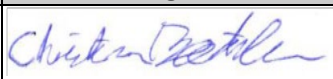
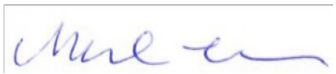
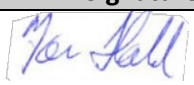
DFM
Danish National Metrology Institute

# Test Report

# Optical Phase-Locked-Loop and Relative Intensity Noise Performance of Two 698 nm NKT Photonics Koheras HARMONIK HP H69 Lasers

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# 1 Executive Summary

We characterize the noise performance of an NKT Photonics Koheras HARMONIK HP H69 laser system emitting 698 nm light using a heterodyne beat between two nominally identical systems, such that all reported results refer to the combined noise of both lasers. From the beat-note signal, we derive phase-noise and frequency-noise spectra, as well as Allan and modified Allan deviation statistics. With offset phase locking implemented via the module's internal piezo actuator, low-frequency noise is strongly suppressed and the modified Allan deviation of the beat note reaches a relative frequency stability of $8\times10^{-18}$ at 1 s. Using an external AOM-based lock, the 1 s stability of the beat note is further improved to below $2\times10^{-18}$, surpassing the performance of the best commercial cavity-stabilized laser references.

We additionally characterized the relative intensity noise (RIN) of the 698 nm output using shot-noise-limited self-homodyne detection. At 4 mW detected power, the calculated shot-noise reference corresponds to (−157.7 ± 0.4) dBc/Hz. The measured RIN ranges (−140.7 ± 4) dBc/Hz between 2.5–20 kHz, (−143.7 ± 2) dBc/Hz between 12-20 kHz and exhibits classical excess-noise features near 0.7, 1.0, and 1.5 MHz, uncertainties are stated as expanded uncertainties.

# 2 Introduction and Scope

High-stability, narrow-linewidth, high-power lasers are essential for precision spectroscopy, optical frequency standards, quantum technology, and high-resolution metrology. In these applications, phase, frequency, and power stability directly impact measurement accuracy and long-term reliability.

NKT Photonics developed the Koheras HARMONIK HP H69 laser system to deliver high spectral purity and high output power at 698 nm through sum-frequency generation of 1970 nm and 1082 nm fiber lasers. As Denmark's National Metrology Institute, DFM independently evaluates the spectral noise and stability of this platform.

The scope of this report is to:

- Provide a quantitative characterization of phase noise and frequency noise
- Present the corresponding noise power spectral density
- Evaluate the frequency stability using Allan deviation
- Characterize the relative intensity noise (RIN)

The results are intended to support NKT Photonics in validating the laser design and in communicating its performance to end users.

# 3 Experimental Setup and Methods

## 3.1 Laser systems

Each Koheras HARMONIK HP H69 system consists of two single-frequency fiber lasers, emitting light with wavelengths of 1082 nm and 1970 nm. These are amplified and combined in a Koheras HARMONIK module for sum-frequency generation at 698 nm. In this test, we used two nominally identical Koheras HARMONIK H69 systems, operated according to specifications, each delivering 10 W of optical output power at 698 nm. In this configuration, this corresponded to 10 W at 1970 nm and 9.5–10.6 W at 1082 nm (the 1082 nm channel can be tuned up to 16 W if required) at the input to the sum-frequency generation module.

**Serial numbers for the Koheras HARMONIK HP H69 systems:**

| Module | System 1 | System 2 |
|---|---|---|
| Y10 Boostik (@ 1082nm) | K0144482 | K0145409 |
| T20 Boostik (@ 1970nm) | K0145429 | K0145418 |
| SFG Harmonik (@ 698nm) | 2535F001.03 | 2539F003.01 |

## 3.2 Beat-note setup

The system outputs all three wavelengths. The 1970 nm and 1082 nm beams are not required for the 698 nm stability evaluation and are dumped. The 698 nm outputs from the two modules are attenuated using two beam splitters (6% reflection per surface) per beam, combined, and further attenuated with a 90%-reflectance beam splitter plus an OD-1 neutral density filter. The resulting powers at the detector are 0.37 mW and 0.30 mW for the two systems. The combined beat note is detected on an amplified photodetector (Thorlabs PDA10A2).

This is a heterodyne beat between two similar lasers, and the extracted noise represents the **combined relative noise of both laser systems**.

