Sub-Hz Stability and Linewidth Transfer across O- and C-Bands Using Commercial Off-the-Shelf Products

Henry Timmers[1] & Seth B. Cataño-Lopez[2]

[1] Vescent Technologies Inc., [2] Thorlabs

SUMMARY

Vescent Technologies, Inc. and Thorlabs demonstrated the sub-Hz stability and linewidth transfer between optical references in the O-band (1348 nm) and C-band (1542 nm) using their commercial off-the-shelf (COTS) time and frequency product lines. By using Thorlabs' crystalline mirror reference cavities as an absolute optical standard, their linewidth and stability can be disseminated across any quantum-relevant wavelength from 490 to 2050 nm using Vescent's optical frequency combs.

INTRODUCTION

With the advent of industrial quantum technology providing next-generation solutions in quantum computing, sensing, and timing, there is an increasing commercial need for stable, ultra-narrow linewidth laser systems spanning the visible and near infrared spectrum. In quantum computing, the optical phase noise performance of the state preparation and interrogation lasers for an optical qubit directly impacts readout fidelity [1]. For next-generation optical atomic clocks, ultra-narrow linewidth laser systems are required not only for the interrogation of the high-Q optical clock transitions [2, 3], but also for the dissemination and comparison of the optical clock technology [4, 5]. Finally, for a vast majority of quantum computing, timing, and sensor technology, there is a requirement to stabilize all quantum state preparation and readout lasers to a phase coherent, high-stability

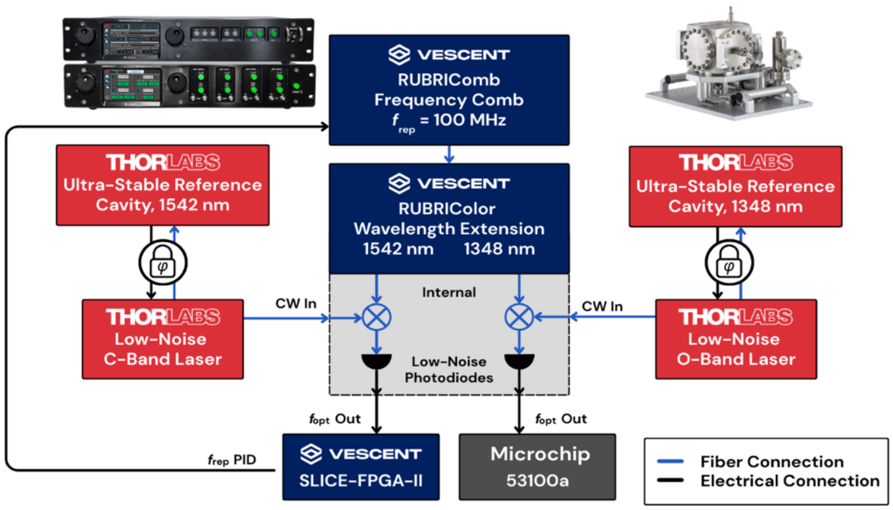

Figure 1 Experimental set-up for the measurement of linewidth and stability transfer between Vescent's RUBRIComb product line and Thorlabs' optical reference cavities.

optical frequency reference [6]. From these requirements, it is clear that there is a critical commercial need for robust and reliable infrastructure that provides laser sources with exquisite linewidth and stability spanning the optical spectrum.

The most reliable approach to achieving a highly coherent, sub-Hz linewidth laser source is to lock a robust seed laser to a high-stability optical frequency reference. These references are conventionally Fabry-Perot resonators, in which the cavity end mirrors are constrained by a precisely machined ultra-low-expansion (ULE) glass spacer and in which the entire assembly is isolated and placed into a vacuum enclosure. The limit of achievable laser stability and linewidth will be set by the residual displacement fluctuations of the cavity mirrors due to a combination of technical noise sources (electronics, environmental isolation, etc.), and fundamental noise sources (coating thermo-optic noise, coating Brownian noise, etc.) [7].

THORLABS' ULTRA-NARROW LINEWIDTH LASER SOLUTIONS

Thorlabs offers a family of low-noise, turnkey laser systems suitable for use as seed lasers, with off-the-shelf options for the C-band (Item # ULN15TK) and the O-band (Item # ULN13TK). Custom wavelengths are also available upon request. These lasers are based on a hybrid design incorporating a single angled-facet gain chip coupled to an exceptionally long fiber Bragg grating, offering Lorentzian linewidths as narrow as 100 Hz. The turnkey lasers incorporate low-noise drive electronics with current and temperature modulation capabilities to facilitate laser locking.

