Self-Similar Ultra-High Q Si_3N_4 Integrated Resonators for Brillouin Laser Linewidth Narrowing and Stabilization

Kaikai Liu[1], Grant M. Brodnik[1], Mark W. Harrington[1], Andrei Isichenko[1], Qiancheng Zhao[1], John Dallyn[2], Ryan O. Behunin[2,3], Paul Morton[4], Scott Papp[5,6], Daniel J. Blumenthal[1]
[1]University of California at Santa Barbara, Department of ECE, Santa Barbara, CA, USA
[2]Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ, USA
[3]Center for Materials Interfaces in Research and Applications, Northern Arizona University, Flagstaff, AZ, USA
[4]Morton Photonics Inc., West Friendship, MD, USA
[5]Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, USA
[6]Department of Physics, University of Colorado Boulder, Boulder, CO, USA

Abstract: We report an ultra-high Q Si_3N_4 waveguide resonator Brillouin laser stabilized to an identical waveguide resonator to achieve a linewidth of 292 Hz and a record high stability of 6.5×10^{-13} at 8 ms.

1. Introduction

Photonic integrated narrow linewidth lasers are an essential component in a wide range of applications including coherent communications [1], atomic and optical clocks [2], and quantum communications and computation [3]. Stimulated scattering Brillouin (SBS) lasers have a unique property in that they can narrow the pump laser linewidth by many orders of magnitude [4] and its fundamental linewidth is ultimately determined by the quantum fluctuation of phonon modes [5]. Recent waveguide-integrated Brillouin laser demonstrations with a 10.5 mW threshold and a fundamental linewidth of 0.72 Hz based on a 65 Million intrinsic Q resonator suffered from a high close-to-carrier frequency noise, leading to an integral linewidth of several kHz due to a high intracavity power that results in a hot cavity lasing operation [6]. This close-to-carrier laser noise can be drastically reduced using high-Q optical reference cavities. While laser stabilization systems are typically implemented at the table scale, recent efforts toward compact operation employ microcavity references [7], whispering gallery mode resonators [8,9], and spiral waveguide resonators [10] to achieve order 10s to several 100s of Hz integral linewidths and stability of 3.9×10^{-13} at 400 μs averaging time. However, these architectures require either bulk optical components or custom packaged fiber-tapered evanescent coupling to access the reference cavity optical mode. Full waveguide integration of stabilized optical sources is highly desired as a route to truly compact, foundry mass-scalable, high spectral purity optical sources for use in field deployed applications such as digital signal processor (DSP)-free coherent communications in future low-power datacenter interconnects [11].

In this paper we report a photonic integrated Si_3N_4 waveguide resonator based SBS laser stabilized to an identical waveguide resonator, achieving a 12x integral linewidth reduction from 3.66 kHz to 292 Hz and a record high, for a chip scale reference, carrier stability of 6.5×10^{-13} at 8 ms averaging time and reaching the resonator's fundamental thermo-refractive noise limit. We refer to these two identical waveguide resonators fabricated on a single silicon wafer as "self-similar" resonators, as one is pumped with a high optical power for Brillouin lasing and the other is probed with a very low optical power for laser stabilization and integral linewidth reduction. By operating the reference cavity lock under cold cavity conditions, we are able to limit the impact of relative intensity noise (RIN) to photothermal frequency noise conversion on the linewidth broadening of the Brilouin laser. The single wafer fabrication of both resonators represents a major step toward highly compact, high spectral purity sources that are able to be fabricated at scale.

2. Brillouin lasing and self-similar stabilization

The ultra-high-Q Si_3N_4 resonator has a high-aspect ratio waveguide core geometry (7 μm by 40 nm) to mitigate scattering loss [12]. The loaded and intrinsic Qs are measured to be 28 and 65 Million [6]. We use a hybrid semiconductor laser as the pump laser [13] that is locked to the resonator using a Pound-Drever-Hall (PDH) scheme for the Brillouin laser operation at 1550 nm. The first Stokes (S1) of the Brillouin laser is operating just below the second order Stokes lasing [5]. S1 is then fed into an acousto-optic modulator in the second PDH lock, as illustrated in Fig. 1(a). Two methods are used to measure the laser frequency noise: an unbalanced Mach-Zehnder interferometer (uMZI) with an free spectral range (FSR) of 1.026 MHz as an optical frequency discriminator (OFD) and a heterodyne measurement with a stable laser system (SLS) whose beatnote is fed into a frequency counter for the frequency noise measurement. The OFD measurement is used for the far-from-carrier frequency noise and the SLS measurement is used for the close-to-carrier frequency noise. Both measurements are then stitched, as can be seen in Fig. 1(b), and the overlap between the OFD and SLS measurements indicates the agreement and reliability of the two measurements. The frequency noise spectrum of the stabilized Brillouin laser reaches the reference resonator's thermo-refractive noise (TRN) limit, simulated according to Ref. [14].