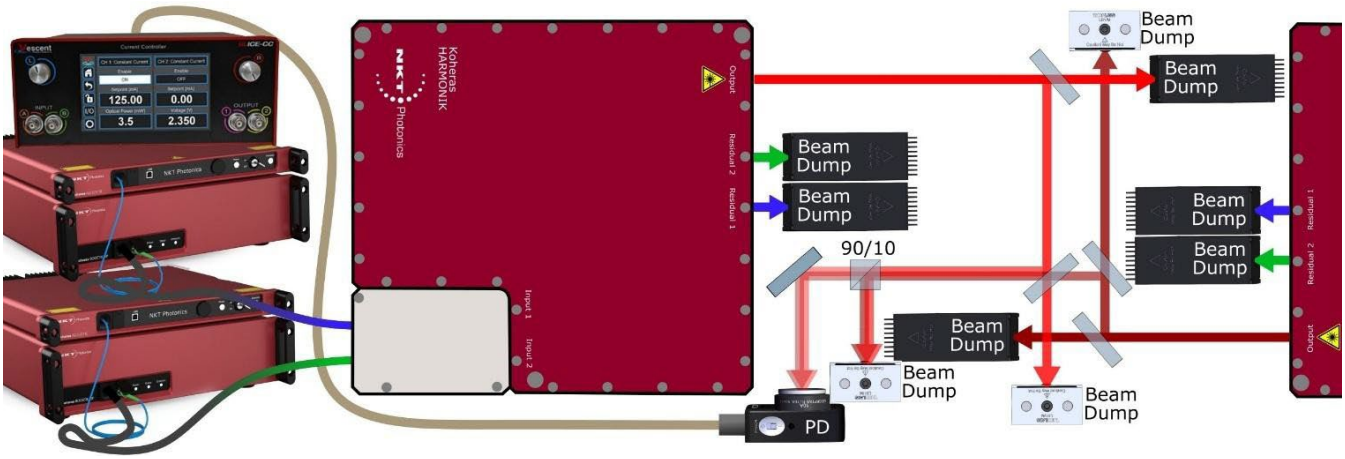



**Figure 1:** Experimental setup for measuring the relative noise between two nominally identical Koheras HARMONIK HP H69 systems, the right laser system (system 2) is truncated, as it is a replica of the left system (system 1), without the locking feedback. The light used for sum-frequency generation at 1970 nm (blue) and 1082 nm (green) is dumped after sum generation, while the 698 nm light (dark and light red) is attenuated to 0.30 mW and 0.37 mW, respectively.

## 3.3 Optical Phase-lock configuration

The beat note is offset phase-locked using a Vescent SLICE-OPL servo controller. The detected beat has a signal-to-noise ratio of 65 dB in a 10 kHz resolution bandwidth. Feedback to steer the output light frequency is applied first through the internal piezo actuator acting on the 1082 nm laser of system 1. The tuning range of laser's piezo actuator is set to 32% to avoid digitization limits in the SLICE-OPL; although no such digitization effects

were observed in our measurements. SLICE-OPL servo settings: gain −58.7 dB, PI corner 1 kHz, PD corner 1.5 kHz. These parameters were optimized to minimize residual noise at Fourier components below 9 kHz.

For all measurements, the beat-note signal is divided by a factor of 16 in the SLICE-OPL in order to extend the effective capture and locking range of the phase lock. Phase excursions exceeding π radians between the lasers would otherwise cause cycle slips, resulting in the loss of one RF cycle. We find that, when acting only on the piezo, the laser cannot be reliably phase-locked without dividing the beat note by at least a factor of 2.

In a second configuration, the beat note is offset-locked via an acousto-optic modulator (AOM) placed between the seed laser and the amplifier. The AOM is locked with the Vescent SLICE-OPL servo controller, while a Moku:Lab is used as a voltage-controlled oscillator (VCO) to drive the AOM. A slow feedback loop is applied to the piezo actuator of the 1082 nm laser to keep the required AOM frequency within its tuning range. This slow piezo lock uses the auxiliary output of the SLICE-OPL operated at its lowest gain setting, and in this configuration the tuning range of the laser's piezo actuator is set to 8%. For the AOM lock, the SLICE-OPL servo settings are: gain −35.4 dB, PI corner 200 kHz, PD corner 300 kHz. The Moku:Lab is operated with a sensitivity of 2.0 MHz/V. The Moku:Lab exhibits relatively elevated noise at Fourier frequencies beyond the bandwidth of the measurements presented here. While this excess high-frequency noise does not impact the demonstrated low-frequency stability, it may be undesirable for applications that require very low phase noise over a broader Fourier-frequency range.

### 3.4 Data acquisition and processing

Noise was measured with two complementary instruments:

1. **Microchip 53100A phase-noise analyzer (PNA)**: records beat-note phase fluctuations directly, providing phase-noise and derived frequency-noise spectra and Allan / modified Allan deviations with low close-to-carrier noise floor.
2. **Agilent 53230A frequency counter**: logs instantaneous beat frequency at high time resolution, useful for identifying narrow spectral features and fast frequency changes, but reaches its measurement floor for low frequencies when measuring the locked laser system.

Both measurement instruments as well as the SLICE-OPL are referenced to the same 10 MHz source.

## 4 Results

### 4.1 Optical Phase-Lock Performance

The phase stability of the offset phase lock was evaluated by recording the phase difference between the beat note and its 10 MHz locking reference as a function of time, as shown in Fig. 2. The system maintained a continuous lock for the entire 6-hour measurement duration, demonstrating stable operation. For the AOM-based lock, the measurement was purposefully discontinued after approximately 1 hour.

