# A Simple Frequency Stabilization Technique for Averaging Birefringent Noise in Crystalline Mirror Coatings


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***Summary*— We present a technique to stabilize laser frequency to an average of different cavity modes via Pound-Drever-Hall (PDH) scheme. This technique was applied to eliminate the laser frequency instability arising from fluctuation of the birefringence in $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline mirror coatings by locking to the average frequency of orthogonally polarized cavity modes.**



***Keywords*— *laser frequency stabilization; crystalline mirror coating; Gallium Arsenide; interferometry; birefringent noise***


## I. Introduction

The performance of the most stable lasers [1] is mainly limited by Brownian thermal noise in amorphous optical coatings. Crystalline optical coatings with low mechanical loss are expected to reduce this noise in precision interferometry by a factor of ten [2]. Therefore, we set up a new cryogenic silicon cavity with crystalline mirror coatings, and its frequency instability induced by Brownian thermal noise is predicted to be $1 \times 10^{-17}$.

$Al_{0.92}Ga_{0.08}As/GaAs$ crystalline mirror coatings exhibit birefringence [2-3], yet its physical origin is still unknown. We observe that birefringence fluctuations significantly degrade the frequency stability of our optical resonator [4]. Birefringence fluctuations cause anticorrelated frequency fluctuations for the two orthogonal polarization eigenmodes. The birefringent noise can thus be suppressed by locking the laser to an average of the two polarization eigenfrequencies. This can be in principle achieved by locking a second laser to the optical resonator. However, a completely independent laser locking setup would require separate residual amplitude modulation control, laser intensity stabilization, and fiber noise cancellation, resulting in considerable additional complexity.

Here we report a simpler locking scheme which uses a single laser delivered via a single optical path to the cavity. We demonstrate that this scheme is effective in suppressing the birefringence noise of the crystalline mirror coatings.

## II. Experimental Setup

Our locking scheme generates an overall PDH error signal with equal contributions from both polarization eigenmodes. This is realized by creating two spectral lines with phase modulation in a waveguide EOM and coupling them simultaneously into the optical resonator. A schematic of the main building blocks is shown in figure 1.

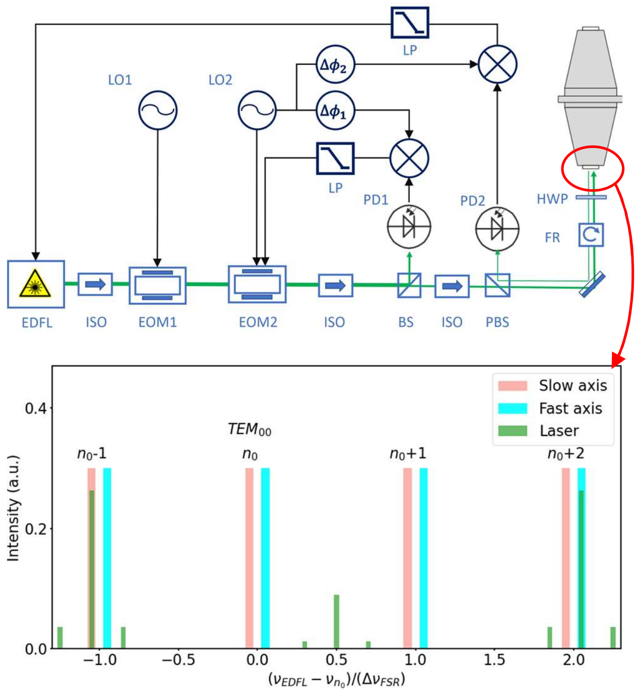


Fig. 1. Experimental setup of the locking scheme (top). The frequency components of the light (green), and the cavity resonances of fast (cyan) and slow (red) axes are displayed as a function of $\Delta\nu_{FSR}$ (bottom). EDFL: erbium doped fiber laser, ISO: optical isolator, EOM: electro-optic modulator, (P)BS: (polarization) beam splitter, FR: faraday rotator, HWP: half wave plate, PD: photodetector, LP: loop filter, LO: local oscillator.

