Chip-Scale, Optical-Frequency-Stabilized PLL for DSP-Free, Low-Power Coherent QAM in the DCI

Grant M. Brodnik[1], Mark W. Harrington[1], Debapam Bose[1], Andrew M. Netherton[1], Wei Zhang[2], Liron Stern[2], Paul. A. Morton[3], John E. Bowers[1], Scott B. Papp[2,4], Daniel J. Blumenthal[1,*]

*[1]University of California at Santa Barbara, Department of ECE, Santa Barabara, CA 93016 USA, *danb@ece.ucsb.edu*
[2]Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO USA
[3]Morton Photonics, West Friendship, MD 21794 USA
[4]Department of Physics, University of Colorado, Boulder, CO USA

Abstract: We demonstrate a DSP-free 16-QAM/50GBd link based on independent transmit and LO frequency-stabilized ultra-narrow-linewidth SBS lasers, with ~40Hz integral linewidths and $7\text{x}10^{-14}$ fractional frequency stability. The low-BW optical-frequency-stabilized-PLL with $3\text{x}10^{-4}$ rad^2 phase error operates within 1% of DSP and self-homodyne.
OCIS codes: 060.0060, 130.0130, 140.0140

1. Introduction

Hyperscale data centers (HDCs) will drive internet traffic to an astounding 20 zettabytes by 2021 and will represent 53 percent of all installed data centers [1]. HDCs are expected to drive switch ASICs, the ethernet engines of the data center interconnect (DCI), to scale from 12.8 Tbps today to over 100 Tbps pushing the limits of today's non-coherent systems in terms of power dissipation, density, and engineerable solutions. One solution is to bring coherent WDM into the intra-DCI (< 2km). However, power hungry electronics such as those associated with DSP or high bandwidth optical- and electronic- phase locked loops (OPLLs, EPLLs) must be eliminated and alternative techniques employed. We have proposed a **FRE**quency **S**tabilized **C**oherent **O**ptical (FRESCO) link [2], demonstrated here for the first time, that leverages techniques from high-end scientific applications such as optical-frequency transfer over fiber [3] and atomic clocks [4]. A main component of FRESCO is the Optical-Frequency-Stabilized PLL (OFS-PLL), requiring only low bandwidth feedback (~100kHz) that can be implemented in Bi-CMOS with mW power consumption, relatively independent of baud rate. OFS-PLL eliminates components including electronic mixers and high speed XOR logic used in analog EPLLs accounting for ~4W for 200 Gbps QPSK [5]. The Tx and LO frequency stability also alleviates OPLL homodyne receiver issues related to carrier phase recovery and bandwidth due to loop delay [6].

Here, we report an OFS-PLL based, DSP-free, carrier phase locked coherent QAM fiber link, based on μ-Cavity-Stabilized Stimulated Brillouin Scattering (CS-SBS) narrow-linewidth transmit and LO lasers. We measure residual phase error of $3\text{x}10^{-4}$ rad^2 with the OFS-PLL engaged with received residual carrier power down to -34 dBm. The measured phase error is suitable for high-order modulation up to 512-QAM [7]. We transmit 16-QAM data modulated up to 50 GBd (200 Gbps) for a single polarization over 200 m. We compare the error vector magnitude (EVM) for three link configurations and demonstrate that OFS-PLL performance is comparable to a DSP-based carrier phase recovery receiver and a self-homodyne reference receiver. Implemented with low bandwidth and low power ~100-700 kHz feedback loops, this level of performance is possible due to the measured ~1 Hz fundamental and ~40 Hz integral linewidths and $7\text{x}10^{-14}$ fractional-frequency stability (FFS) over 100 ms for both the Tx and LO CS-SBS lasers. The results presented here are applicable to the proposed FRESCO integrated transceiver and link architecture shown in Fig. 1a [2]. The CS-SBS laser is designed to drive a shared optical comb for ultra-stable low linewidth WDM carrier generation and can serve as transmit and LO for an integrated silicon photonics Tx and Rx.

