Phase and Frequency Stabilization of Single-Frequency Fiber Lasers to a Commercial Optical Frequency Comb

SUMMARY

Vescent Technologies, Inc. and NKT Photonics (NKTP) demonstrate techniques for phase/frequency locking NKTP fiber laser systems to Vescent's RUBRIComb® optical frequency comb product line [1]. Using commercial off-the-shelf (COTS) laser systems, we show stability and linewidth transfer from a high-stability acetylene reference to an NKTP fiber laser [2] via the RUBRIComb® by implementing three distinct locking methods and comparing the locked performance at different operating wavelengths.

INTRODUCTION

With the advent of industrial quantum computing, the need for robust, reliable narrow linewidth laser sources is crucial for addressing multiple quantum transitions while maintaining high measurement fidelity. A widely used method of laser frequency stabilization requires locking individual laser systems to an ultra-low-drift, high finesse optical reference cavity. However, this solution has several disadvantages: (1) Volume manufacturing of these bespoke reference cavities is not particularly scalable or cost efficient; (2) the cavity must be well-isolated from temperature and vibrational disturbances, adding extra cost, complexity, and size to the system; (3) systems must employ "de-drifting" algorithms to account for the inevitable drift of the cavity resonance; and (4) maintaining long-term alignment into high-finesse cavities is challenging, requiring specially trained personnel and detrimentally affecting operational reliability. Frequency-stabilized laser systems deployed outside the laboratory require commercial solutions that offer 100% operational uptime, scalable costs, and tolerance to real-world environmental conditions. In this application note, we demonstrate Vescent's high performance and industrial RUBRIComb® product locked to an acetylene optical frequency reference, as a global reference to discipline NKTP's suite of narrow linewidth, industrial-grade fiber lasers. We demonstrate stability and linewidth transfer from the RUBRIComb® to the NKTP fiber laser systems at multiple operational wavelengths and incorporating different phase/frequency locking schemes.

Both the Vescent RUBRIComb® and NKTP BASIK product lines provide high-performance fiber laser solutions with industrial reliability. The Vescent RUBRIComb®, an optical frequency comb offering turnkey operation in a 2U rackmount package, has previously been shown to remain coherently phase locked over a range of environmental perturbations. In combination with the SLICE-FPGA-II control module, the RUBRIComb® can be fully phase stabilized within minutes and remains locked for months at a time. Similarly, the NKTP line of BASIK fiber lasers offers narrow linewidth CW laser modules at multiple wavelengths in a compact 0.55 L volume. The NKTP ACOUSTIK Platform is a 3U rack mountable chassis that allows for control of various optical modules via a centralized GUI. It can integrate up to 4 individually controlled

BASIK fiber laser, a variety of optical fiber amplifiers as well as fiber coupled optical frequency conversion modules, electro optic, and acousto-optic modulators. Lasers can be dynamically added and removed from the ACOUSTIK chassis, allowing customization for various applications. The combination of the RUBRIComb's 460-2050 nm wavelength coverage via RUBRIColor™ extension modules and the BASIK ecosystem's diverse spectral coverage enables an industrial, robust, and reliable infrastructure for universal stabilization of CW lasers for quantum computing.

EXPERIMENTAL SETUP

Figure 1 shows a block diagram of the experimental setup. To disseminate linewidth and frequency stability across the optical spectrum, we must first lock the RUBRIComb® to a stable optical frequency reference. This is achieved by first self-referencing the RUBRIComb® and then locking it to a Stabiλaser frequency reference from the Danish National Metrology Institute (DFM) [3]. The Stabiλaser is an acetylene-stabilized 1542 nm fiber laser system demonstrating an integrated optical linewidth < 500 Hz and supporting a 1 second fractional instability < 2E-13 and a long-term flicker floor of ~2E-14. We refer to this frequency-stabilized RUBRIComb® as a local timing system (LTS) and use this configuration to transfer the Stabilaser stability to quantum-relevant wavelengths via locking of a narrow linewidth BASIK laser to the LTS. This enables both narrow linewidth and drift-free long-term stability at each wavelength, directly traceable to the single acetylene reference.