The optical cavities are made from readily available crystalline coating supermirrors based on semiconductor GaAs/AlGaAs Bragg structures with finesses greater than 300,000 and excess losses on the order of 3 ppm or better [8]. The crystalline structure and material properties of the mirror coating enable high-power handling, a large transparency window extending up to 10 mm [9], and low mechanical loss, providing a significantly lower Brownian noise contribution compared to standard ion-beam-sputtered mirror coatings [10]. Thorlabs offers this technology as a COTS solution, with optical cavities based on a standard geometry at select wavelengths, and custom wavelengths available upon request.

VESCENT'S RELIABLE FREQUENCY COMB PRODUCT LINE

However, the need to have a stable reference cavity at every quantum-relevant wavelength can quickly become intractable and is often an experimental bottleneck for scaling up quantum systems. Therefore, an optical tool is required to translate the linewidth and stability of the sub-Hz reference cavity across the optical spectrum. Vescent's optical frequency comb technology provides such a toolkit, offering scalable solutions for commercial and deployed quantum technology. Vescent's commercial frequency comb system, the RUBRIComb product line, supports in-loop instabilities as low as 1×10^{-17} at one second and offers reliable, high-performance operation both within and outside the laboratory setting. The core frequency comb technology has been verified to operate over a wide temperature range (0-50 °C), in harsh vibrational environments (integrated vibrations up to 1.6 g_{rms}), and in significant shock environments (peak shock events in excess of 10 g_{peak}). The RUBRIColor product line extends this reliable performance across the electro-magnetic spectrum, supporting sub-Hz linewidth and stability transfer across wavelengths from 490 nm to 2050 nm, and all at a budget-friendly price point.

SUB-HZ STABILITY AND LINEWIDTH TRANSFER

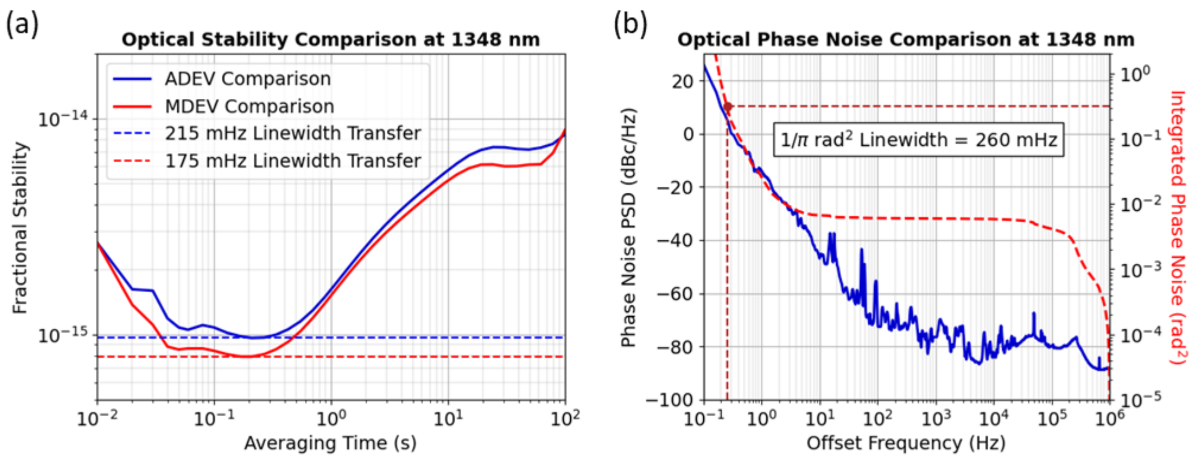

Figure 2 (a) ADEV and MDEV analysis of the 1348 nm optical heterodyne signal demonstrating sub-Hz linewidth and stability transfer between 1542 nm and 1348 nm. (b) Corresponding phase noise power spectral density (PSD) of the 1348 nm optical heterodyne signal supporting an integrated linewidth of 260 mHz.

In this application note, we show how stability from Thorlabs' crystalline mirror reference cavities can be reliably disseminated and transferred using Vescent's robust RUBRIComb and RUBRIColor technology between the O-band and C-band. This experimental set-up is shown in Fig. 1. Briefly, a self-referenced, 100 MHz RUBRIComb with an optical output spanning the telecommunications band is phase-locked to a 1542 nm laser locked to the crystalline mirror reference cavity. The cavity imparts sub-Hz linewidth onto the 1542 nm seed laser. When the comb is phase-locked to this seed laser, it acquires the same linewidth and stability as the cavity. To demonstrate the ultra-narrow linewidth operation of the phase-locked frequency comb, we set up a second optical frequency reference by locking a 1348 nm seed laser to an additional crystalline mirror reference cavity. Finally, we translate the spectrum of the RUBRIComb source to 1348 nm using a supercontinuum long (SCL) extension module in Vescent's RUBRIColor product line. The nearest comb tooth from the RUBRIColor extension is heterodyned against the 1348 nm cavity stabilized source, and the photodetected output is measured using a 53100A phase noise analyzer from Microchip.

