Narrow Linewidth Lasers for Low-Energy Coherent Communications

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Abstract: We present chip-scale lasers with ~1Hz fundamental linewidths, ~30Hz integral linewidths, and stability better than 2×10^{-13} (50ms) enabling energy-efficient, ultra-low residual phase error carrier recovery for DSP-free, high-capacity coherent communications in tomorrow's data center interconnects. **OCIS codes:** 060.0060; 130.0130; 140.0140

1. Introduction

As internet traffic in data center interconnects (DCIs) continues its accelerated growth [1], there is an urgent need for energy-efficient, compact, and scalable solutions to meet these growing capacity demands. One solution is to bring spectrally-efficient, high order modulation formats to short reach links within the DCI. However, existing coherent architectures, while well-suited for longer (10s-100s of km) links, currently rely on digital signal processing (DSP) for data recovery operations and may be too power intensive to fit this role within future DCIs. This has motivated promising DSP-free approaches to coherent communications, such those employing electrical/optical phase locked loops (E/OPLLs) for polarization tracking and carrier recovery [2], [3] and pilot-tone aided transmission [4]. However, standard E/OPLLs [5] that employ large linewidth (>100s kHz) commercial semiconductor lasers demand high-bandwidth, high-power feedback loops and typically achieve phase synchronization performance not suitable for higher order (>QPSK) formats. Carrier phase recovery using low power electronics without the need for pilot-tones or Costas loops with performance suitable for higher order coherent QAM in DCIs has remained a challenge.

We present a DSP-free approach for high order QAM carrier phase recovery by leveraging techniques common in time and frequency standards precision experiments. First, we discuss the cavity-stabilized stimulated Brillouin scattering (CS-SBS) laser with ~1Hz fundamental linewidth (FLW), ~30 Hz integral linewidth (ILW), and Allan deviation of fractional frequency instability (ADEV FFI) better than 2×10^{-13} at 50 ms, using chip-scale technologies. Next we describe fiber links using stabilized lasers as both transmitter and receiver with an optical-frequency-stabilized phase locked loop (OFS-PLL), achieving an ultra-low residual phase error variance of 3×10^{-4} rad^2 optical phase synchronization with only low power, low bandwidth (<1 MHz) feedback loops [6], [7]. This performance and energy efficiency offer promise for bringing spectrally efficient, high order QAM links to tomorrow's DSP-free DCIs.

2. Chip-scale, spectrally pure lasers

The cavity-stabilized stimulated Brillouin scattering laser is shown in Fig. 1 [6]. SBS lasing realized in an ultra-low optical loss SiN platform [8] reduces the fundamental linewidth of a narrow linewidth semiconductor pump laser [9]. The SBS carrier is then stabilized to a chip-scale 1 Billion Q optical reference cavity [10] using low bandwidth Pound-Drever-Hall feedback loops, reducing the integral linewidth and anchoring the carrier.

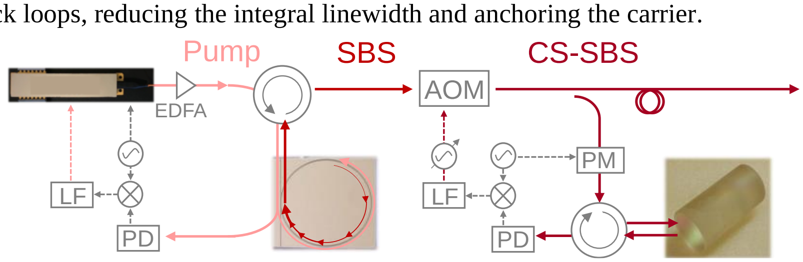

Figure 1. Cavity-stabilized stimulated Brillouin scattering (CS-SBS) laser [6]. An amplified narrow linewidth semiconductor laser [9] is used to pump an integrated SBS laser. An acousto-optic modulator is used to stabilize the SBS laser using a 1 Billion Q optical reference cavity [10]. Low bandwidth (<1 MHz) Pound-Drever-Hall (PDH) feedback loops incorporate phase modulators, photodiodes (PDs), electronic mixers, voltage controlled oscillators (VCOs), and loop filters (LFs).

Two stable lasers of the same design are connected over 200m of optical fiber as a transmitter (Tx) and receiver (Rx) pair (Fig. 2a) [6]. Frequency noise of the independent optical carriers (Fig. 2b) was measured using an asymmetric Mach-Zehnder interferometer as an optical frequency discriminator (OFD). At low offset frequencies

(<10 kHz), frequency noise of the heterodyne beat note between Tx and Rx lasers (Fig. 2c) was measured using an electrical frequency discriminator (EFD). Long term stability of the Tx/Rx stable laser heterodyne beat note was characterized by its overlapping Allan deviation fractional frequency stability (Fig. 2d).

