27 Hz Integral Linewidth Laser Based on a 5-billion Q Microfabricated Reference Cavity

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Abstract: We stabilize a semiconductor laser to a manufacturable, microfabricated micro-Fabry-Perot dielectric reference cavity of 5 billion quality factor, achieving thermorefractive-noise-limited performance. A 27 Hz 1/π integral linewidth and 1.5×10^{-13} fractional frequency stability are measured. © 2022 The Author(s)

1. Introduction

Stabilized lasers are a critical component of a wide range of applications including optical atomic clocks [1], quantum sensing and computation [2], and frequency-stabilized fiber communications and sensing [3, 4]. These lasers achieve ultra-low linewidths and precision carrier stability by Pound-Drever-Hall (PDH) type locking to table-scale Fabry-Pérot vacuum-spaced silicon mirror cavities with unprecedented stability [5], enabling gravitation wave detection [6] and measurements of gravitational redshift [7]. Miniaturization of these types of lasers has been achieved with compact whispering-gallery-mode resonators (WGMRs) [8] and waveguide integrated reference cavities [9-11]. Recently, a scalable microfabrication method was developed to make low-loss dielectric-filled Fabry-Pérot resonators achieving quality factors exceeding 5 billion [12].

In this work, we report the application of microfabricated ultra-high Q micro-Fabry-Perot (uFP) resonators for laser frequency stabilization. The uFP resonator has dimensions 0.5” diameter and 0.5” in length and is mounted in a vacuum-free enclosure. We lock a 1550 nm fiber-extended cavity semiconductor laser [13] to a uFP cavity using a Pound-Drever-Hall (PDH) feedback loop [14]. We measure frequency noise to be 30 mHz^2/Hz at 10 kHz offset from carrier, reaching close to the cavity thermorefractive noise (TRN) limit. We measure a stabilized laser output with a 27 Hz integral linewidth ($1/\pi$ integral) and 92 Hz β-separation integral linewidth with an Allan deviation of 1.5×10^{-13} at 3 ms. The estimated TRN-limited integral linewidth is 21 Hz. The resonator cavity lifetime is measured to be of 4.3 μs corresponding to a loaded Q of 5.2 billion. We compare this to a stabilized reference laser (SRL) which is stabilized to a table-top vacuum-spaced ultra-low expansion glass cavity (Stable Laser Systems, SLS) using a heterodyne beat note measurement. Due to the high Q, the PDH lock can achieve a bandwidth of ~1 MHz and is able to reach the TRN limited frequency noise in the range 1 to 50 Hz. These results demonstrate the potential to bring a miniature solution of mass-producible integrated reference cavities to atomic clocks, microwave photonics, quantum applications, and energy-efficient coherent communication systems.

2. Cavity fabrication, characterization, and laser stabilization

The uFP resonator is designed to operate at 1550 nm and has a microfabricated spherical mirror bonded to a flat mirror. The fabrication process starts with a low-absorption flat fused silica substrate (Supersil 3001). A photoresist reflow process creates a nearly spherical curve surface onto which a >99.999% highly reflective coating is applied (for more information see reference [12]). A picture of the fabricated resonator of radius 0.5” and length 0.5” is shown in Fig. 1(a) and the inset shows the surface profile of this mirror prior to coating. The resonator has a radius of curvature of 1.34 m and a 16.4 GHz free spectral range (FSR). We determined the resonator quality factor in two different ways. We measured the lifetime via cavity ring-down measurements, where Fig. 1(b) shows the decay in the transmitted light intensity when the resonant input 1550 nm laser was turned off. We read out the energy decay time or lifetime of the resonator to be 4.28 µs, corresponding to a linewidth of 37.2 kHz and a quality factor of 5.2 billion [12]. We also measured the resonator linewidth by sweeping the laser frequency across a cavity resonance, shown in Fig. 1(c). By applying sidebands to the laser for calibrating the frequency sweep we measure a linewidth of 41 kHz corresponding to a cavity lifetime of 3.8 µs and a loaded Q of 4.7 billion.

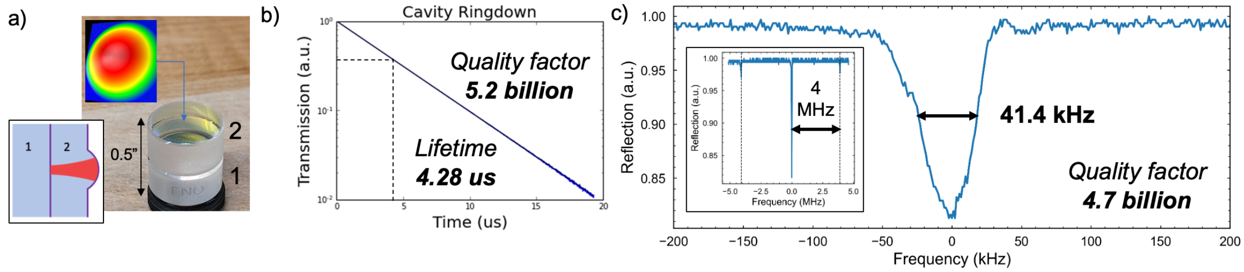

Figure 1. a) Resonator cavity with two mirrors. Inset: mirror surface profile. b) Cavity ring-down measurement [12]. c) Cavity linewidth measurement using the calibrated sideband method (inset shows sidebands). The laser sweep under-estimates the resonator extinction ratio.

