Novel Noise Contributions in Crystalline Mirror Coatings

J. Yu, T. Legero, F. Riehle, C. Y. Ma, S. Herbers, D. Nicolodi, D. Kedar[*], E. Oelker[*,#], J. Ye[*], and U. Sterr
Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
Jialiang.yu@ptb.de
[*]JILA, NIST and University of Colorado, Boulder, USA
[#]University of Glasgow, Glasgow, UK

Summary— **We discovered and characterized a novel birefringent noise in $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline mirror coatings at cryogenic temperature. We also determined the upper limit of coating Brownian noise in a reliable way. Our results indicate that excess noise related to semiconductor could be an obstacle to reaching the low Brownian thermal noise floor of these coatings. Our investigations on crystalline mirror coatings provide important design considerations for precision interferometry at cryogenic temperature.**

Keywords—crystalline mirror coating; cryogenic; Gallium Arsenide; interferometry; birefringent noise; thermal noise

I. Introduction

The most frequency stable oscillators are based on high-finesse optical cavities. Ultra-stable lasers based on cryogenic silicon resonators with dielectric mirror coatings have reached 4×10^{-17} fractional frequency instabilities [1-2] and serve as local oscillators for the most stable atomic clocks [3,4]. The frequency instability of these laser systems is limited by thermal noise, with the dominant contribution arising from Brownian thermal noise of the high-reflectivity mirror coatings. Crystalline mirror coatings exhibit lower mechanical losses and thus lower Brownian thermal noise than dielectric coatings [4]. As a result, applying these crystalline coatings serves as a promising approach for further improvement of laser frequency stability.

We operate a 21 cm long single crystal silicon optical resonator with crystalline mirror coatings at 124 K. The Brownian thermal noise floor of this resonator is expected to be 1×10^{-17}, assuming the mechanical loss of GaAs at 124 K is equal to its room temperature value.

After suppressing all known technical noise sources below the thermal noise level, we found that the measured frequency instability of this resonator is significantly higher than predicted, indicating the existence of additional noise sources or higher mechanical losses in the crystalline coatings. In this paper, we present a detailed characterization of the noise contributions in crystalline coatings and describe how we suppress the anti-correlated birefringent noise.

II. Experimental Setup

A schematic of the main building blocks of our experimental setup is illustrated in Fig. 1. Two erbium doped fiber lasers at 1.5 µm are locked on cavity resonances from both sides of the optical resonator with the Pound-Drever-Hall (PDH) technique. Both lasers are equipped with independent electronic and optical setups to suppress non-common technical noise sources including residual amplitude modulation, optical power fluctuations and optical path length fluctuations. The contribution of vibrational noise is reduced to below the expected thermal noise by supplementing a commercial active vibration isolation (AVI) platform with additional seismometer and tilt sensors. These sensors feed a digital control loop acting on the AVI platform setpoint to improve the suppression of low frequency accelerations. Frequency noise induced by

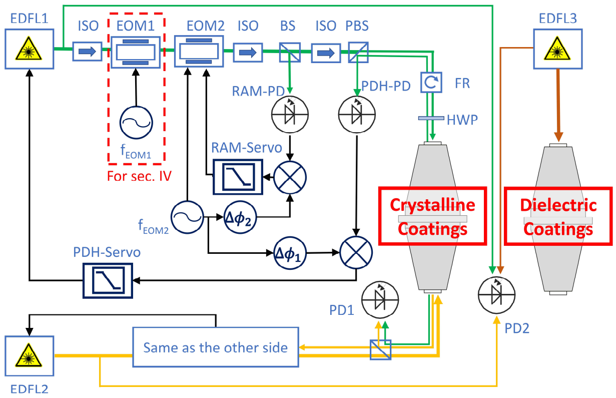

Fig.1. Experimental setup. EDFL: erbium doped fiber laser, ISO: optical isolator, EOM: electro-optic modulator, (P)BS: (polarization) beam splitter, FR: faraday rotator, HWP: half wave plate, PD: photodetector.

temperature fluctuations is also suppressed by stabilizing the system at its zero-crossing point of the coefficient of thermal expansion. Influence of parasitic etalons is diminished by tilting the optical surfaces and adding optical isolators. With these efforts, the sum of technical noise contributions is well below the predicted Brownian thermal noise floor between 5 s and 1000 s averaging time for both lasers. The frequency fluctuations of the two lasers are measured by referencing them to another cryogenic silicon cavity with dielectric mirror coatings [2]. The EOM1 is used only for the measurements described in section IV.

III. Birefringent Noise

Static birefringence is observed in $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline coatings [5-6], but its physical origin is not well understood. In our cavity the crystalline axes of the two mirror coatings are aligned in parallel. The resulting birefringence splits the cavity resonances into two polarization eigenmodes that are about 200 kHz apart.

