Semiconductor laser stabilized by a photonic integrated 4 meter coil-waveguide resonator

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Abstract: We stabilize a semiconductor laser to a photonic-integrated, Si_3N_4, 4 meter coil resonator, achieving thermorefractive-noise-limited frequency noise. The laser exhibits a record low 87 Hz 1/π and 2.1 kHz β-separation integral linewidth and 2.6×10^{-13} fractional frequency stability.

1. Introduction

Spectrally pure stabilized lasers are essential for a wide range of precision applications including atomic and optical clocks [1], quantum communications, sensing and computation [2,3], and metrology [4]. With existing technology, lasers achieve ultra-low linewidths and precision carrier stability by locking a fiber, semiconductor or Brillouin laser [5,6] to a large mode volume, athermalized optical reference cavity [7]. State of the art performance on the order of 10 mHz integrated or total linewidth is achieved using lab-scale, vacuum-spaced silicon or low expansion glass spacers [8]. Photonic integration will reduce the size, cost, weight, power consumption, and environmental sensitivity of these systems and open vast new applications, including energy efficient high-capacity coherent WDM fiber data center interconnects [9], quantum and atomic systems [1,3], and ultra-low phase noise microwave sources [10]. Compact bulk-optic approaches include microcavities and whispering gallery mode resonators [11], capable of stabilizing a semiconductor laser to 25 Hz integral linewidth and 1×10^{-13} stability at 20 ms. To date there have been limited demonstrations of integrated waveguide cavity stabilization lasers, including a deep etched and reflowed spiral waveguide achieving 3.9×10^{-13} at 400 µs stability [12] and an all-waveguide 30 Million Q resonator with a carrier stability of 6.5×10^{-13} at 8 ms [13].

In this paper, we report a significant advance in photonic integrated laser stabilization. We lock a semiconductor laser [5] to an ultra-low loss Si_3N_4 waveguide 4.0 meter long coil-waveguide resonator using a Pound-Drever-Hall (PDH) loop [14] and we measure the stabilized laser frequency noise, demonstrating that it reaches the resonator's thermorefractive noise (TRN) limit down to 800 Hz. The TRN limit scales inversely with the resonator volume [15,16], giving significant advantages to integrating a long coil resonator loop that is difficult to achieve with table-top resonators. We measure an 87 Hz integral linewidth (1/pi integral) and 2.1 kHz β-seperation integral linewidth and Allan deviation of 2.6×10^{-13} at 6 ms at 1550 nm, the lowest linewidth and highest stability reported to date for an all-waveguide resonator, to the best of our knowledge. The integrated coil resonator has 49.1 MHz free spectral range (FSR) and intrinsic and loaded Qs of 80 Million and 55 Million Q, respectively. We compare this laser to a table-top vacuum spaced ultra-low expansion glass cavity (Stable Laser Systems, SLS) and show that due to a fast optical response time the PDH achieves a locking bandwidth of ~1 MHz and thus is able to reach its thermorefractive noise limited frequency noise range of 800 Hz - 50 kHz, which is comparable to the lock bandwidth limited performance of the SLS stabilized laser. These results demonstrate the potential to bring characteristics of table-top and miniaturized ultra-high Q resonators to planar all-waveguide solutions and pave the path towards integrated, wafer-scale compatible reference cavities for atomic clocks, microwave photonics, quantum applications, and energy-efficient coherent communications systems.

2. Coil resonator design, characterization and laser stabilization

The 4-meter Si_3N_4 coil waveguide resonator (see Figure 1(a)), designed to operate at 1550 nm, employs a 6 µm wide by 80 nm thick waveguide core with a 15 µm thick thermal oxide lower cladding and 6 µm thick oxide upper cladding.

The coil waveguide spacing is 40 µm and the minimum bending radius is 9.0 mm. The resonator Q, measured using a radio frequency (RF) calibrated fiber Mach-Zehnder interferometer (MZI) technique [17] is 80 Million intrinsic and 55 Million loaded, respectively (Fig. 1(b)), corresponding to a 0.39 dB/m waveguide propagation loss.

The laser stabilization demonstration and frequency noise measurement setup are shown in Fig. 1(a). The resonator is mounted on an active temperature controlled stage, inside a passive enclosure on a floating optical table [13]. The PDH lock requires only ~0.2 mW optical power, due to the high coil-resonator Q, and the feedback loop bandwidth is ~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 noise components greater than 1 kHz (see Ref. [6,13] for further details). For frequency noise below ~1 kHz frequency offset, we employ a stable reference laser (SRL) consisting of a 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 carrier drift of at ~0.1 Hz/s. The low frequency noise is measured by heterodyne detection of the coil-resonator stabilized laser with the SRL, photomixed in a high-speed photodetector, resulting in a heterodyne beatnote of ~80 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. [13].

