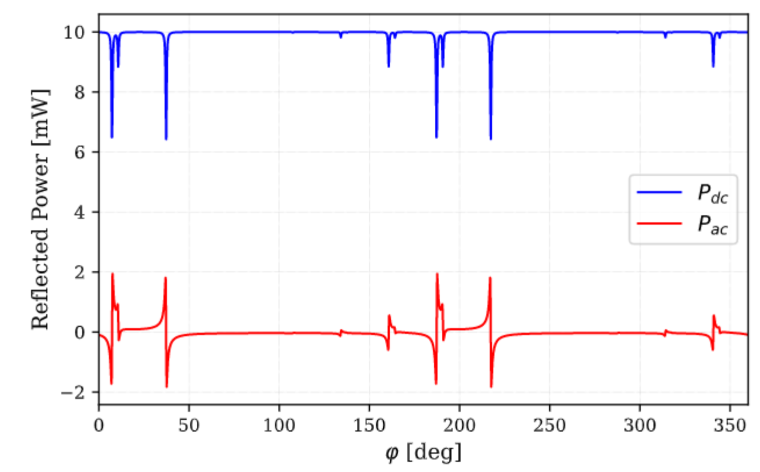


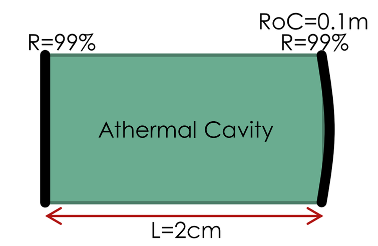


MODE MATCHING

Running the above simulation with the inclusion of Radius of Curvature (RoC) to the end face of the cavity shows that the circulating power within the cavity is very poor even for zero misalignment angle. So, it's evident that the beam parameters and the cavity eigenmodes aren't matched.

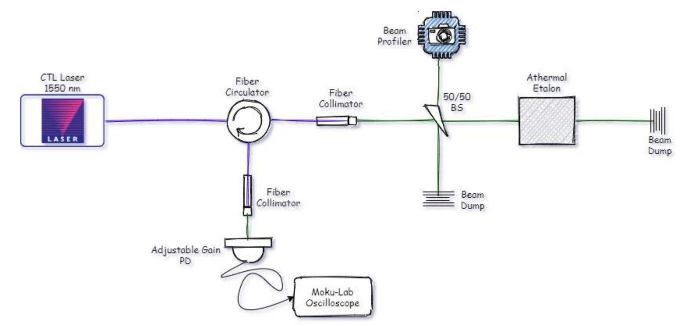
With *cav* and *trace* commands it's rather straightforward to get mode matching criteria. For RoC of 10cm, Gaussian beam having a waist size of 89µm at the input side of the cavity matches the modes and the cavity is stable as well. This significantly improves the over-all noise level as well. For a misalignment of 500µrad (cavity response is shown below), including the higher-order modes, the displacement noise estimation is $2.29 \times 10^{-17}\ m/\sqrt{Hz}$.

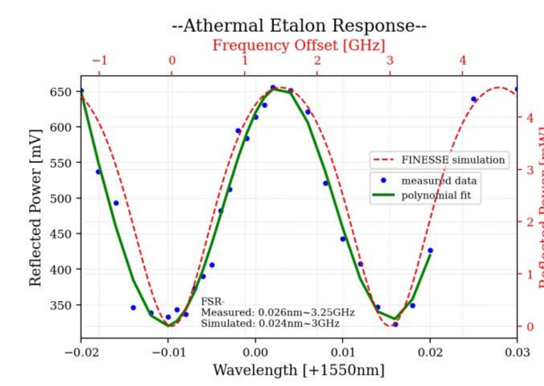


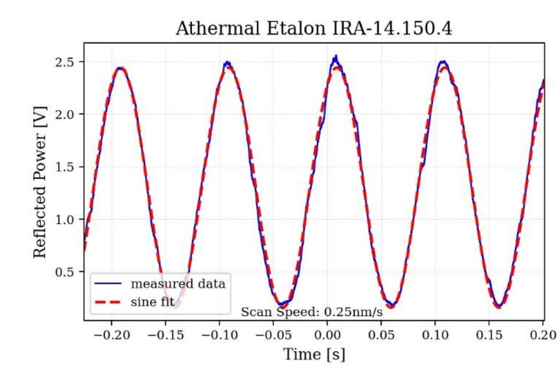


INITIAL EXPERIMENTS

While tuning the CTL laser frequency, we measured the reflected power from the athermal etalon samples. The cavity responses match close to what we simulated before.







By carefully aligning the set-up, we could achieve a contrast value > 85%. Experimentally we observed a FSR of 2.9539 GHz, against the theoretical value of 2.9609 GHz.

Currently we are setting-up heterodyne locking for two such athermal cavities.

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GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

References

1. Eichholz J., *et al.*, Physical Review D 92, 022004 (2015)
2. Athermal glass for infrared optics, M.J. Davis, M. Kocher, Current Developments in Lens Design and Optical Engineering XIX. Vol. 10745. International Society for Optics and Photonics, 2018.
3. http://www.gwoptics.org/finesse/
4. Oliver Gerberding *et al.*, Physical Review Applied 7, 024027 (2017)

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