Narrow Linewidth Stimulated Brillouin Scattering (SBS) Lasers

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***Abstract*— A sub-Hz fundamental linewidth all-waveguide photonic integrated Brillouin laser is described. Principles behind the laser dynamics and resulting record low linewidths and phase and frequency noise will be presented. New systems-on-chip applications are enabled by the potential to operate from visible to infrared.**

Keywords*— Brillouin lasers, silicon nitride photonics, low loss waveguides, narrow linewidth lasers, photonic integration, optical communications, optical spectroscopy, optical sensing.

I. Introduction

Highly coherent ultra-low linewidth lasers are poised to make the leap from the laboratory to the chip. Applications including ultra-high capacity coherent communications [1,2], atomic clocks [3], metrology [4,5], microwave photonics [7], spectroscopy [8], optical gyroscopes [9], optical combs [10,11] and frequency synthesizers [12] will benefit from chip-scale integration. However, scaling sub-Hz fundamental linewidth (white noise floor) and low frequency noise (technical, 1/f, etc.) performance to the chip-scale presents significant challenges. To impact a broad range of applications, a high coherence laser integration platform should also have the ability to operate from the visible to the infrared. Stimulated Brillouin scattering (SBS) lasers are capable of extremely low linewidths, yet photonic integration of SBS lasers using a wafer-scale platform that enables higher functionality photonic circuits has remained elusive. Using the silicon nitride (Si_3N_4) platform we address many of these issues including ultra-low loss for a high Q resonator and large optical cavities capable of supporting large intensity and transparency from ~400 nm – 2350 nm. The platform is compatible with other Si_3N_4 active and passive components and with CMOS and wafer-scale foundry processes.

II. Laser Overview

Our Brillouin laser is a monolithic integrated waveguide bus-coupled ring resonator fabricated using simple low-loss Si_3N_4/SiO_2 waveguides [22] CMOS foundry compatible process steps. The laser operates via nonlinear photon-phonon coupling within the optical guiding region and does not employ an acoustic waveguide. The waveguides support TE only modes and produce optical amplification by harnessing the SBS resonant scattering process where a weak Stokes beam is amplified as it propagates along the waveguide by energy transfer from a strong pump beam. Unique to this design is the generation of unguided phonons, in contrast to other integrated designs that utilize acoustic guiding, leading to a Brillouin gain phonon decay rate 3-4 times larger than comparable integrated SBS lasers [16,19]. The large mode-volume bus coupled resonator combined with a loaded Q on the order of 28 Million enables the sub-Hz fundamental linewidth . The combination of fast phonon decay and long photon lifetime, suppresses the transfer of pump phase noise to the Brillouin laser emission. This broadened gain bandwidth also relaxes the phase matching conditions and improves resonator fabrication tolerances. The ability to generate large optical intensity attributes to the absence of nonlinear loss present in silicon waveguides as well as transparency from the visible through the infrared. The laser is able to operate in cascaded order mode, generating out to 10 equally spaced frequency lines that can be used for comb applications or microwave synthesis.

In this talk we describe the theoretical basis for the integrated cascaded-order Brillouin laser [25] and review its design, fabrication and properties that lead to narrow linewidth emission. We will also describe laser phase, frequency and linewidth measurements [26], potential applications, and future technology directions.

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References

[1] A. Kakkar *et al.*, "Laser Frequency Noise in Coherent Optical Systems: Spectral Regimes and Impairments," *Sci. Rep.*, vol. 7, no. 1, p. 844, 2017.

[2] J. Pfeifle *et al.*, "Coherent terabit communications with microresonator Kerr frequency combs," pp. 1–11, 2013.

[3] N. Poli, C. W. Oates, P. Gill, and G. M. Tino, "Optical atomic clocks," *Riv. del Nuovo Cim.*, vol. 36, no. 12, pp. 555–624, 2013.

[4] T. Kessler *et al.*, "A sub-40 mHz linewidth laser based on a silicon single-crystal optical cavity," vol. 6, no. October, pp. 2–7, 2011.

[5] S. B. Papp *et al.*, "A microresonator frequency comb optical clock," vol. 1, no. 1, pp. 10–14, 2013.