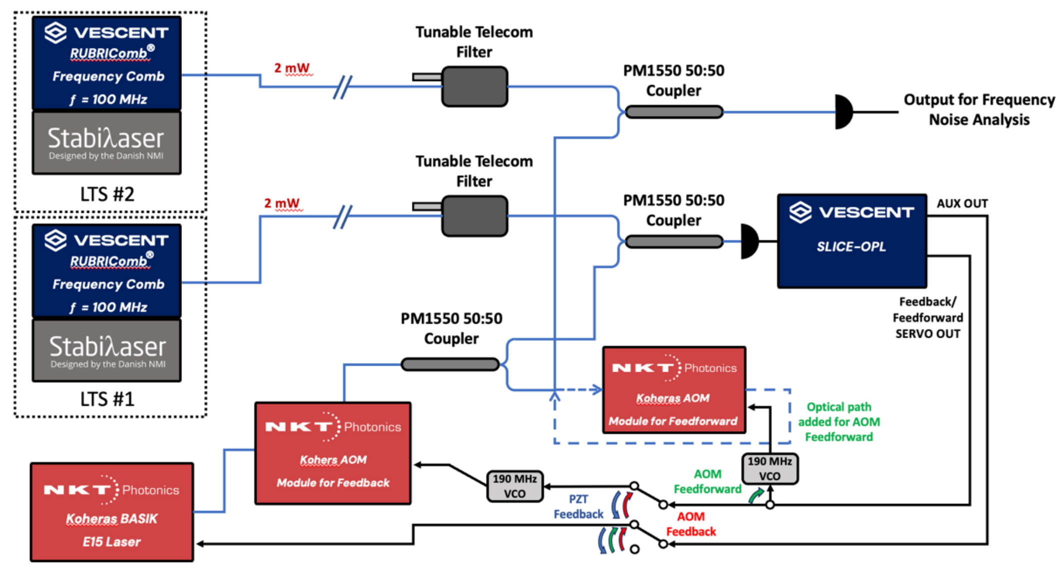

__Figure 1__: Experimental setup for locking NKTP BASIK laser to Vescent RUBRIComb® to make out-of-loop frequency noise measurements for characterization of the stability transfer of different locking methods. The three distinct locking schemes are shown, including PZT feedback (blue), AOM feedback (red) and AOM feedforward (green).

To demonstrate this stability transfer, first we lock a 1550 nm BASIK laser by optically mixing with the RUBRIComb® and generating an RF heterodyne beat signal. Using Vescent's SLICE-OPL Offset Phase Lock Servo, this beat signal is phase locked to an LTS system (LTS #1) with feedback to the BASIK laser frequency. RUBRIComb® light from LTS #2 is then optically mixed with the phase-stabilized BASIK laser, and the RF beat signal is detected to measure out-of-loop frequency noise. Here we demonstrate locking of the BASIK laser to the RUBRIComb® via three separate methods: 1) feedback to the internal PZT of the BASIK module, 2) feedback to an external AOM, and 3) feedforward to an external AOM. Figure 1 above shows the locking schemes for each configuration. For both AOM locking configurations, the tuning voltage of a VCO (Crystek CVCO55CW-0100-0200) is modulated to precisely adjust the drive frequency of the RF input to the AOM. The AOM feedback and feedforward methods differ due to the placement of the AOM in the optical path and the actuator signal processing. The feedback method modulates the AOM drive frequency before the optical heterodyne photodetection, whereas the feedforward method drives a downstream AOM with the inverted optical heterodyne, directly cancelling the phase noise in the CW laser out to a bandwidth determined by the latency of the control system [4]. Measurement of the frequency noise of each of these configurations allows for comparison in the performance of each method.

RESULTS

Figure 2 (a) shows the results of the out-of-loop frequency noise measured for each locking method with the Microchip 53100A Phase Noise Analyzer. The integrated linewidth of the free-running laser, as calculated by the 1/p rad^2 method [5], is approximately 2.1 kHz. When feeding back to the internal PZT of the BASIK module, the narrow actuator bandwidth limits the ability of the phase locked loop to servo noise for offset frequencies > 10 kHz, shown by the large increase in frequency noise at the servo bumps near 8 kHz. As a result, the integrated linewidth in the PZT stabilized laser system is broadened to 7.5 kHz but drift at low offset frequency near DC is effectively removed.