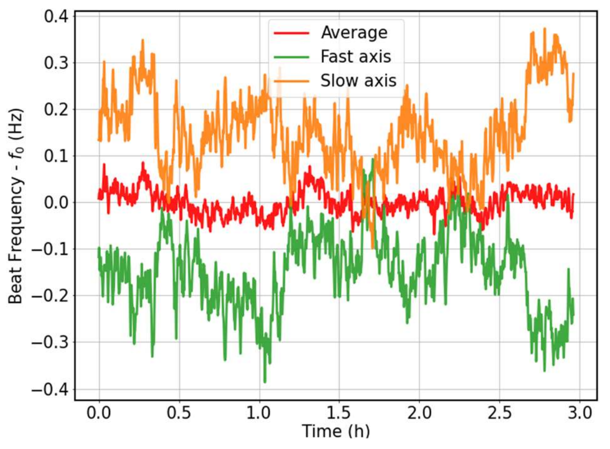

Fig.2. Frequency fluctuations in the beat signal between an ultra-stable reference laser and the two polarizaton eigenmodes along fast (green) / slow (orange) axes and their averaged beat signal (red).

Our setup allows us to stabilize each laser independently on each of the two polarization eigenmodes of the cavity. When the polarizations of the excited cavity modes are orthogonal, their frequency fluctuations that are anti-correlated (Fig.2), indicating birefringence fluctuations of the crystalline coatings.

Because of their common mode area and similar temperature coefficient of refractive index, this anticorrelation between the two polarization eigenmodes cannot be explained by thermo-elastic or thermo-refractive effects [7]. We attribute this novel birefringent noise to the semiconductor property of crystalline coatings. When the polarizations of the two lasers are parallel, the same refractive index of the mirror coatings is

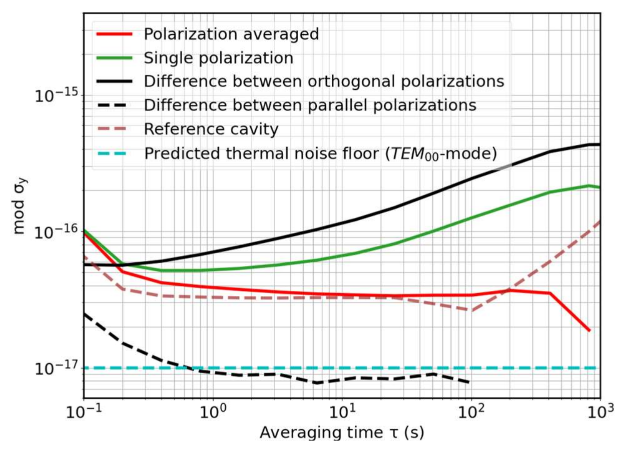

Fig. 3. Frequency instability of the average of two polarizations (red) is much lower than those of the individual polarization eigenmode (green) and of the difference between two orthogonal polarizations (black solid). The frequency instability between parallel polarizations (black dashed) reveals technical noise. The frequency instability of a silicon cavity with dielectric mirror coatings (brown dashed) and the predicted Brownian thermal noise of crystalline coating for TEM_{00} mode (cyan dashed) are included for comparison.

probed, and the difference includes mainly the non-common technical noise sources.

The frequency instability of the two lasers determined via three-cornered-hat (TCH) method, and the merit of averaging the two polarization eigenmodes are visible in the modified Allan deviation (Fig.3).

As shown in Fig.3, the performance of the resonator is limited by the birefringent noise of the crystalline coatings. The anti-correlation of the noise exhibited by the two polarization eigenmodes can be exploited to improve the frequency stability of the cavity by taking the average frequency of the two polarization axes. The obtained frequency stability is however still significantly higher than the predicted Brownian thermal noise.

To reduce the complexity of polarization averaging, we developed a dual-frequency locking technique that allows to cancel birefringent noise by using only one laser. This is achieved by exciting both polarization eigenmodes simultaneously using two of the additional spectral lines generated with EOM1 in Fig.1, which generates an overall PDH-error signal containing equally weighted contributions from both polarization eigenmodes. With this dual-frequency locking technique, we suppress the birefringence noise by at least one order of magnitude [8].