[6] J. Li, H. Lee, and K. J. Vahala, "Microwave synthesizer using an on-chip Brillouin oscillator," *Nat. Commun.*, vol. 4, pp. 1–7, 2013.

[7] M. O. M. Erklein *et al.*, "Widely tunable , low phase noise microwave source based on a photonic chip," vol. 41, no. 20, 2016.

[8] A. Cygan *et al.*, "Cavity mode-width spectroscopy with widely tunable ultra narrow laser," *Opt. Express*, vol. 21, no. 24, p. 29744, 2013.

[9] J. Li, M.-G. Suh, and K. Vahala, "Microresonator Brillouin gyroscope," *Optica*, vol. 4, no. 3, p. 346, 2017.

[10] P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, "Optical frequency comb generation from a monolithic microresonator," *Nature*, vol. 450, no. 7173, pp. 1214–1217, 2007.

[11] P. Liao *et al.*, "Dependence of a microresonator Kerr frequency comb on the pump linewidth," *Opt. Lett.*, vol. 42, no. 4, p. 779, 2017.

[12] D. T. Spencer *et al.*, "An Integrated-Photonics Optical-Frequency Synthesizer," *arXiv Prepr.*, p. 1708.05228, 2017.

[13] A. Mooradian, "Laser linewidth derickson.pdf," *Phys. Today 38 42-50*, vol. 42, no. 1985, 2012.

[14] S. Gundavarapu *et al.*, "Integrated Waveguide Brillouin Laser," *arXiv Prepr.*, p. 1709.04512, 2017.

[15] T. Huffman, G. M. Brodnik, C. Pinho, S. Gundavarapu, D. Baney, and D. J. Blumenthal, "Integrated Resonators in an Ultra-Low Loss Si3N4/SiO2 Platform for Multifunction Applications," *IEEE Photonics Soc. J. Sel. Top. Quantum Electron.*, no. c, 2018.

[16] H. Lee *et al.*, "Chemically etched ultrahigh-Q wedge-resonator on a silicon chip," *Nat. Photonics*, vol. 6, no. 6, pp. 369–373, 2012.

[17] I. S. Grudinin, A. B. Matsko, and L. Maleki, "Brillouin lasing with a CaF2 whispering gallery mode resonator," *Phys. Rev. Lett.*, vol. 102, no. 4, pp. 1–4, 2009.

[18] N. T. Otterstrom, R. O. Behunin, E. A. Kittlaus, Z. Wang, and P. T. Rakich, "A silicon Brillouin laser," 2017.

[19] B. Morrison *et al.*, "Compact Brillouin devices through hybrid integration on Silicon," vol. 4, no. 2013, p. 2016, 2017.

[20] K. Wörhoff, R. G. Heideman, A. Leinse, and M. Hoekman, "TriPleX: A versatile dielectric photonic platform," *Adv. Opt. Technol.*, vol. 4, no. 2, pp. 189–207, 2015.

[21] P. Munoz *et al.*, "State of the art of Silicon Nitride photonics integration platforms," *2017 19th Int. Conf. Transparent Opt. Networks*, no. 2005, pp. 1–4, 2017.

[22] J. F. Bauters *et al.*, "Planar waveguides with less than 0.1dB/m propagation loss fabricated with wafer bonding," *Opt. Express*, vol. 19, no. 24, pp. 24090–24101, 2011.

[23] J. Geng and J. Shibin, "Pump-to-Stokes transfer of relative intensity noise in Brillouin fiber ring lasers," *Conf. Lasers Electro-Optics*, vol. 80, no. 2, pp. 177–183, 2004.

[24] A. Debut, S. Randoux, and J. Zemmouri, "Linewidth narrowing in Brillouin lasers: Theoretical analysis," *Phys. Rev. A - At. Mol. Opt. Phys.*, vol. 62, no. 2, pp. 1–4, 2000.

[25] R. Behunin, N. T. Otterstrom, P. T. Rakich, S. Gundavarapu, and D. J. Blumenthal, "Fundamental noise dynamics in cascaded-order Brillouin lasers," *arXiv Prepr.*, p. 1802.03894, 2018.

[26] S. Gundavarapu *et al.*, "Sub-Hz Linewidth Photonic-Integrated Brillouin Laser," *arXiv Prepr.*, p. 1802.10020, 2018.