The integral linewidth is calculated by integrating the single sided phase noise from the highest measured frequency offset (10MHz) to the frequency offset at which the integral is 1/π rad^2 [8]. The standard approach to measure the laser linewidth is by calculating the full-width-half-maximum (FWHM) linewidth of the beatnote between the to-be-measured laser and an SLS laser, which nominally agrees with the integral linewidth calculated from the noise spectrum, according to Ref. [8]. As seen in Fig. 1(b) and 1(c), the beatnote linewidths and the integral linewidths agree well with each other. Fig. 1(d) shows Allan deviation achieves a carrier stability of 6.5×10^{-13} at 8 ms. The phase diffusion in the time domain extracted from the beatnote signal is shown in Fig. 2, demonstrating the direct impact on the laser phase diffusion from the stabilization.

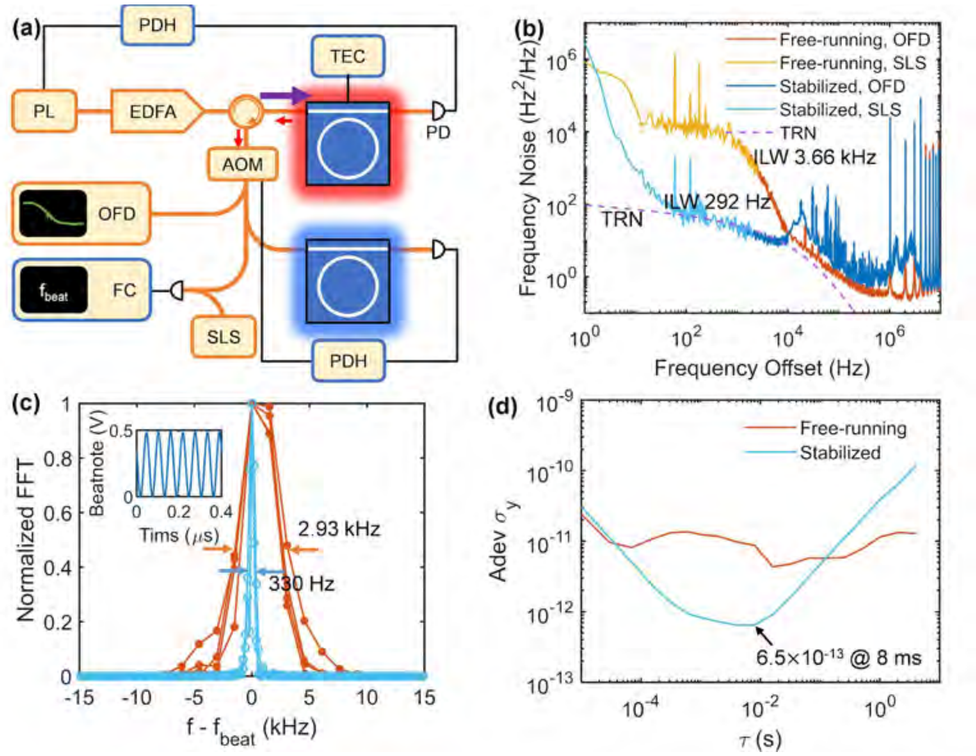

Fig. 1. (a) Experiment diagram for the Brillouin laser stabilized to a self-similar ultra-high-Q resonator. PL, pump laser. EDFA, erbium-doped fiber amplifier. AOM, acousto-optic modulator. TEC, temperature controller. PD, photodetector. FC, frequency counter. SLS, Stable Laser systems reference laser. (b) OFD (optical frequency discriminator) and SLS reference laser heterodyne measurements of frequency noise and the ILW is narrowed from 3.66 kHz to 292 Hz. TRN, thermo-refractive noise. (c) Beatnote linewidths and (d) Allan deviation for the free-running and stabilized Brillouin laser shows a linewidth narrowing from 2.93 kHz to 330 Hz and a carrier stability of 6.5×10^{-13} at 8 ms.

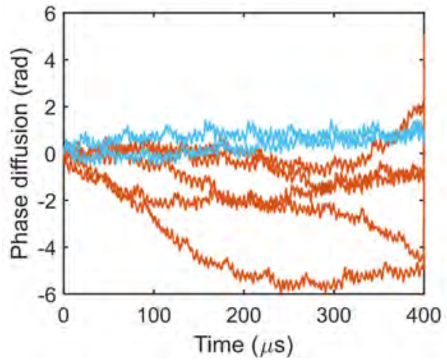

Fig. 2. Phase diffusion of the free-running and stabilized Brillouin laser.