IV. Brownian thermal noise in optical coatings

The nature of the observed frequency noise sources can be investigated by probing the spatial correlation between different cavity transverse modes: coating Brownian thermal noise with a correlation length on the order of the coating thickness is spatially uncorrelated, this will induce largely uncorrelated frequency fluctuations between different transverse cavity modes. Other known noise contributions have much stronger spatial correlation, and they will cause near to completely correlated frequency shifts for different cavity

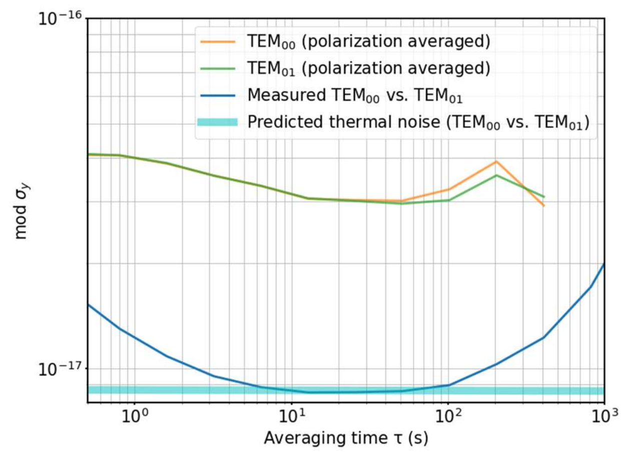

Fig..4. Measured fractional frequency instabilities of TEM_{00}-mode (orange) and TEM_{01}-mode (green) with the birefringent noise averaged out. The fractional frequency instablity of the beat between the first laser (TEM_{00}) and the second laser (TEM_{01}) (blue) is compared with its predicted coating Brownian thermal noise value for crystalline coating (cyan).

modes. Hence, the upper limit of coating Brownian thermal noise can be determined by measuring the difference in frequency fluctuations between two cavity transverse modes.

To perform this measurement, we stabilize one laser to the polarization averaged TEM_{00} mode and the other to the averaged TEM_{01} mode via dual-frequency locking technique. The frequency stability of the beat-note between these two lasers is in very good agreement with the predicted coating Brownian thermal noise level of 0.9×10^{-17} in modified Allan deviation between 10 s and 100 s averaging time (Fig.4). In contrast, the frequency stabilities of both cavity transverse modes, determined via TCH-method, are significantly higher than the predicted value. This result validates our estimation on the coating Brownian thermal noise, and at the same time indicates the existence of unidentified excess noise. Furthermore, this excess noise has a correlation length much larger than the cavity mode diameter, and it is independent of optical power.

V. Conclusions

Our measurements prove that $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline mirror coatings preserve their low mechanical losses at 124 K (i.e. $\phi_{124} = \phi_{300K} = 2.5 \times 10^{-5}$). However, other noise sources degrade the frequency stability above the predicted thermal noise limit. This seems to point to much richer processes in crystalline semiconductor mirror coatings, with birefringent noise being just one example. Even after removing the birefringent noise via polarization averaging, the performance of our resonator is still limited by some unknown flicker noise at 3.5×10^{-1} . It is currently unknown if this excess noise is a universal property of crystalline coatings. Further investigation with other mirror pairs and at other temperature is therefore essential for improving our understanding of noise processes in crystalline coatings.

Acknowledgments

We acknowledge support by the Project 20FUN08 NEXTLASERS, which has received funding from the EMPIR programme cofinanced by the Participating States and from the European Union's Horizon 2020 Research and Innovation Programme, and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy–EXC-2123 QuantumFrontiers, Project-ID 390837967; SFB 1227 DQ-mat, Project-ID 274200144. This work was partially supported by the Max Planck-RIKEN-PTB Center for Time, Constants and Fundamental Symmetries. JILA further acknowledges support by NIST, DARPA and the Air Force Office of Scientific Research.

References

[1] S. Häfner et al., "8 $\times10^{-17}$ fractional laser frequency instability with a long room-temperature cavity", Opt. Lett., vol. 40, pp. 2112–2115, 2015

[2] D. G. Matei et al., "1.5 µm lasers with sub-10 mHz linewidth", Phys. Rev. Lett, vol. 118, pp. 263202, 2017.

[3] S. Dörscher et al,. "Optical frequency ratio of a $^{171}Yb^{+}$ single-ion clock and a ^{87}Sr lattice clock", Metrologia, 2021

[4] E. Oelker et al,. "Demonstration of 4.8 × 10−17 stability at 1 s for two independent optical clocks", Nat. Photonics, vol. 13, p. 714 – 719, 2019

[5] G. D. Cole et al., "Tenfold reduction of Brownian noise in optical interferometry", Nat. Photonics, vol. 7, p. 644-650, 2013

[6] G. Winkler et al., "Mid-infrared interference coatings with excess optical loss below 10 ppm", Optica, vol. 8, pp. 686-696, 2021

[7] V. B. Braginsky et al., "Thermodynamical fluctuations and photo-thermal shot noise in gravitational wave antennae", Phys. Lett A, vol. 264, pp. 1-10, 1999

[8] J. Yu et al., "A Simple Frequency Stabilization Technique for Averaging Birefringent Noise in Crystalline Mirror Coatings", EFTF-IFCS proceedings, 5095, 2022