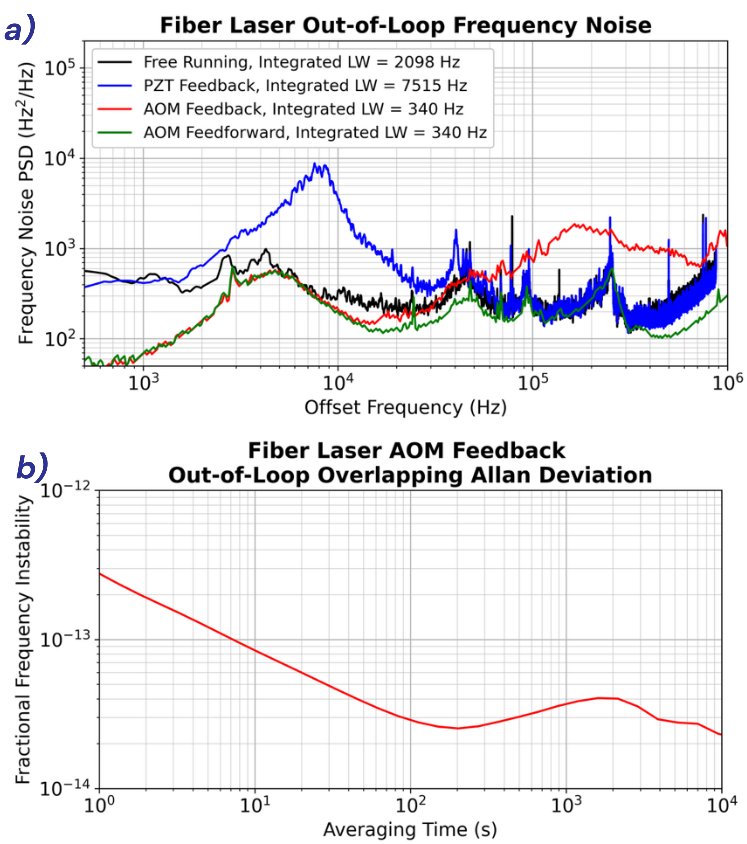

Figure 2: *Out-of-loop frequency noise of locking a BASIK laser module to a RUBRIComb® Optical Frequency Comb. Linewidths are calculated and shown in the legend as the 1/p rad^2 integrated linewidth [5]. (a) Comparison of the frequency noise for various locking methods. (b) Long term frequency counting of the AOM feedback locking scheme as shown by the overlapping allan deviation.*

When utilizing feedback to an external AOM, the performance is significantly improved due to the higher actuator bandwidth, resulting in an integrated linewidth of 340 Hz. This linewidth corresponds to the linewidth of the acetylene reference, showing a 1:1 stability transfer from the reference to the BASIK laser via the RUBRIComb®. Long term stability for the AOM feedback method is shown in Figure 2 (b) as expressed by the overlapping allan deviation (OADEV). Similarly, when implementing the AOM feedforward configuration shown in Figure 1 (b), the linewidth was narrowed to 340 Hz as well. In both cases, the stability transferred to the BASIK laser was limited by the stability of the reference. The feedforward implementation was additionally able to circumvent servo-induced noise at high offset frequencies, demonstrating superior high-frequency performance compared to feedback methods.

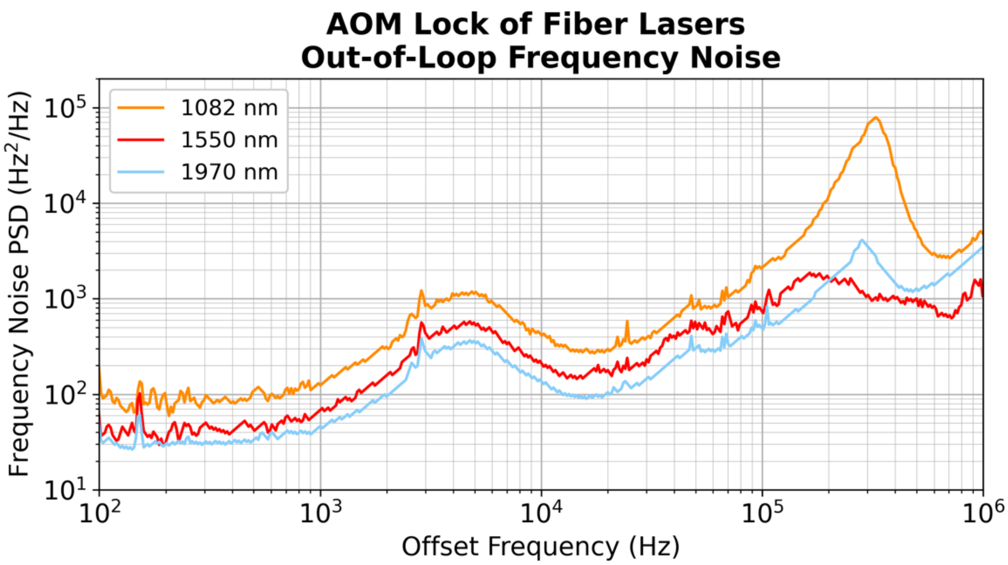

Figure 3: *Out-of-loop frequency noise of locking a BASIK laser module to a RUBRIComb® Optical Frequency Comb at various wavelengths.*

In addition to the various locking schemes, locking of the BASIK module was conducted at multiple wavelengths. Three BASIK modules were chosen with center wavelengths at 1082 nm, 1550 nm, and 1970 nm. The RUBRIComb® output was shifted to the relevant wavelength for each measurement using Vescent's RUBRIColor™ product. The AOM feedback configuration shown in Figure 1 was used to lock each module. The out-of-loop frequency noise was measured for each wavelength and is shown above in Figure 2 (b). Successful locks were achieved for each of the three wavelengths. Further, quadratic scaling of the frequency noise PSD is observed due to the fundamental noise properties of optical frequency combs [6].

CONCLUSION

This work highlights a robust commercial pathway for stabilizing multiple laser systems using reliable COTS components with minimal setup time. The RUBRIComb® transfers the 340 Hz linewidth of an optical reference onto an NKTP BASIK fiber laser via an external AOM actuator, achieving 1:1 stability transfer. Additional feedback to the laser's internal PZT achieves stability transfer limited to the kHz range. These locking methods can be readily tuned to multiple quantum-relevant wavelengths from a single optical reference. The collaboration between Vescent Technologies and NKT Photonics delivers a complete, turnkey solution for laser stabilization across diverse quantum applications.

REFERENCES

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