Common cavity waveguide coil-resonator stabilized hybrid integrated WDM laser with 89 Hz integral linewidth

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Abstract: We stabilize a hybrid-integrated multi-wavelength laser to a photonic-integrated 4.0-meter-coil resonator, with 48 MHz FSR, achieving an 89 Hz integral linewidth and 4.3×10^{-13} frequency stability at 10.5 ms for 2 different wavelength channels.

1. Introduction

Stabilized integrated lasers are essential for a wide range of precision applications including atomic and optical clocks [1], quantum communications and sensing [2,3], and fiber sensing applications [4]. State of the art performance on the order of 10 mHz integrated is achieved using lab-scale vacuum housed, cryogenically cooled, high-finesse crystalline silicon Fabry Perot cavities [5]. Photonic integration and device miniaturization will reduce the size, weight and power consumption (SWaP), and environmental sensitivity of these systems. Compact bulk-optic approaches include microcavities and whispering gallery mode resonators, capable of stabilizing a semiconductor laser to 25 Hz integral linewidth and 1×10^{-13} stability at 20 ms [6] and a 1 million finesse Fabry Perot cavity with lithographically micro-fabricated mirrors in a temperature controlled vacuum achieves a frequency stability of 7×10^{-15} at 1 s [7]. Recently, a photonic integrated coil-resonator was used to stabilize an external fiber grating laser to a 36 Hz integral linewidth [8]. Stabilization of fully integrated, multi-channel, wavelength division multiplexed (WDM) semiconductor laser sources is needed to enable highly parallel precision stabilized fiber and other WDM applications.

In this paper, we report stabilization of a fully integrated multi-channel WDM hybrid laser to a common-cavity integrated coil-resonator cavity, achieving an 89 Hz integral linewidth and a fractional frequency stability of 4.3×10^{-13} at 10.5 ms. We frequency-lock a hybrid-integrated 16-wavelength-channel comb laser [9], with a 125 GHz channel spacing, to an ultra-low loss Si_3N_4 waveguide 4.0-meter-long waveguide coil resonator with 48 MHz free spectral range (FSR). The configuration allows all WDM channels to lock to the same cavity to overlay the reference cavity grid with ~2600 FSRs between WDM channels, providing a high degree of mutual coherence between channel as well as laser linewidth narrowing and stabilization of the WDM lasers. We stabilize 2 of the 16 WDM channels as an initial demonstration. The stabilized laser integral linewidth at the 1544.4 nm wavelength channel is reduced from its free-running 30 kHz to 89 Hz with the frequency noise reduced by more than 4 orders of magnitude below 1 kHz frequency offset, reaching ~10 Hz^2/Hz from 100 to 1000 Hz offset. We achieve the similar level of performance, 109 Hz integral linewidth and 4.3×10^{-13} at 10.5 ms, at 1546.0 nm. With further locking loop optimization, the laser frequency noise can potentially reach the waveguide coil resonator thermo-refractive noise limited level of 1 Hz^2/Hz below 1 kHz offset and locking of all channels to the same resonator enables high mutual coherence between all WDM lasers. This level of laser frequency noise and stability from a fully integrated hybrid laser can benifit applications such as low-noise microwave oscillators, fiber sensing, and energy-efficient coherent communications systems.

2. Coil resonator, laser stabilization setup and frequency noise measurements

The laser stabilization and frequency noise measurement setup are shown in Fig. 1(a). The hybrid-integrated comb laser has 16 wavelength channels spanning from 1538 nm to 1552 nm, and consists of 16 gain chips with ~8 mW output each, coupled to 16 silica waveguides via ball lenses through an arrayed waveguide grating [9]. The 4-meter-long coil resonator with a small FSR of 48 MHz provides optical references for each WDM channel. The coil waveguide resonator with a waveguide dimension of 6 μm by 80 nm has 102 million intrinsic Q at 1550 nm and a FSR of 48 MHz [8] that is packaged in a temperature-controlled metal enclosure (Fig. 1(a)) on a floating optical table.

The wavelength channels at 1544.4 nm and 1546.0 nm are individually stabilized with other channels turned off using a Pound-Drever-Hall (PDH) digital locking loop that is implemented using a Red Pitaya FPGA board (STEMlab 125-14 Low Noise) and `pyrpl` Python API, where the FPGA electronic noise was not found to be a limiting factor. To characterize the frequency noise and Allan deviation (ADEV) of the free-running and stabilized laser we use a delayed self-heterodyne laser frequency to measure noise components above than 3 kHz, and to overcome fiber noise for frequency noise below 3 kHz we perform a heterodyne beat note measurement with a Vescent fiber frequency comb locked to a stable-laser-systems (SLS) ultra-low-expansion high-finesse cavity stabilized laser. The fiber Mach-Zehnder interferometer (MZI) has an 8.4 MHz FSR with one arm frequency shifted by 27.1 MHz with an acousto-optic modulator (AOM). The stabilized fiber comb is amplified and filtered with a 1 nm bandwidth filter for photomixing with the stabilized hybrid integrated laser on a balanced photodetector. The results are shown in Fig. 1(b) and 1(c). The integral linewidth of the stabilized hybrid laser channel at 1544.4 nm is reduced from the free-running 30 kHz to the stabilized 89 Hz with the frequency noise reduced by up to 4 orders of magnitude to around 10 Hz^2/Hz at 100 to 1000 Hz offset. The stabilized laser ADEV reaches the minimum of 4.3×10^{-13} at 10.5 ms (Fig. 1(c)). The laser frequency drift is reduced from ~2.4 MHz/s to ~2.1 kHz/s (Fig. 2(a)).