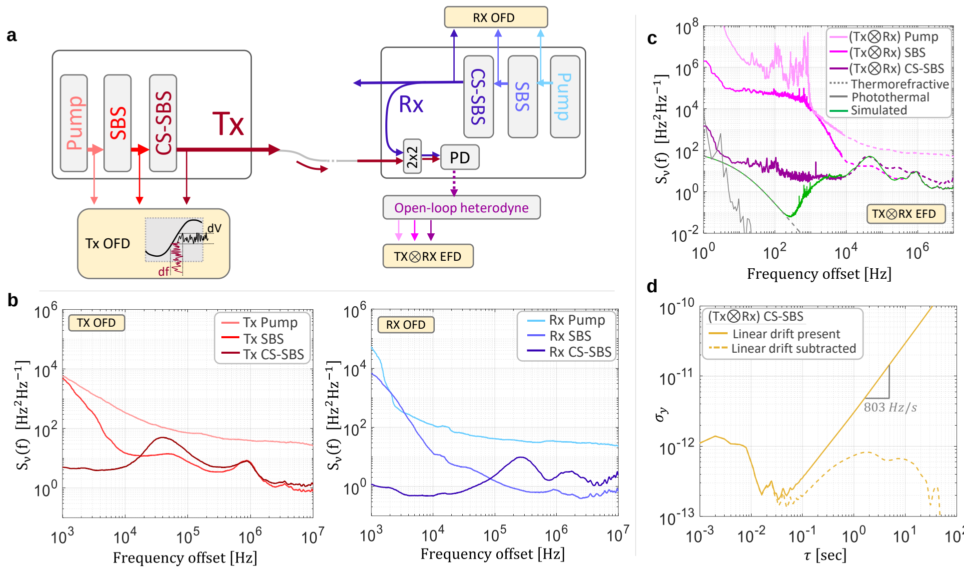

Figure 2. a) Two cavity-stabilized SBS lasers (CS-SBS) connected by optical fiber [6]. b) Transmit (Tx) and receiver (Rx) laser frequency noise measured with an optical frequency discriminator (OFD). c) Frequency noise of heterodyne beat note between Tx and Rx lasers measured with an electrical frequency discriminator (EFD). Modeled thermorefractive, photothermal noise and CS-SBS laser locked to a thermal-noise limited reference cavity (green) are shown. d) Overlapping Allan deviation fractional frequency instability with/without 803 Hz/s drift present.

SBS lasing narrowed the fundamental linewidth of the semiconductor pump laser, observed in the far-from-carrier frequency noise measurements of the independent transmit and receive lasers (Fig. 2b). For the Tx laser, SBS lasing reduced far-from-carrier (>1 MHz) frequency noise from ~ 30 Hz^2Hz^{-1} to below 1 Hz^2Hz^{-1}. For the Rx laser, SBS lasing reduced FN from ~ 25 Hz^2Hz^{-1} down to ~ 0.5 Hz^2Hz^{-1}. The corresponding fundamental linewidths for Tx and Rx SBS lasers were ~2.4 Hz and ~1.0 Hz, respectively.

Cavity stabilization of the SBS laser reduced in-loop frequency noise and drift, as observed in close-to-carrier noise reduction in the FN plots of heterodyne beat notes between Tx and Rx lasers in Fig. 2c. Beat note frequency noise of Tx/Rx pump lasers and Tx/Rx stabilized lasers show a reduction of more than 4 orders of magnitude, down to ~ 10 Hz^2Hz^{-1} at frequency offsets between 10 Hz and 10 kHz. The corresponding Tx/Rx beat note integral linewidths, calculated by a standard integration of phase noise approach [11], was reduced from 2.97 kHz for the pump laser heterodyne down to 43 Hz for the stable laser heterodyne. Assumptions of Gaussian lineshapes and equal contributions from Tx and Rx lasers to the heterodyne ILW corresponds to independent optical ILWs of ~ 30 Hz. Carrier instability (Fig. 2d) reached a minimum <2×10^{-13} timescales of ~50 ms. Linear drift of 803 Hz/s was subtracted to show the effect of center frequency drift between reference cavities, due to long (daily) timescale temperature fluctuations of the laboratory.

3. Optical phase synchronization

The fiber connected stable lasers were then extended to optical phase synchronization in a low bandwidth optical-frequency-stabilized phase locked loop (OFS-PLL) [6], [7] shown in Fig. 3. Tunability of the receiver-side stabilized laser was achieved by filtering an optically phase modulated single sideband with a fiber Bragg grating.