The results are shown in Fig. 1(c) and 1(d). The integral linewidths, calculated from the stitched frequency noise spectra for the free-running and stabilized laser in Fig. 1(c), are 2.37 kHz and 87 Hz, respectively. The Allan deviation for the stabilized laser reaches the minimum of 2.6×10^{-13} at 6 ms, almost two orders of magnitude improvement over the unstabilized laser in terms of both ADEV and stability time. The stabilized laser's frequency noise spectrum falls onto the resonator-intrinsic thermorefractvie noise at frequencies from 800 kHz to 50 kHz.

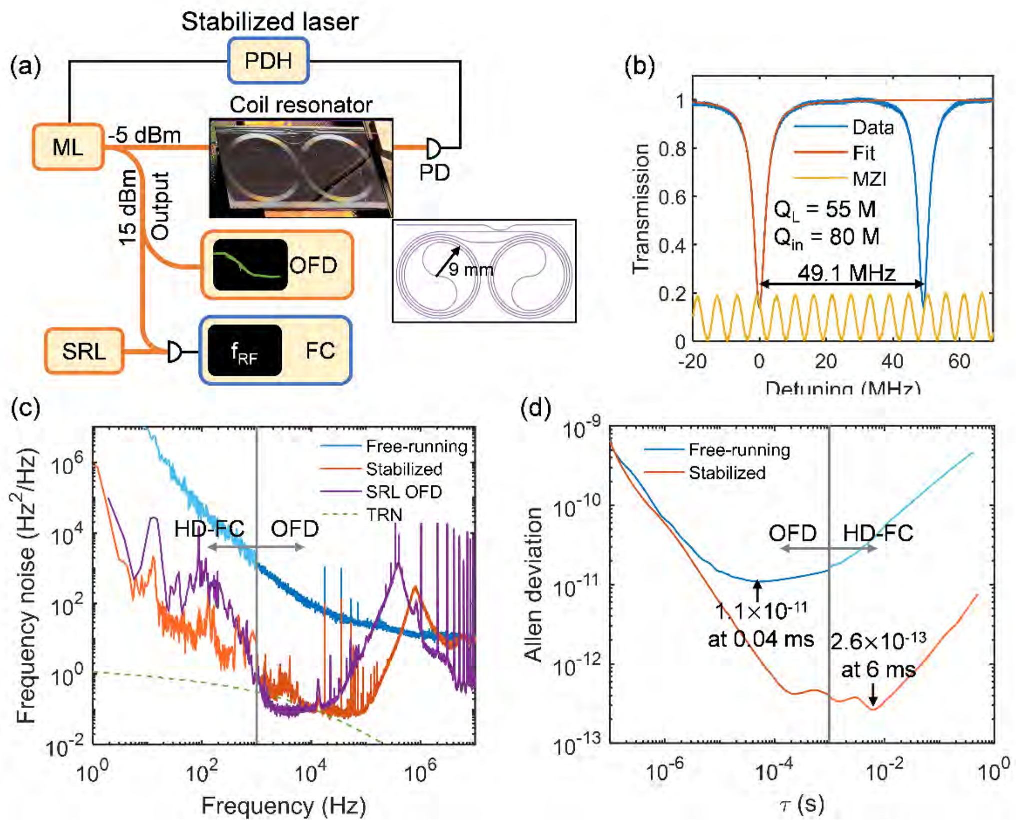

Fig. 1. 1550 nm laser stabilization with 4-meter coil waveguide resonator. (a) A Morton laser (ML) is PDH locked to the coil resonator. The OFD method measures frequency noise above 1kHz. A frequency counter (FC) measures noise for of heterodyne beatnote between laser and stable reference laser (SRL) for frequencies below 1kHz. OSC, oscilloscope; PD, photodetector; HD-FC, heterodyne-frequency counter. (b) Measured coil resonator FSR of 49.1 MHz and intrinsic 80 Million and loaded 55 Million Q. (c) OFD and SRL frequency noise measurements for the free-running and stabilized laser. (d) Allan deviation of heterodyne beatnote centered at ~81 MHz, recorded by the frequency counter at averaging time τ above 1 ms; Allan deviation is calculated from the OFD frequency noise at averaging time τ below 1 ms.

3. Conclusion

We demonstrate a significant advance in photonic integrated laser stabilization, achieved by locking a fiber-extended cavity semiconductor laser to a 4.0 meter long round-trip coil waveguide resonator with a free spectral range (FSR) of ~49 MHz. We demonstrate that the stabilized laser frequency noise reaches the resonator thermo-refractive noise (TRN) limit from 1 kHz frequency offset to 100 kHz, with noise performance and TRN comparable to the lock bandwidth limit of a table-top SLS stabilized laser. We measure an integral 87 Hz linewidth and Allan deviation of 2.6×10^{-13} at 6 ms at C band 1550 nm, which we believe is the lowest linewidth and highest stability reported for an all-waveguide cavity design, to the best of our knowledge. This level of performance shows the potential for wafer-scale integrated stabilized lasers for precision applications including and energy-efficient coherent communications systems, quantum, atomic clocks, and microwave photonics.