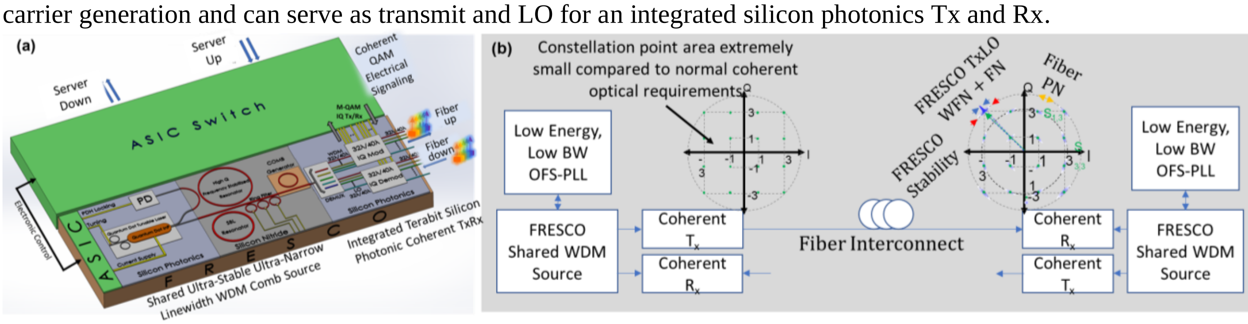
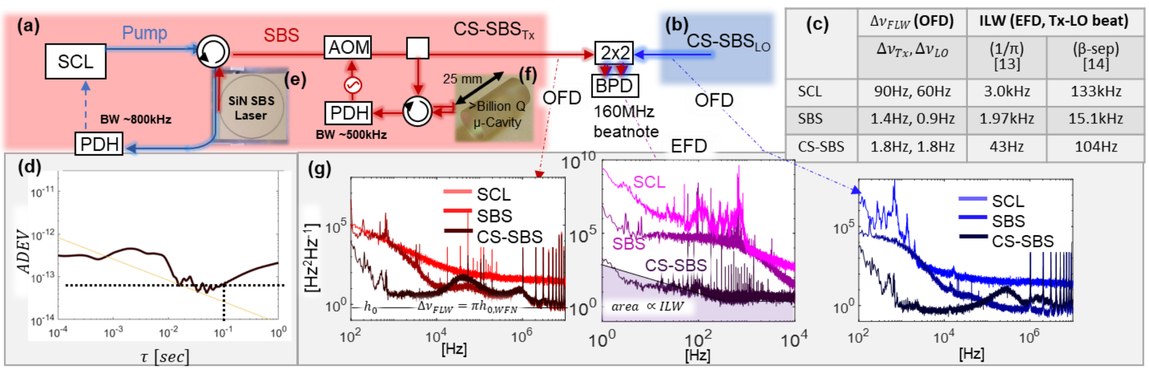


Fig. 1 Photonic integrated frequency stabilized coherent optical (FRESCO) transceiver and DSP-free low energy high capacity link.

The cost, complexity, and energy of the stabilized shared WDM source can be amortized over the WDM channels of a FRESCO transceiver. A FRESCO link is illustrated in Fig. 1b with transmit constellation with 10s of Hz phase noise and $7\text{x}10^{-14}$ fractional-frequency stability mixed with a LO with comparable phase noise and fractional frequency stability, enabling low-bandwidth optical phase lock and constellation recovery that can support Tbps channels.

2. μ-Cavity-Stabilized Stimulated Brillouin Scattering (CS-SBS) Transmit and LO Lasers