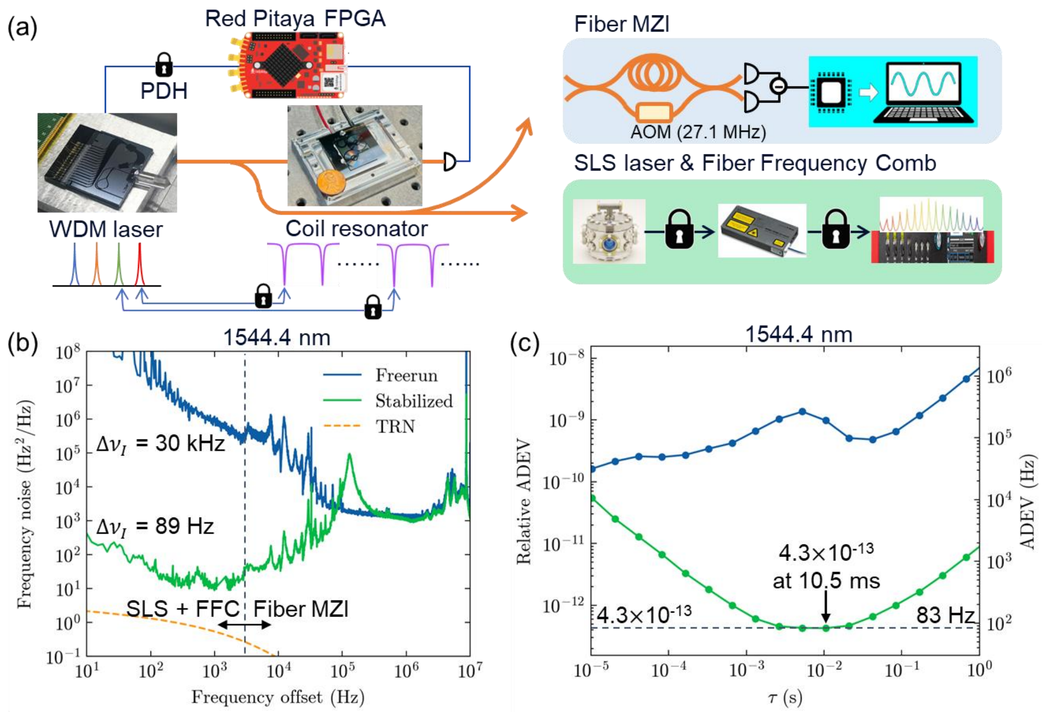

Fig. 1. Hybrid-integrated laser stabilized to a 4-meter-long coil waveguide resonator. (a) PDH digital locking circuit setup and laser noise measurements using self-delayed heterodyne laser noise measurement, Stable-Laser-Systems (SLS) laser and Vescent fiber frequency comb. (b) Measured frequency noise spectrum. $\Delta\nu_I$, integral linewidth. TRN, thermo-refractive noise. (c) Allan deviation (ADEV) from the beatnote laser noise measurement using the SLS and fiber frequency comb. τ is the averaging time.

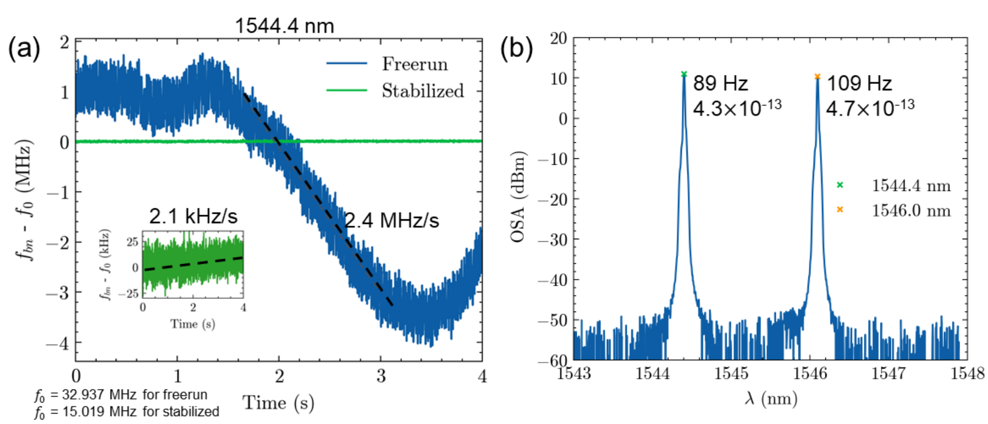

Fig. 2. (a) Free-running and stabilized laser channel at 1544.4 nm. (b) Laser stabilization performance at different wavelength channels, integral linewidth and minimum ADEV. OSA, optical spectral analyzer.