The behavior of the piezo lock is consistent with intermittent phase excursions beyond π radians and therefore requires that the beat note be divided down before phase detection; without this division, the phase lock can lose track of the reference due to cycle slips. Such excursions can arise from impulsive mechanical disturbances within the servo bandwidth that cannot be fully suppressed by the internal piezo actuator, as well as from higher-frequency (out-of-band) laser noise that is not adequately corrected by the present loop. Measurements with

the AOM-based lock show that the increased servo bandwidth enhances the suppression of rapid frequency fluctuations and reduces the phase noise, strongly suppressing π-level phase excursions.

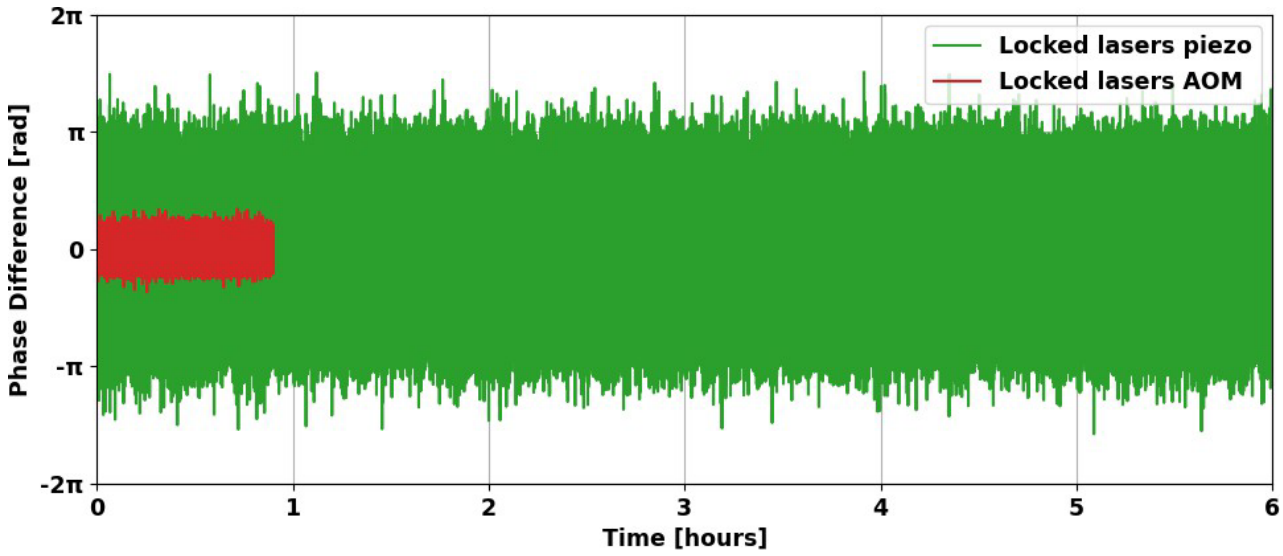



**Figure 2:** Phase difference between the beat note and its 10 MHz reference. Data rate: 100 Hz. Measured with a Microchip 53100A phase-noise analyzer.

## 4.2 Phase- and Frequency-Noise Spectra

Frequency- and phase-noise spectra were extracted from the same phase-difference time series shown in Fig. 2. The measurements were repeated with the phase lock disabled to provide a free-running reference under otherwise identical optical power levels and detection conditions. The phase-noise measurements are shown in Fig. 3, and the corresponding frequency-noise measurements are shown in Fig. 4.

In the piezo-locked configuration, the frequency noise is reduced at Fourier frequencies below 9 kHz, consistent with effective suppression by the servo loop. Any narrow features visible in the locked spectra are most likely due to mechanical or acoustic perturbations within the servo bandwidth that cannot be fully corrected by the laser's internal piezo actuator. To increase frequency resolution, the data were also recorded with an Agilent 53230A frequency counter, which reveals multiple distinct frequency peaks. The counter data are shown for the locked laser down to 300 Hz because, below this frequency, the beat note starts to reach the counter's measurement noise floor.

In the AOM-locked configuration, the frequency noise is reduced at Fourier frequencies below 30 kHz, possibly limited by the delay introduced by the Moku:lab acting as a VCO.

Overall, these results demonstrate that the phase lock improves the spectral noise performance primarily in the low-frequency region. The locking feedback bandwidth is limited by the bandwidth of the piezo or the Moku:lab, while the remaining high-frequency noise could be further reduced by using a higher-bandwidth VCO or, alternatively, an EOM to extend suppression beyond the present loop limit.