The DSP-free coherent OFS-PLL is based on independent, highly coherent, chip-scale μ-cavity-stabilized SBS (CS-SBS) transmit and receiver local oscillator (LO) lasers (Fig. 2a,b). The CS-SBS laser design achieves 10s of Hz integral linewidth (ILW) (Fig. 2c) and $7\text{x}10^{-14}$ FFS over 100 ms (Fig. 2d), and is based on a photonic integrated SBS laser [8] (Fig. 2e) stabilized to a >1 Billion Q compact Fabry-Perot reference μ-cavity [9] (Fig. 2f). A hybrid semiconductor pump laser [10] is locked to an integrated silicon nitride (Si_3N_4) bus-coupled resonator using an 800 kHz Pound-Drever-Hall (PDH) loop [6] to optically pump the SBS laser. The transmit and LO carriers are each locked to independent reference μ-cavities by actively tuning the laser output over a small range with a voltage-controlled oscillator (VCO) driven acousto-optic modulator (AOM). The high stability and low frequency noise characteristics of the μ-cavity lock stabilizes the CS-SBS carrier frequency and reduces the close-to-carrier (CTC) frequency noise and integral laser linewidth by several orders of magnitude. Frequency noise (FN) is measured using an optical frequency discriminator (OFD) [11] and the FN for Tx and LO pump lasers, unstabilized SBS lasers, and μ-cavity stabilized SBS lasers are shown in Fig. 2g (left and right traces) showing ~1 Hz fundamental linewidths (white noise floor) for each CS-SBS laser. To measure the CTC FN without noise limits of the OFD, we photo-mix the independent CS-SBS Tx and LO lasers and convert the electrical frequency noise of the heterodyne tone to a voltage using an electrical frequency discriminator (EFD) [12], observing a decrease in CTC FN by more than 5 orders of magnitude (Fig. 2g, middle). Summarized in Fig. 2c, we apply two integral linewidth calculation methods [13], [14] with frequency stabilization yielding ILW of <50 Hz and ~100 Hz using 1/π and β-separation methods, respectively.

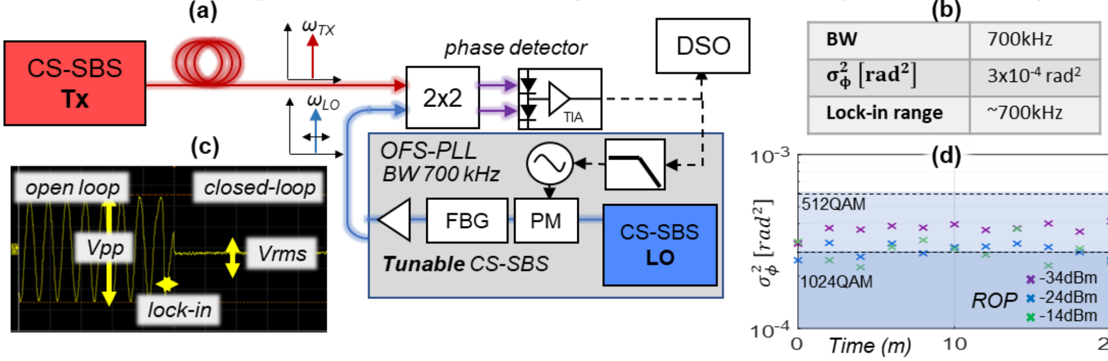


(c)	$\Delta\nu_{FLW}$ (OFD)	ILW (EFD, Tx-LO beat)	
	$\Delta\nu_{Tx}, \Delta\nu_{LO}$	(1/π) [13]	(β-sep) [14]
SCL	90Hz, 60Hz	3.0kHz	133kHz
SBS	1.4Hz, 0.9Hz	1.97kHz	15.1kHz
CS-SBS	1.8Hz, 1.8Hz	43Hz	104Hz

Fig. 2 (a) Tx cavity stabilized SBS: semiconductor laser (SCL), acousto-optic modulator (AOM), Pound-Drever-Hall (PDH). (b) LO CS-SBS. (c) Measured linewidth summary. (d) ADEV. (e) SBS laser. (f) Reference μ-cavity. (g) Laser OFD and beatnote EFD FN measurements.