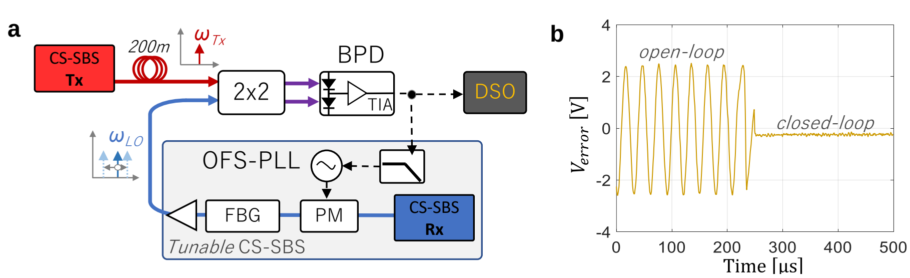

Figure 3. a) Two cavity-stabilized SBS lasers (CS-SBS) are employed in the optical-frequency-stabilized phase locked loop (OFS-PLL) [6]. A balanced detector (BPD) with transimpedance amplifier (TIA) is an optical phase detector. Phase modulator (PM), fiber Bragg grating (FBG) realize a tunable sideband as local oscillator. b) phase error sampled by digital storage oscilloscope (DSO) in open- and closed-loop operation

A zero-fringe-slip transition from open- to closed-loop operation is shown in Fig. 3b. Performance of the OFS-PLL was further characterized by measuring Tx/LO stabilized optical-signal-to-noise ratios (OSNR), OFS-PLL closed-loop residual phase error power spectral density (PSD), and closed-loop residual phase error variance (integration of residual phase error PSD), σ_ϕ^2, for various received optical powers as shown in Fig. 4.

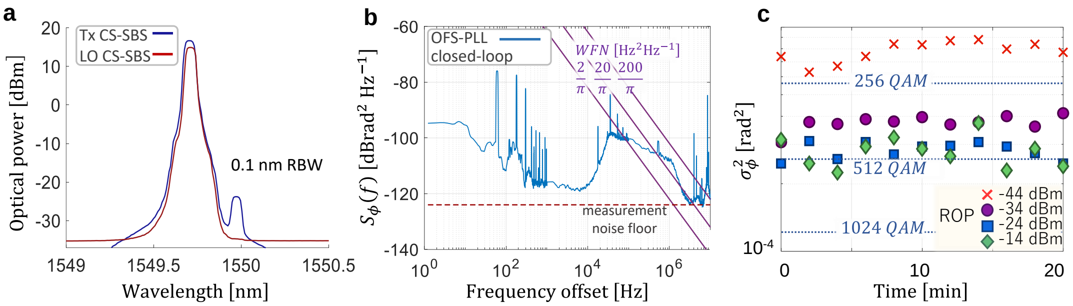

Figure 4. a) Optical spectrum analyzer (0.1 nm resolution bandwidth) traces of transmit and receiver/local oscillator CS-SBS lasers. A sideband of the tunable LO CS-SBS laser is observed ~40 dB below carrier. b) Closed-loop residual phase error power spectral density of the optical-frequency-stabilized phase locked loop (OFS-PLL). Heterodyne reference lines for two, white-frequency-noise only lasers each with fundamental linewidths of 1, 10, and 100 Hz are shown. c) Closed-loop residual phase error variance measured over time for various received powers with phase error thresholds for phase-noise-limited high order QAM links [6].

Optical spectrum analyzer measurements of the Tx and LO stabilized lasers show OSNRs better than 45 dB. A sideband of the LO laser that was not fully suppressed by the FBG is observed ~40 dB below the carrier. The residual phase error variance was measured to be 3×10^{-4} rad^2 at received optical powers as low as -34 dBm, suitable for direct residual carrier locking and high order QAM transmission in a phase-noise-limited link [6].

4. Conclusion

We have described chip-scale stabilized lasers based on SBS linewidth narrowing coupled with carrier stabilization to compact, ultra-high-Q reference cavities, to realize ~1 Hz fundamental linewidth, ~30 Hz integral linewidth, and 2×10^{-13} (50 ms) ADEV FFI sources for precision fiber optic links. This level of spectral purity and stability enables use of an optical-frequency-stabilized phase locked loop (OFS-PLL) that achieves ultra-low residual phase error variance of 3×10^{-4} rad^2 using only low bandwidth (<1 MHz), low power electronics. Future realizations of the OFS-PLL can benefit from greater levels of photonic integration, such as heterogeneously integrated pump sources [12], single sideband modulators [13], waveguide based reference cavities [14], and mW-tier Bi-CMOS electronics for further reduced power and footprint. Extension to wave-division multiplexed (WDM) operation while maintaining high-spectral purity [15] can amortize cost and complexity over multiple optical channels. This performance and energy-efficiency offer promise for bringing high order QAM transmission to future DSP-free, high capacity data center interconnects.

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