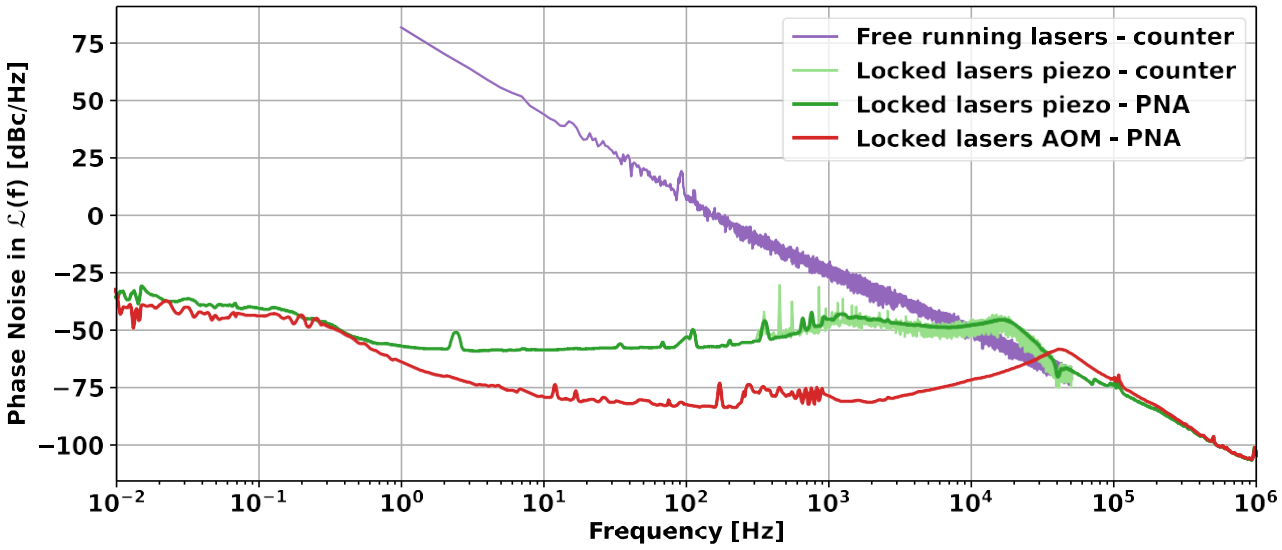



**Figure 3:** Phase noise measurements taken with an Agilent 53230A frequency counter (light green and purple) and a Microchip 53100A phase-noise analyzer (PNA) (dark green and dark red). The data for the free-running lasers were corrected for linear drifts before computing the noise.

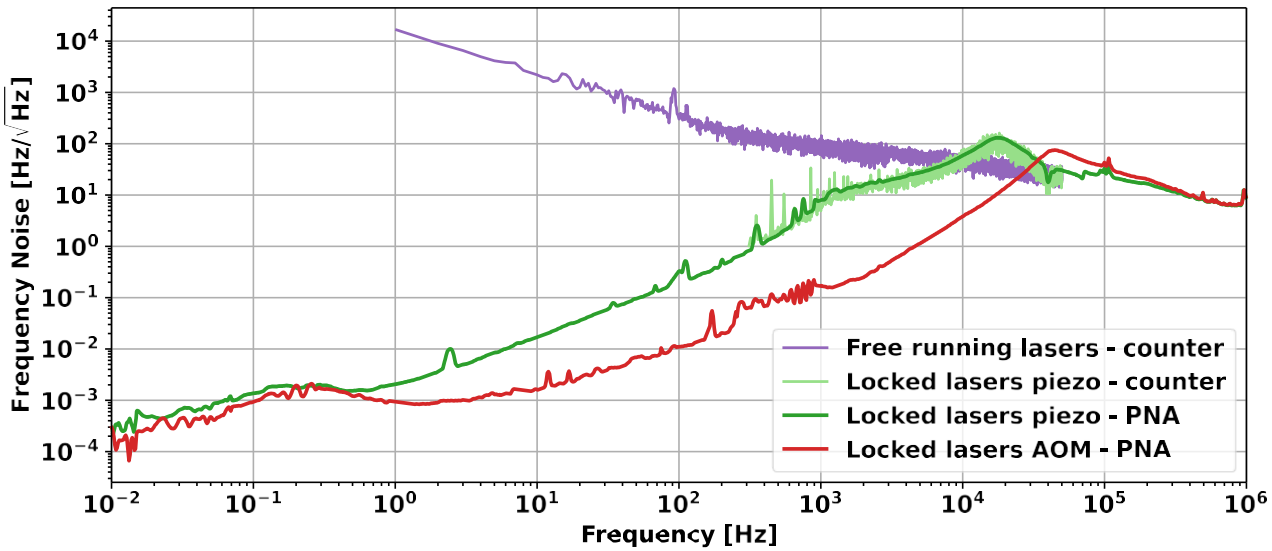



**Figure 4:** Frequency noise measurements taken with an Agilent 53230A frequency counter (light green and purple) and a Microchip 53100A phase-noise analyzer (PNA) (dark green and dark red). The data for the free-running lasers were corrected for linear drifts before computing the noise.