The laser stabilization setup is shown in Fig 2a. The resonator is mounted in a Teflon enclosure similar to that of [15]. The Teflon assembly is placed inside an aluminum enclosure and the assembly is temperature stabilized with a resistive heater. The reflection signal from the resonator cavity is extracted with a fiber-based circulator and directed to a photodetector used for locking. Sidebands at a frequency of 25.8 MHz are applied with a phase modulator and the lock has a feedback loop bandwidth of ~1 MHz. To measure the free-running and stabilized frequency noise and laser carrier stability (ADEV), we use two independent methods. An MZI with a 1.026 MHz FSR is used as an optical frequency discriminator (OFD) for laser frequency offsets greater over 1 kHz (see Ref. [10, 16] for further details). For frequency noise below ~1 kHz frequency offset, we employ a stable reference laser (SRL) consisting of an NP Photonics Rock™ single frequency fiber laser that is PDH locked to a Stable Laser Systems™ ultra-low expansion cavity, capable of Hz-level linewidth at 1550 nm with a measured carrier drift of at ~0.06 Hz/s. The low frequency noise is measured by heterodyne detection of the resonator-stabilized laser with the SRL, photo-mixed in a high-speed photodetector, resulting in a heterodyne beat-note of ~234 MHz. The frequency noise of the heterodyne signal is measured and recorded on a frequency counter (Keysight 53230A). The OFD and SRL frequency noise measurements and their limitations are discussed in detail in Ref. [10]. The results are shown in Fig. 2(b-d). Using the stitched SRL and OFD frequency noise spectra, the $1/\pi$ integral linewidths [8] from for the free-running and stabilized laser in Fig. 1(d) are 2.3 kHz and 27 Hz, respectively. The locked laser β-separation integral linewidth is 92 Hz and the Allan deviation for the resonator-stabilized laser reaches the minimum of 1.5×10^{-13} at 3 ms, almost two orders of magnitude improvement over the unstabilized laser in terms of Allan deviation (ADEV). The stabilized laser's frequency noise spectrum falls onto the cavity-intrinsic thermorefractive noise at frequencies from 1 to 50 Hz. The cavity ADEV begins to increase at time scales over 10 milliseconds due to non-zero thermal expansion at room temperature as the system is vacuum-free and there is no athermal cavity design.

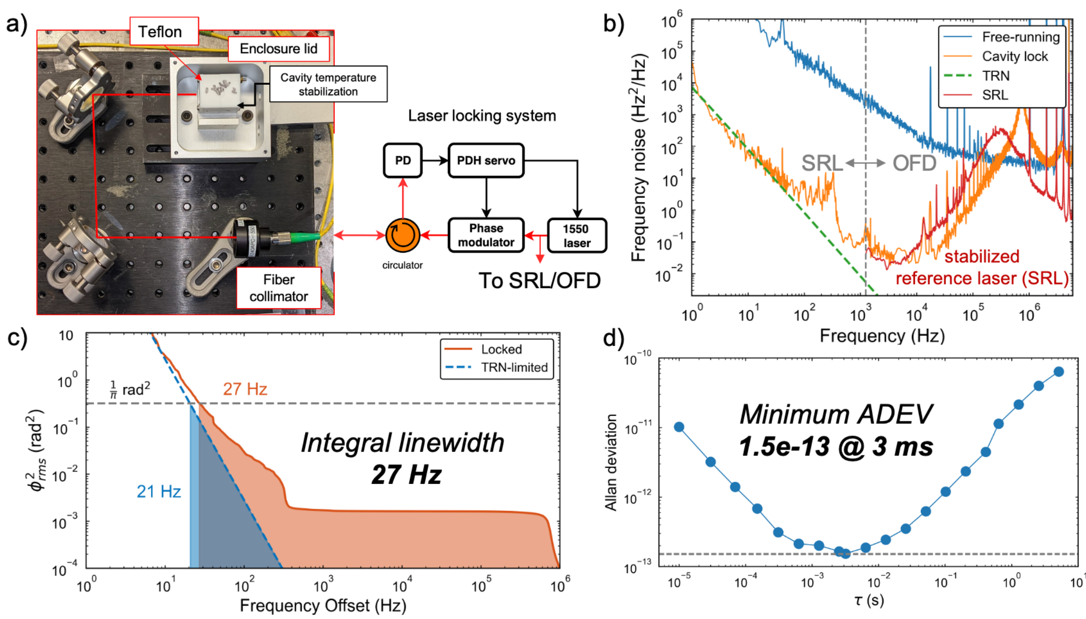

Figure 2. a) Cavity enclosure and laser locking setup schematic. The cavity is mounted in a Teflon enclosure and held on a temperature-controlled stage inside an aluminum enclosure. b) Frequency noise measurements taken with the stabilized reference laser (SRL) and optical frequency discriminator (OFD) methods. c) Integrated phase noise used to extract the integral linewidth. d) Allan deviation measured from the SRL beat-note measurement recorded on a frequency counter.

3. Conclusion

We demonstrate the application of microfabricated ultra-high Q micro-optic Fabry-Perot resonators to laser frequency stabilization. The resonator quality factor of 5 billion enables strong feedback for stabilizing a semiconductor laser. We measure a locked laser integral linewidth of 27 Hz and Allan deviation of 1.5×10^{-13} at 3 ms at 1550 nm, reaching the thermorefractive noise (TRN) limit at certain frequency offsets. The locked laser noise performance is comparable to the lock bandwidth limit of a table-top SLS-stabilized laser. In this resonator fabrication process, the resonator size can be tailored for various reference cavity applications, such as in tradeoffs of TRN-limited noise and cavity size. The fabrication technique is also amenable to wafer-scale fabrication. The vacuum-free dielectric-based system enables this cavity to be used in compact applications and is amenable to integration with photonic grating-couplers for visible wavelengths [17]. This level of performance shows the potential for wafer-scale integrated laser stabilization for precision applications including and energy-efficient coherent communications systems, quantum, atomic clocks, and microwave photonics.

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