Fig. 2 shows the results of the stability and linewidth measurement from the 1348 nm optical heterodyne signal. In the analysis of the heterodyne signal, we assume equal noise contributions between the 1348 nm comb tooth and the cavity-stabilized seed laser. In Fig. 2 (a), we plot both the Allan Deviation (ADEV) and Modified Allan Deviation (MDEV) analysis of the optical heterodyne. The ADEV analysis demonstrates a minimum in its frequency instability of 9.6×10^{-16} at 210 ms, corresponding to a 215 mHz linewidth performance. The MDEV analysis demonstrates an even better stability of 7.9×10^{-16} at 210 ms. To verify the accuracy of these numbers, we also collected the optical phase noise of the 1348 nm heterodyne signal down to an offset frequency of 100 mHz, as shown in Fig. 2 (b). Using the $1/\pi$ rad^2 linewidth characterization method [11], we measure an integrated linewidth of the optical heterodyne to be 260 mHz, in good agreement with the minimum in the ADEV performance and presenting a self-consistent linewidth and stability measurement.

The results of the measurement campaign validate the performance of these COTS systems and provide a solution for extending operation to arbitrary quantum wavelengths. By utilizing the COTS offerings of the crystalline mirror reference cavity as an absolute optical reference, the linewidth and stability performance of the cavity can be translated to any quantum-relevant wavelength within the optical span of 490-2050 nm, using a RUBRIComb to coherently link all colors to this absolute optical reference. The long-term performance can be steered using either a GPS-disciplined oscillator or an atomic frequency reference [12] to de-drift the cavity.

CONCLUSION

In conclusion, Vescent and Thorlabs have demonstrated linewidth and stability transfer of 215 mHz between two high-performance optical reference cavities using their COTS laser systems. This collaborative demonstration presents a scalable commercial infrastructure for the dissemination of sub-Hz linewidth and stability across the optical spectrum required for next-generation quantum solutions.

REFERENCES

[1] H. Nakav *et al.*, "Effect of fast noise on the fidelity of trapped-ion quantum gates," *Phys. Rev. A,* vol. 107, p. 042622 , 2023.

[2] W. F. McGrew *et al.*, "Atomic clock performance enabling geodesy below the centimetre level," *Nature,* vol. 564, pp. 87-90, 2018.

[3] E. Oelker et al., "Demonstration of 4.8e-17 stability at 1 s for two independent optical clocks," Nature Photonics, vol. 13, pp. 714-719, 2019.

[4] Boulder Atomic Clock Optical Network (BACON), "Frequency ratio measurements at 18-digit accuracy using an optical clock network," Nature, vol. 591, pp. 564-569, 2021.

[5] T. Lindvall et al., "Coordinated international comparisons between optical clocks connected via fiber and satellite links," Optica, vol. 12, no. 6, pp. 843-852, 2025.

[6] T. Bothwell et al., "Deployment of a transportable Yb optical lattice clock," Opt. Lett., vol. 50, no. 2, pp. 646-649, 2025.

[7] T. Chalermsongsak et al., "Broadband measurement of coating thermal noise in rigid Fabry–Pérot cavities," Metrologia, vol. 52, pp. 17-30, 2015.

[8] G. D. Cole et al., "High-performance near- and mid-infrared crystalline coatings," Optica, vol. 3, no. 6, p. 647, 2016.

[9] G.-W. Truong et al., "Mid-infrared supermirrors with finesse exceeding 400 000," Nat Commun, vol. 14, no. 7846, 2023.

[10] G. D. Cole et al., "Tenfold reduction of Brownian noise in high-reflectivity optical coatings," Nature Photonics, vol. 7, p. 644–650, 2013.

[11] D. R. Hjelme et al., "Semiconductor Laser Stabilization by External Optical Feedback," IEEE J. Quant. Electron., vol. 27, no. 3, pp. 352-372, 1991.

[12] "Stabiλaser 1542ε," Danish National Metrology Institute, [Online]. Available: https://stabilaser.dk/.