## 4.3 Fractional Frequency Stability (Allan / Modified Allan Deviation)

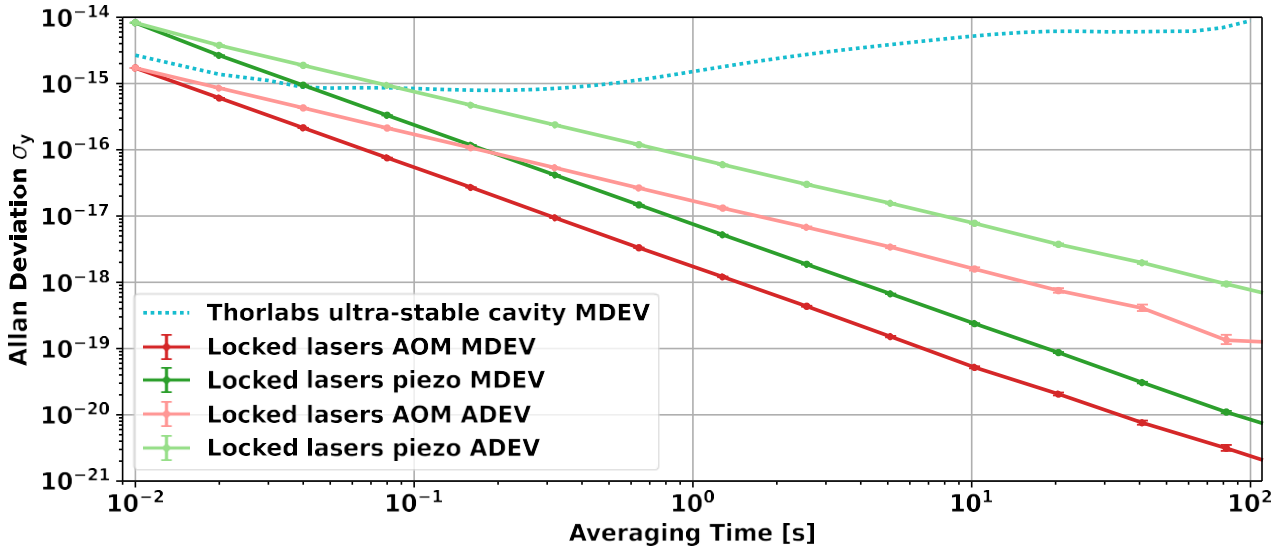



**Figure 5:** Fractional-frequency stability of the phase-locked beat note versus averaging time. The standard Allan deviation (light red and light green) and modified Allan deviation (dark red and dark green) are computed from the recorded phase-difference data in fig. 2, while the dashed blue curve shows the published modified Allan deviation of a Thorlabs crystalline-mirror cavity [1].

The frequency stability of the phase-locked laser system is characterized using the modified Allan deviation (MDEV), shown in Fig. 5. With the AOM-based lock, the MDEV reaches a fractional stability below $2 \times 10^{-18}$ at 1 s, placing the system in a better performance class than the best commercially available local reference cavities, such as Thorlabs' crystalline-mirror cavities reported in [1]. The piezo-locked laser surpasses the cavity-limited stability at integration times of 0.04 s and continues to average down for longer integration times, indicating sustained suppression of residual low-frequency noise, reaching a fractional stability of $8 \times 10^{-18}$ at 1 s.

## 4.4 Beat-Note Power Spectral Density

To further assess the spectral quality of the beat note, we measured its power spectral density, shown in Fig. 6. The spectrum was recorded on a Rohde & Schwarz FPC1500 spectrum analyzer using a 10 kHz resolution bandwidth and averaging over 10 traces. Under these conditions, the carrier exhibits a signal-to-noise ratio of approximately 65 dB, demonstrating a clean, high-contrast beat with a low noise floor.