A similar level of laser linewidth and frequency stability is measured using the channel at 1546.0 nm, while other channels are turned off (Fig. 3). The laser channel at 1546.0 nm is stabilized to an integral linewidth of 109 Hz with an ADEV of 4.7×10^{-13} at 21 ms. It is worth noting that the 65 MHz low-noise Red Pitaya FPGA digital locking circuit achieves a locking bandwidth of 140 kHz, which is found out to be limited by the laser tuning speed rather than the

FPGA. The resonance grids with only 48 MHz spacing enable multiple wavelength channels to be locked to the same cavity in a wide wavelength range.

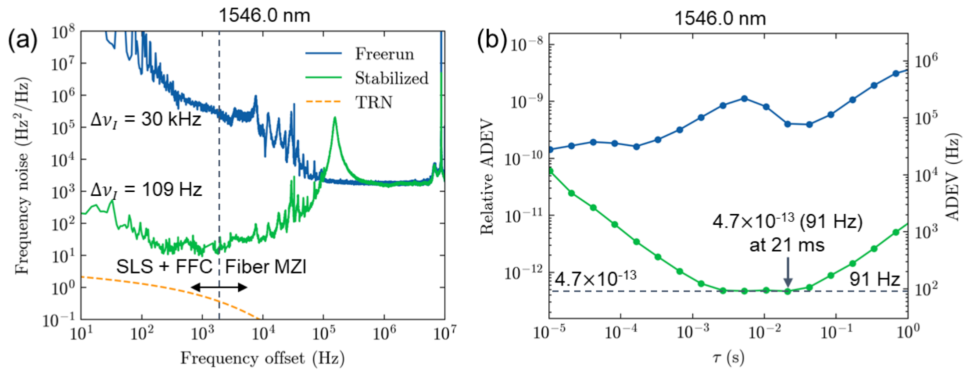

Fig. 3. Free-running and stabilized laser channel at 1546.0 nm. (a) Frequency noise spectrum. (b) ADEV.

3. Conclusion and Discussion

We demonstrate stabilization of hybrid WDM laser multiple channels to a 4-meter-long coil resonator with a 48 MHz FSR, achieving an 89 Hz integral linewidth and an ADEV of 4.3×10^{-13} at 10.5 ms at 1544.4 nm and a 109 Hz integral linewidth and an ADEV of 4.7×10^{-13} at 21 ms at 1546.0 nm. The 4-meter-long coil waveguide resonator, with 48 FSR and 102 million intrinsic Q and ultra-low thermo-refractive noise limit enables locking of multiple WDM channels locked to the same coil resonator, providing a high degree of mutual coherence and laser linewidth narrowing and stabilization. The stabilized laser integral linewidth at the 1544.4 nm wavelength channel is reduced from its free-running 30 kHz to the stabilized 89 Hz with the frequency noise reduced by more than 4 orders of magnitude below 1 kHz frequency offset, reaching to about 10 Hz^2/Hz at around 100 to 1000 Hz offset. This is the first proof-of-concept demonstration towards frequency locking of all the laser comb channels to one coil waveguide resonator for fiber sensing or telecommunication applications. Scalability, low frequency noise, and high optical power makes our approach well-suited to enhance the performance of various applications, including low-noise microwave oscillators, fiber sensing, and energy-efficient coherent communication systems.

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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. 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).
4. A. Mecozzi, C. Antonelli, M. Mazur, N. Fontaine, H. Chen, L. Dallachiesa, and R. Ryf, "Use of Optical Coherent Detection for Environmental Sensing," J. Light. Technol. **41**, 3350–3357 (2023).
5. 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).
6. 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).
7. C. A. McLemore, N. Jin, M. L. Kelleher, J. P. Hendrie, D. Mason, Y. Luo, D. Lee, P. Rakich, S. A. Diddams, and F. Quinlan, "Miniaturizing Ultrastable Electromagnetic Oscillators: Sub- 10 − 14 Frequency Instability from a Centimeter-Scale Fabry-Perot Cavity," Phys. Rev. Appl. **18**, 054054 (2022).
8. K. Liu, N. Chauhan, J. Wang, A. Isichenko, G. M. Brodnik, P. A. Morton, R. O. Behunin, S. B. Papp, and D. J. Blumenthal, "36 Hz integral linewidth laser based on a photonic integrated 4.0 m coil resonator," Optica **9**, 770 (2022).
9. S. Grillanda, C. Bolle, M. Cappuzzo, R. Papazian, B. Farah, F. Pardo, P. Iannone, N. Fontaine, M. Mazur, R. Kopf, and M. Earnshaw, "Hybrid-Integrated Comb Source With 16 Wavelengths," J. Light. Technol. **40**, 7129–7135 (2022).
10. E. D. Black, "An introduction to Pound–Drever–Hall laser frequency stabilization," Am. J. Phys. **69**, 79–87 (2000).