3. Conclusion

We demonstrate a photonic integrated Brillouin laser stabilized to a self-similar ultra-high-Q resonator, achieving integral linewidth reduction from 3.66 kHz to 292 Hz (12x reduction) and a record high carrier stability of 6.5×10^{-13} at 8 ms averaging time and reaching the resonator's fundamental thermo-refractive noise limit and stabilization. Future work includes fabrication and operation of these devices that does not require wafer dicing and discrete optical components, such as the AOM in the PDH lock. Further, to realize a fully integrated narrow linewidth optical source, low threshold SBS lasing in ultra-high-Q SiN platform can be achieved [15], enabling direct pumping by heterogeneously integrated SiPh lasers [16]. Thermal engineering of the waveguide platform can further reduce integral linewidths and improve long-term stability by reducing the contribution of close-to-carrier cavity noise dominated by photothermal and thermo-refractive noise [17].

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPAE), U.S. Department of Energy, under Award Number DE-AR0001042. The views, opinions and/or findings expressed are those of the author(s) and should not be interpreted as representing the official views or policies of the U.S. Government or any agency thereof.

1. K. Kikuchi, "Fundamentals of Coherent Optical Fiber Communications," J. Light. Technol. **34**, 157–179 (2016).
2. A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, "Optical atomic clocks," Rev. Mod. Phys. **87**, 637–701 (2015).
3. A. Orieux and E. Diamanti, "Recent advances on integrated quantum communications," J. Opt. **18**, 083002 (2016).
4. A. Debut, S. Randoux, and J. Zemmouri, "Linewidth narrowing in Brillouin lasers: Theoretical analysis," Phys. Rev. A **62**, 023803 (2000).
5. R. O. Behunin, N. T. Otterstrom, P. T. Rakich, S. Gundavarapu, and D. J. Blumenthal, "Fundamental noise dynamics in cascaded-order Brillouin lasers," Phys. Rev. A **98**, 023832 (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. 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).
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. W. Loh, A. A. S. Green, F. N. Baynes, D. C. Cole, F. J. Quinlan, H. Lee, K. J. Vahala, S. B. Papp, and S. A. Diddams, "Dual-microcavity narrow-linewidth Brillouin laser," Optica **2**, 225 (2015).
10. 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).
11. G. M. Brodnik, M. W. Harrington, D. Bose, A. M. Netherton, W. Zhang, L. Stern, Paul. A. Morton, J. E. Bowers, S. B. Papp, and D. J. Blumenthal, "Chip-Scale, Optical-Frequency-Stabilized PLL for DSP-Free, Low-Power Coherent QAM in the DCI," in *Optical Fiber Communication Conference (OFC) 2020* (OSA, 2020), p. M3A.6.
12. J. F. Bauters, M. J. R Heck, D. John, D. Dai, M.-C. Tien, J. S. Barton, A. Leinse, G. Heideman, D. J. Blumenthal, J. E. Bowers, F. Burmeister, J. P. Mack, H. N. Poulsen, M. L. Masanović, B. Stamenić, D. J. Blumenthal, J. E. Bowers, B. Larsen, L. Nielsen, K. Zenth, L. Leick, C. Laurent-Lund, L. Andersen, and K. Mattsson, "Ultra-low-loss high-aspect-ratio Si3N4 waveguides," Opt. Express **19**, 3163 (2011).
13. 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).
14. 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).
15. 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 Q Planar Integrated All-Waveguide Resonator with a 3.4 Billion Absorption Limited Q and Sub-MHz Linewidth," ArXiv200907428 Phys. (2020).
16. G. M. Brodnik, S. Liu, M. W. Harrington, D. Bose, M. A. Tran, D. Huang, J. Guo, L. Chang, P. A. Morton, J. E. Bowers, and D. J. Blumenthal, "Ultra-Narrow Linewidth Chip-Scale Heterogeneously Integrated Silicon/III-V Tunable Laser Pumped Si/Si3N4 SBS Laser," CLEO 2020 2 (2020).
17. Q. Zhao, R. O. Behunin, P. T. Rakich, N. Chauhan, A. Isichenko, J. Wang, C. Hoyt, C. Fertig, M. hong Lin, and D. J. Blumenthal, "Low-loss low thermo-optic coefficient Ta2O5 on crystal quartz planar optical waveguides," APL Photonics **5**, 116103 (2020).