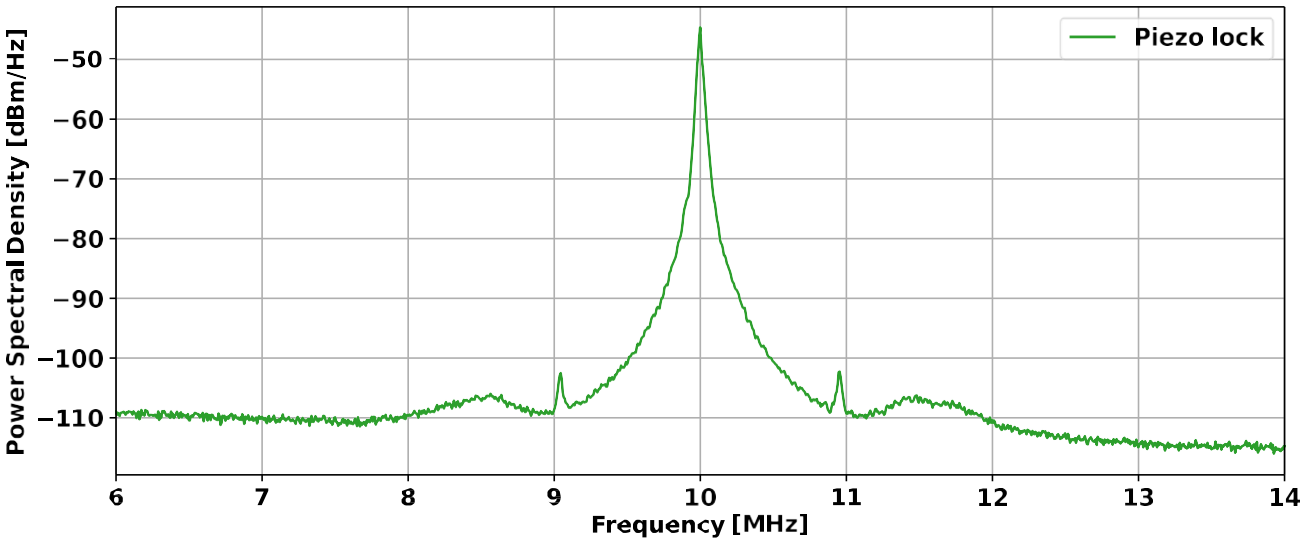



**Figure 6:** Power spectral density spectrum of the beat note acquired with a Rohde & Schwarz FPC1500. The trace is the average of 10 sweeps using a 10 kHz resolution bandwidth, yielding a signal-to-noise of 65 dB.

## 4.5 Relative Intensity Noise (RIN) Measurements

The experimental setup for relative intensity noise (RIN) measurements uses the same optical setup as shown in Fig. 1 to attenuating the optical beam from system 1. The 698 nm SFG laser is attenuated and coupled into an optical fiber instead of being measured at the photodiode. The other end of the fiber is coupled out in a separate RIN characterization setup; the beam then passes through half-wave plates and polarizing beam splitters to set the optical power incident on two silicon photodetectors (DC–150 MHz). RIN is measured with a self-homodyne scheme: the summed AC photocurrents measure the classical amplitude (intensity) noise, while the differenced signal suppresses common-mode technical noise and provides a shot-noise-limited reference.

The measured spectra are calibrated to the shot-noise level. When shot-noise limited, the expected RIN floor (after correcting for detector quantum efficiency) is

$$\mathrm{RIN}_{\mathrm{SN}} = 2\,h\nu/\mathcal{P},$$

where $\mathcal{P}$ is the mean detected optical power and ν is the optical frequency. For 698 nm, this corresponds to (−157.7 ± 0.4) dBc/Hz at 4.0 mW with a quantum efficiency of 85%. All quoted uncertainties are given as expanded uncertainties. The dominant uncertainties arise from systematic and measurement uncertainties in the optical power and from the absolute resolution of the electrical spectrum analyzer.

The resulting noise power spectrum is shown in Fig. 7, where the blue and orange traces are the amplitude noise from the two individual detectors and the red trace is the shot-noise reference. The electronic noise floor lies ~10 dB below shot noise, confirming shot-noise-limited detection over the measurement band. Converting the same dataset to RIN units (by summing the detector signals, subtracting electrical noise, and normalizing to the shot-noise-limited reference) yields the high-frequency RIN spectrum in Fig. 8, with excess-noise features around ~0.7 MHz and ~1.5 MHz attributed to classical technical noise; the double-peaked structure is consistent with slightly different noise properties of the two lasers driving the SFG process being transferred to the generated field. A feature near ~1 MHz is probably a residual noise from the laser electronics.