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1. A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, "Optical atomic clocks," Rev. Mod. Phys. **87**, 637–701 (2015).
2. A. Orieux and E. Diamanti, "Recent advances on integrated quantum communications," J. Opt. **18**, 083002 (2016).
3. H.-S. Zhong, H. Wang, Y.-H. Deng, M.-C. Chen, L.-C. Peng, Y.-H. Luo, J. Qin, D. Wu, X. Ding, Y. Hu, P. Hu, X.-Y. Yang, W.-J. Zhang, H. Li, Y. Li, X. Jiang, L. Gan, G. Yang, L. You, Z. Wang, L. Li, N.-L. Liu, C.-Y. Lu, and J.-W. Pan, "Quantum computational advantage using photons," 5 (2020).
4. C. Xu, L. Zhang, S. Huang, T. Ma, F. Liu, H. Yonezawa, Y. Zhang, and M. Xiao, "Sensing and tracking enhanced by quantum squeezing," Photonics Res. **7**, A14 (2019).
5. P. A. Morton and M. J. Morton, "High-Power, Ultra-Low Noise Hybrid Lasers for Microwave Photonics and Optical Sensing," J. Light. Technol. **36**, 5048–5057 (2018).
6. S. Gundavarapu, G. M. Brodnik, M. Puckett, T. Huffman, D. Bose, R. Behunin, J. Wu, T. Qiu, C. Pinho, N. Chauhan, J. Nohava, P. T. Rakich, K. D. Nelson, M. Salit, and D. J. Blumenthal, "Sub-hertz fundamental linewidth photonic integrated Brillouin laser," Nat. Photonics **13**, (2018).
7. J. Ling, Y. He, R. Luo, M. Li, H. Liang, and Q. Lin, "Athermal lithium niobate microresonator," Opt. Express **28**, 21682 (2020).
8. D. G. Matei, T. Legero, S. Häfner, C. Grebing, R. Weyrich, W. Zhang, L. Sonderhouse, J. M. Robinson, J. Ye, F. Riehle, and U. Sterr, "1.5 μ m Lasers with Sub-10 mHz Linewidth," Phys. Rev. Lett. **118**, 263202 (2017).
9. D. J. Blumenthal, H. Ballani, R. O. Behunin, J. E. Bowers, P. Costa, D. Lenoski, P. A. Morton, S. Papp, and P. T. Rakich, "Frequency Stabilized Links for Coherent WDM Fiber Interconnects in the Datacenter," J. Light. Technol. 1–1 (2020).
10. J. Li, H. Lee, and K. J. Vahala, "Microwave synthesizer using an on-chip Brillouin oscillator," Nat. Commun. **4**, 2097 (2013).
11. W. Zhang, L. Stern, D. Carlson, D. Bopp, Z. Newman, S. Kang, J. Kitching, and S. B. Papp, "Ultranarrow Linewidth Photonic-Atomic Laser," Laser Photonics Rev. **14**, 1900293 (2020).
12. H. Lee, M.-G. Suh, T. Chen, J. Li, S. A. Diddams, and K. J. Vahala, "Spiral resonators for on-chip laser frequency stabilization," Nat. Commun. **4**, 2468 (2013).
13. K. Liu, J. H. Dallyn, G. M. Brodnik, A. Isichenko, M. W. Harrington, N. Chauhan, D. Bose, P. A. Morton, S. B. Papp, R. O. Behunin, and D. J. Blumenthal, "Photonic circuits for laser stabilization with ultra-low-loss and nonlinear resonators," ArXiv210703595 Phys. (2021).
14. E. D. Black, "An introduction to Pound–Drever–Hall laser frequency stabilization," Am. J. Phys. **69**, 79–87 (2000).
15. G. Huang, E. Lucas, J. Liu, A. S. Raja, G. Lihachev, M. L. Gorodetsky, N. J. Engelsen, and T. J. Kippenberg, "Thermorefractive noise in silicon-nitride microresonators," Phys. Rev. A **99**, 061801 (2019).
16. M. L. Gorodetsky and I. S. Grudinin, "Fundamental thermal fluctuations in microspheres," J. Opt. Soc. Am. B **21**, 697 (2004).
17. M. W. Puckett, K. Liu, N. Chauhan, Q. Zhao, N. Jin, H. Cheng, J. Wu, R. O. Behunin, P. T. Rakich, K. D. Nelson, and D. J. Blumenthal, "422 Million intrinsic quality factor planar integrated all-waveguide resonator with sub-MHz linewidth," Nat. Commun. **12**, 934 (2021).