3. Optical Frequency Stabilized Phase-Locked-Loop (OFS-PLL)

The OFS-PLL is realized by adding the final low bandwidth phase lock at the receiver as shown in Fig. 3a. Performance is measured by transmitting the carrier without data over 200m of fiber and measuring the residual phase error. The carrier and LO tones are photo-mixed on a balanced photodetector to generate a phase error signal [11], shown in Fig. 3c under open- and closed-loop operation. The error signal is used to control a 6 GHz voltage-controlled oscillator (VCO) that drives an optical single-sideband-modulator for LO frequency tuning and homodyne phase lock. We achieve low residual phase error of $3\text{x}10^{-4}$ rad^2 using a ~700 kHz feedback loop (Fig. 3b) with stability measured out to 20 minutes (experiments are regularly performed over > 6-hour periods with this stability). OFS-PLL residual carrier sensitivity below -34 dBm (Fig. 3d) sufficient for locking without the addition of in- or out-of-band carrier is demonstrated. The achieved phase error is sufficient for high order QAM denoted by thresholds on Fig. 3d [12].



(b)	
BW	700kHz
σ_ϕ^2 [rad^2]	$3\text{x}10^{-4}$ rad^2
Lock-in range	~700kHz

Fig. 3 (a) OFS-PLL performance measured using unmodulated carrier over 200 m of fiber. (b) OFS-PLL performance. (c) Error signal voltage in open- and closed-loop operation. (d) Phase error vs ROP. Thresholds for phase-noise limited coherent links labeled [7].

4. 32 – 50 GBd 16 QAM FREquency Stabilized Coherent Optical (FRESCO) Link

A 16-QAM single polarization coherent data transmission experiment at three baud rates (32, 40 and 50 GBd) with the OFS-PLL engaged is shown in Fig. 4a. The better than -34dBm OFS-PLL sensitivity allows the phase lock to operate on the residual carrier in the QAM data signal independent of baud rate, without requiring a Costas loop [5] or the addition of in/out-of-band carrier [15], each of which has issues with QAM, WDM, or limitations on baud rate. A coherent receiver and optical modulation analyzer (OMA) system (Keysight N4391A and real-time scope recover the signal for link diagnostics. A single laser self-homodyne reference receiver (Fig. 4b) was tested for baseline EVM. To compare the OFS-PLL to a DSP, the link was run with frequency correction and phase tracking enabled with two independent lasers (Fig. 4c). EVM (-10dBm ROP) is measured for 32, 40 and 50 GBd as shown in Fig. 4d. With data modulated on the unlocked and locked OFS-PLL as in Fig. 3c, we show the results of the OFS-PLL in Fig. 4d for unlocked and locked constellations. The link performance at these baud rates shows a small EVM penalty (<1%) for the low power OFS-PLL as compared to DSP and self-homodyne. Built-in DSP algorithms for frequency offset correction and phase tracking are bypassed and only CDR and root-raised-cosine (RRC) matched filtering are performed used. The OFS-PLL operation does not rely on the pulse shaping, however the use of RRC in the QAM transmitter and receiver in Fig.4 is to accommodate the OMA EVM measurements with the reference constellation.

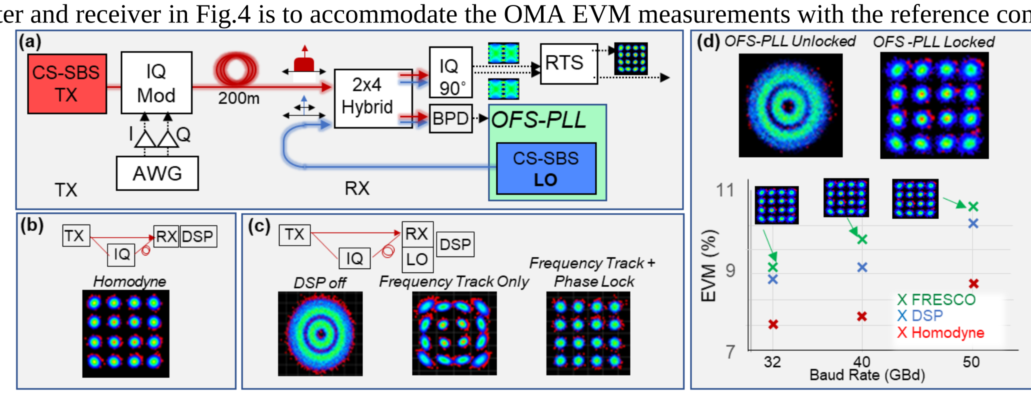


Fig. 4 (a) FRESCO data link, (b) Self-homodyne measuring baseline EVM. (c) DSP coherent EVM setup. (d) FRESCO with OFS-PLL (un)locked. EVM comparison -10dBm ROP self-homodyne reference link and DSP, showing FRESCO tracking with DSP and homodyne.