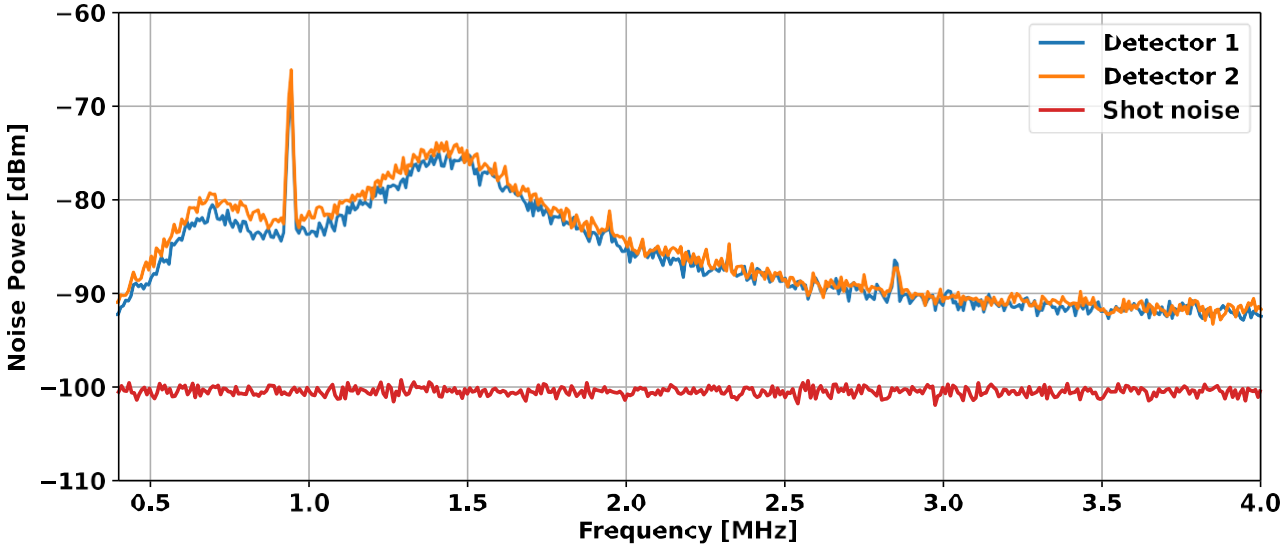



**Figure 7**: Noise power spectrum of the SFG laser at the 698 nm measured with a resolution bandwidth of 10 kHz, a video bandwidth of 1 kHz and averaged 10 times. The blue and orange traces show the amplitude noise measured on the two individual detectors, while the red trace corresponds to the shot-noise reference. The electronic noise floor is ~10 dB below shot noise, ensuring shot-noise-limited detection. Excess-noise features originate from classical technical noise.

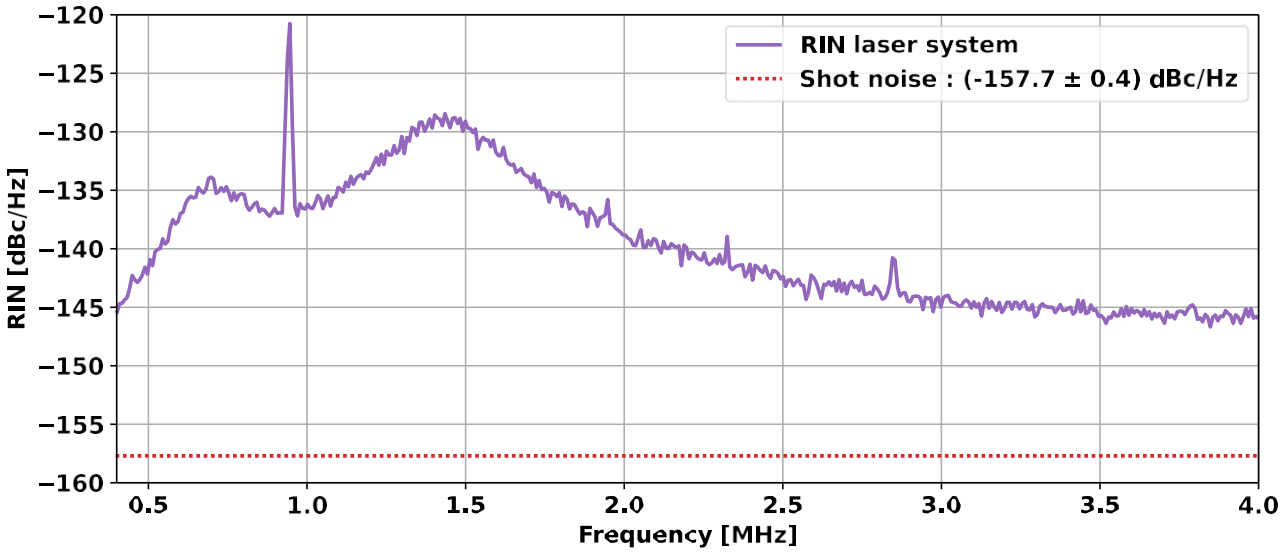



**Figure 8**: Relative intensity noise (RIN) of the SFG laser measured using self-homodyne detection in the frequency range 400 kHz to 4 MHz. The dataset from Figure 7 is rescaled to RIN units by summing the two detector signals, subtracting the measured electrical noise and normalizing to the shot-noise-limited RIN of (−157.7 ± 0.4) dBc/Hz, shown as the dashed red line.