The mirrors are optically contacted to the cavity with the slow/fast axis aligned with respect to each other. This leads to a splitting of the linear polarized cavity eigenmodes of $\Delta\nu_{BR}$ = 200 kHz. The light at the cavity is linearly polarized, at 45° to the slow/fast axis of the mirror. The first order sidebands of an electro-optic modulator (EOM1) are used to excite the two polarization eigenmodes. The modulation frequency $f_{mod1}$ of EOM1 was set to address modes separated by more than a free spectral range $\Delta\nu_{FSR}$:

$$f_{mod1} = (n + 0.5)\Delta\nu_{FSR} + 0.5\Delta\nu_{BR},\ n = 0,1,2 \ldots$$

In our setup, we choose $f_{mod} \approx 1.5\Delta\nu_{FSR}$, and the modulation index of $M = 1.8$ rad to maximize the optical power used to generate PDH error signal and avoid spurious signals from the carrier and the higher order sidebands. The frequency spectrum of the incident beam along with the $TEM_{00}$ modes of the resonator is also illustrated in figure 1.

Scanning the laser frequency gradually across the cavity resonance, three PDH-error signals will be observed: upper sideband resonant on slow axis, both sidebands in resonance, and lower sideband resonant on fast axis. By locking to the central error signal, the laser is stabilized to the average of the two polarization eigenmodes, that are equally weighted in this error signal.

## III. Results

The achieved frequency instability with this dual frequency lock is shown in figure 2. To evaluate the noise of this method, an additional laser is coupled from the opposite side of resonator and locked to adjacent cavity modes. The observed relative noise between the two lasers is well below $10^{-17}$.

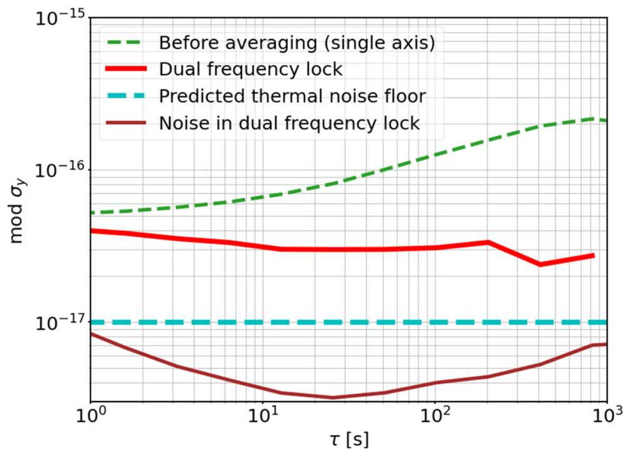


Fig. 2. Frequency stability of cryogenic silicon resonator with crystalline mirror coating when a laser is locked on fast axis (green). The birefringent noise was suppressed with dual frequency locking (red). The frequency fluctuations between two lasers locked simultaneously to the same cavity indicate the noise of this locking method (brown), which is lower than the predicted thermal noise floor in this optical resonator (cyan).

## IV. Disscussion

Dual frequency locking significantly improves the achieved frequency stability of the optical resonator. Yet the lowest measured frequency instability of the resonator is still much higher than the predicted Brownian thermal noise floor, which indicates additional noise sources in the semiconductor mirror coating.

The setup can be simplified by combining the modulations applied by EOM1 and EOM2 on a single phase modulator. In our implementation we used two modulators to minimize the changes to the existing setup, and to avoid possible interferences of the complex modulation applied to a single EOM to the stabilization of residual amplitude modulation.

The performance of dual frequency lock is limited by the smaller PDH error signal and imperfect weighting of the two polarizations. As shown in figure 1, two frequency components are coupled into the cavity. Half of their power is reflected by the front mirror due to polarization-mismatch. This leads to a smaller PDH error signal. Furthermore, the birefringent noise can only be completely cancelled, if the two polarization eigenmodes are perfectly balanced. From our experience, a tenfold reduction of birefringent noise can be easily realized.

## V. Conclusions

Birefringent noise is one obstacle to exploiting the low mechanical loss of $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline coatings. It is still not clear if this noise is universal in optical coatings of crystalline semiconductor materials. With our dual frequency locking scheme, birefringent noise can be largely suppressed with minimum effort.

## 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 .

## References

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

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

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

[4] J. Yu et al., "Noise Contributions in Crystalline Mirror Coatings", EFTF-IFCS proceedings, 5096, 2022