On-chip carrier recovery for coherent optical communications using Brillouin filtering

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Abstract— We demonstrate the first all-optical carrier recovery of coherent signals using on-chip Brillouin gain, replacing digital techniques, with sub-nanosecond latency. This demonstration serves as a proof-of-concept for integrated photonic carrier recovery chips for coherent communications.

Keywords— coherent optical communications; stimulated Brillouin scattering, integrated optics.

I. INTRODUCTION

Coherent technology forms the basis of modern communications systems. In coherent optical communications [1], information is encoded on both the amplitude and phase of the lightwave thus increasing transmission capacity. The realization of multiple functional devices on a single photonic chip for coherent optical communications can potentially improve the cost and energy efficiency of the network, while also offering performance advantages such as reduced phase noise and latency compared to electronic techniques. State-of-the-art coherent optical systems require advanced digital signal processing (DSP) to eliminate relative phase and frequency drifts between the transmitter laser (carrier) and the receiver laser (local oscillator, LO). These drifts can be mitigated if the carrier is ‘self-referenced’ in a self-homodyne [2] coherent receiver, which could potentially lead to lower receiver cost and energy consumption by removing the need for a high-precision LO laser and eliminating the need for complex advanced DSP. However, most approaches for self-homodyne systems [3-5] either limit system capacity or require separate, complex, high-precision analogue tracking electronics.

In this paper, we report the first on-chip carrier recovery in a self-homodyne coherent system, eliminating the need for phase noise compensation and frequency offset estimation. We achieve this using narrowband carrier extraction and regeneration [6] through stimulated Brillouin scattering (SBS) in a high-gain photonic chip [7]. We show that a chip-based solution is not only desirable due to the well-appreciated benefits of size, weight, and power consumption of integrated devices, but critical in enabling SBS-based carrier recovery to replace complex digital phase noise and frequency offset compensation. We compare our on-chip results with fibre-based SBS and demonstrate that SBS carrier recovery on a photonic chip eliminates phase noise and frequency offset. We further propose a photonic integration platform, using a hybrid approach with chalcogenide to achieve SBS, silicon to support functional circuits and indium phosphide for active devices including detectors, to achieve a complete integrated solution. It is envisaged that such a device with carrier recovery and a coherent receiver on a single chip will pave the way for energy- and cost-effective ultra-low latency optical networks with channels beyond 100 Gigabit/second (Gb/s).

II. EXPERIMENTS AND RESULTS

A 116.82Gb/s, 16-level quadrature amplitude modulation (QAM) self-coherent optical orthogonal frequency-division multiplexed (SCO-OFDM) signal was created using an arbitrary waveform generator. The signal was fed to an IQ modulator and then either transmitted over 40 km of fibre or received optically back-to-back (B2B) [8]. The received signal was split using a coupler, with one half (signal) going directly to the coherent receiver and the other half (LO) going into the SBS stage. The coupler introduces sub-nanosecond latency due to propagation delay of the signal, but in principle, the receiver sensitivity should not be reduced, as the coupling ratio can be made much lower (e.g. 99:1) due to the optical amplifier in the

Figure 1. (a) Principle of SBS-based carrier recovery, (b) experimental setup for extracting the carrier using a chalcogenide chip shown in the inset, and (c) filtering of the carrier in an SCO-OFDM signal using narrowband SBS gain.
carrier recovery system (see Fig. 1(b)). The principle of operation is shown in Figure 1 (a): the LO arm is split into two equal parts with one half propagated through a chalcogenide (As$_2$S$_3$) chip and the other half was frequency-shifted by the Brillouin shift in the waveguide, 7.7 GHz (using a phase modulator and a bandpass filter as shown in Figure 1) and counter-propagated to the signal in the photonic chip. This introduces narrowband SBS gain only on the carrier as shown in Figure 1 (c) using an enhanced carrier-to-signal (spectral power density) ratio of 33 dB, thus magnifying the carrier with respect to the SCO-OFDM signal. The chip had an insertion loss of 13 dB and a coupled SBS pump power of ~300 mW resulted in a Brillouin gain of ~15 dB. To make the recovery independent of the wavelength, the combination of the modulator and filter could simply be replaced with a dual parallel Mach Zehnder modulator biased for carrier-suppressed single sideband modulation. Even for polarization multiplexed signals, the residual carrier is still single polarization, and so in principle the self-referenced SBS filter can track the carrier polarization. The narrow linewidth of SBS and the self-referencing nature of our technique allow for the use of a very narrow guard-band of 265 MHz without employing complex frequency alignment circuitry at the receiver. This recovered carrier was subsequently sent to the LO input of the coherent receiver which was connected to an oscilloscope, and the received data were processed offline.

The received signal was noise-loaded using an amplified spontaneous emission source and the quality (Q)-factor was measured as a function of the optical signal-to-noise (OSNR) ratio. At the receiver, either a chip- or 4.5-km-fibre-based optical carrier recovery circuit was used, for B2B and after 40-km propagation. Performance under noise loading is shown in Figure 2 (a). These results indicate that propagation over 40-km fibre does not degrade the signal quality. Fig. 2(a) shows that the chip improves the Q-factor by 1.5 dB at 30 dB OSNR. At the hard–decision forward error correction (FEC)-limit (Q=8.8 dB), the on-chip carrier recovery also enables the extension of the required OSNR of the SCO-OFDM system by 3 dB when compared to the fibre-based system. To show that the chip-based processing can replace carrier recovery DSP, we compare our on-chip SBS processor with a state-of-the-art CO-OFDM system with suppressed carrier that uses an independent LO and DSP-based carrier recovery. Figure 2 (b) shows that the SBS- and DSP-based carrier recovery systems result in the same system performance against OSNR, showing that carrier recovery DSP is unnecessary when SBS-based carrier recovery is used. Finally, an illustration of an envisioned integrated carrier recovery photonic chip combining the Brillouin processor in chalcogenide, circuits in silicon [9] and modulator, filter, amplifier and coherent receiver in Indium Phosphide is shown in Figure 2 (c). We believe that such an integrated circuit will enable sub-10-ps latency due to the short coupler length.

### III. Conclusions

We have demonstrated the first on-chip carrier recovery in a coherent optical communication system using stimulated Brillouin scattering (SBS). In comparison to a state-of-the-art coherent-OFDM system that uses an independent LO and DSP-based clock recovery, our approach revealed similar performance and enhanced data-rate. We also demonstrated significant performance enhancement using on-chip SBS when compared to fibre-based SBS, highlighting the advantage of chip-based optical signal processing. We also eliminated the need for phase noise and frequency offset compensation, thus removing functional blocks from the DSP, minimizing system latency. Such on-chip carrier recovery circuit can be integrated on a hybrid photonic chip with a coherent receiver for high-bandwidth, ultra-low latency coherent communications.

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