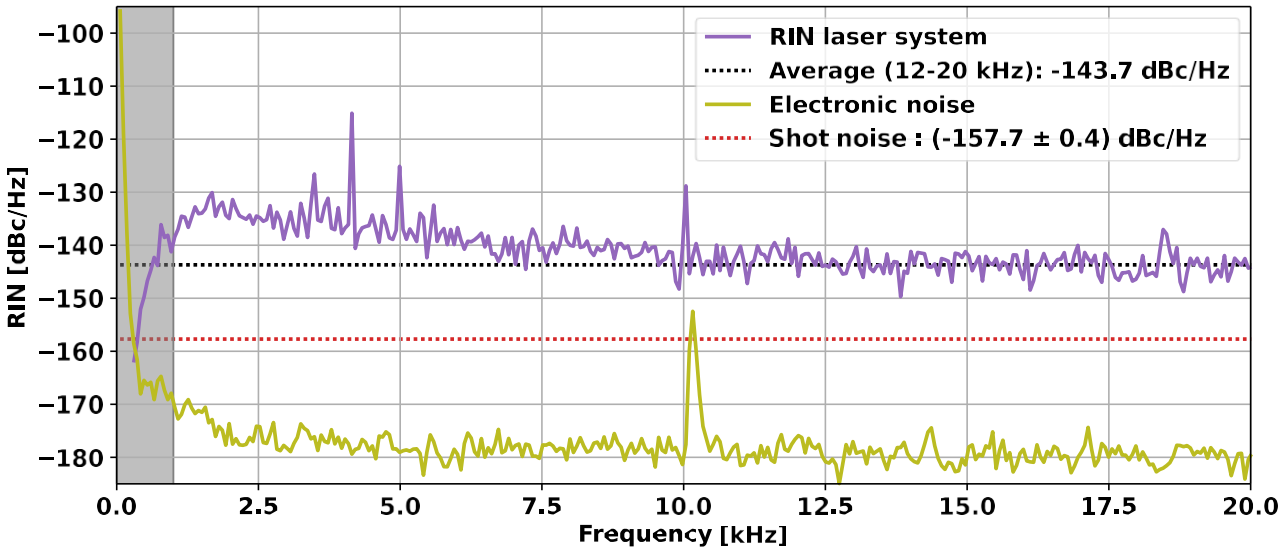



**Figure 9**: Low-frequency RIN of the 698 nm SFG output measured from 1 kHz to 20 kHz with 30 Hz resolution bandwidth and averaged 10 times. The processed RIN trace is shown alongside the shot-noise estimate and the measured electronic noise floor; the 10 kHz feature is attributed to an electrical artifact.

Low-frequency intensity fluctuations were investigated by repeating the measurement with a much smaller resolution bandwidth in the 1–20 kHz region (see Fig. 9). After accounting for the shot-noise reference and subtracting the electronic noise contribution, the RIN over 1–20 kHz is (−140.7 ± 4) dBc/Hz; restricting the range to 12–20 kHz gives (−143.7 ± 2) dBc/Hz. A distinct tone at 10 kHz is consistent with an electronics-related artifact. For Fourier frequencies below roughly 1 kHz, the present measurement chain did not allow a robust RIN determination.

## 5 Summary

An optical phase lock between two identical Koheras HARMONIK HP H69 systems was established, using only the built-in frequency tuning piezo of one of the lasers as actuator. A beat note between the two systems shows high measurement quality (65 dB SNR), enabling robust extraction of phase/frequency noise and Allan devation.

Offset phase locking using a Vescent SLICE-OPL on the internal piezo actuator suppresses frequency noise at frequencies below 9 kHz, limited by the piezo actuator bandwidth. To maintain a robust phase lock with only the piezo actuator, the beat-note signal is divided down before phase detection (by a factor of 16 in our implementation), extending the effective locking range and preventing cycle slips. In this configuration, the modified Allan deviation of the beat note, corresponding to the combined noise of both lasers, reaches a fractional frequency stability of $8 \times 10^{-18}$ at 1 s. Using an external AOM as the fast actuator further increases the servo bandwidth and improves low-frequency noise suppression; with the AOM-based lock, the modified Allan deviation of the beat note reaches below $2 \times 10^{-18}$ at 1 s, surpassing the performance achievable with frequency locking to a leading commercial cavity reference [1].

Residual noise above the loop bandwidth is consistent with the free-running noise level. Extending the servo bandwidth with a faster external actuator (such as an EOM or a higher-bandwidth VCO) is the most direct route to increasing loop bandwidth and reducing frequency noise further.

The 698 nm Koheras HARMONIK HP H69 intensity noise was characterized over 1 kHz to 20 kHz and 0.4 MHz to 4 MHz. Across the measured bandwidth, the electronic noise floor remained at least ~10 dB below the shot-noise level, enabling reliable extraction of laser RIN. At 4 mW detected power, the shot-noise-limited RIN is (−157.7 ± 0.4) dBc/Hz. In the 2.5–20 kHz range, the RIN is (−142.8 ± 4) dBc/Hz, while ranging 12–20 kHz yields (−143.7 ± 2) dBc/Hz. Distinct excess-noise peaks occur near 0.7, 1.0 and 1.5 MHz; a narrow peak near 10 kHz is attributed to an electronic artifact.

# 6 References

[1] Timmers, H., & Cataño-Lopez, S. B. (2025, September 9). *Sub-Hz stability and linewidth transfer across O- and C-bands using commercial off-the-shelf products* (Application note). Vescent Technologies, Inc.; Thorlabs. Link.