5. Conclusion

We demonstrate a DSP-free 16-QAM/50GBd link based on frequency stable lasers, showing promise for moving coherent WDM into the DCI. We utilize chip-scale μ-cavity-stabilized transmit and LO SBS lasers with measured ~1 Hz fundamental and ~40 Hz integral linewidths and 7×10^{-14} fractional frequency stability over 100 ms to implement a low-bandwidth optical frequency stabilized PLL (OFS-PLL). This level of performance demonstrates that frequency stability and linewidths typically reserved for precision time keeping applications can be leveraged to bring coherent QAM into the DCI. The OFS-PLL operates with low-bandwidth control loops and low energy electronics without the need for power hungry mixers and high-speed digital logic. We measure residual phase error to be ~3×10^{-4} rad^2 with a received residual carrier power of < -34 dBm, sufficient for 512-QAM and potentially 1024-QAM, alleviating the need for a Costas loop, pilot tone, or out-of-band carrier transmission. We compared the measured OFS-PLL EVM to a self-homodyne reference and DSP and show comparable performance as the baud rate increases from 32 to 50 GBd. The loop bandwidths are independent of baud rate and the stabilized lasers can be used to drive an optical frequency comb (OFC) for stabilized WDM channels in high capacity, multi-Tbps, DSP-free links.

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0001042

[1] Cisco Systems "Cisco Visual Networking Index: Forecast and Trends, 2017–2022 White Paper," *Cisco Forecast*
[2] D. J. Blumenthal *et al.*, *2019 8th Annu. IEEE Photonics Soc. Opt. Interconnects Conf. OI 2019*, pp. 1–2, 2019.
[3] P. A. Williams, W. C. Swann, and N. R. Newbury, *J. Opt. Soc. Am. B*, vol. 25, no. 8, p. 1284, 2008.
[4] P. O. S. Andrew D. Ludlow, Martin M. Boyd, Jun Ye, E. Peik, *Riv. del Nuovo Cim.*, vol. 36, no. 12, pp. 555–624, 2013.
[5] J. K. Perin, A. Shastri, and J. M. Kahn, vol. 35, no. 21, pp. 4650–4662, 2017.
[6] K. Kikuchi and T. Review, vol. 34, no. 1, pp. 157–179, 2016.
[7] Y. Koizumi, K. Toyoda, M. Yoshida, and M. Nakazawa, vol. 20, no. 11, pp. 12508–12514, 2012.
[8] S. Gundavarapu *et al.*, *Nat. Photonics*, vol. 13, no. 1, pp. 60–67, 2019.
[9] W. Zhang et al. arXiv:1906.00104 (2019).
[10] P. A. Morton and M. J. Morton, *J. Light. Technol.*, vol. 36, no. 21, pp. 5048–5057, 2018.
[11] T. Lu, L. Yang, T. Carmon, and B. Min, *IEEE J. Quantum Electron.*, vol. 47, no. 3, pp. 320–326, 2011.
[12] S. Schilt *et al.*, *Rev. Sci. Instrum.*, vol. 82, no. 12, pp. 1–11, 2011.
[13] D. R. Hjelme, A. R. Mickelson, and R. G. Beausoleil, *IEEE J. Quantum Electron.*, vol. 27, no. 3, pp. 352–372, 1991.
[14] G. Di Domenico, S. Schilt, and P. Thomann, *Appl. Opt.*, vol. 49, no. 25, pp. 4801–4807, 2010.
[15] M. Morsy-Osman *et al.*, *Opt. Express*, vol. 26, no. 7, p. 8890, 2018.