Full-Duplex Coherent Optical System Enabled by Comb-Based Injection Locking Optical Process

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Abstract: A full-duplex coherent optical link based on optical frequency comb and injection-locking optical process is demonstrated. Simultaneous bi-directional transmission of 32-GBd DP-16QAM signal over 80-km fiber is achieved with remote LO delivery.
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1. Introduction

By prediction, the number of global internet users will reach 4 billion in 2020 [1]. Their ever-increasing demand in bandwidth will be the driving force for continuous evolution of today's data center interconnects (DCI) and optical access networks [2, 3]. To meet the high capacity demands, coherent optics has gained increasing attention in emerging DCI and access applications due to its superior performance in terms of sensitivity and spectral efficiency [2-4]. However, the cost is still the major hurdle for large scale deployments in short-haul networks. The coherent technology in long-haul optical system utilizes best-in-class photonic and electronic components. Short-haul network is a totally different environment compared to long haul and metro. Both optical sources, usually lasers as transmitter and local oscillators (LO), are crucial building blocks to optimize the system cost and performance. Low-cost lasers with acceptable degradation in system performance are preferred over the costly external cavity lasers (ECL) due to the short-haul environment having a less demanding optical link power budget. In network locations such as central offices or hubs, the use of optical frequency comb is an attractive solution to replace many independently operated ECLs [5-7] in wavelength-division multiplexing (WDM) systems. Optical injection locking (OIL), the phenomenon where a laser, subjected to external optical signal injection, is phase and frequency locked to the external signal [8-10], offering another viable path towards low-cost coherent transmitter implementation. Combined with optical comb, OIL provides effective optical filtering and amplification, which relaxes the requirement on the comb source and improves optical signal-to-noise ratio (OSNR) [7].

Additionally, in many optical access networks' scenarios, single-fiber topology is deployed which means downstream and upstream transmission takes place on a single strand of fiber [2]. Therefore, simultaneous bidirectional transmission is needed for future coherent optical networks in single-fiber topologies. This efficient use of fiber resources also facilitates enterprise connectivity and optical link redundancy.

A full-duplex point-to-point (P2P) coherent optical network with transmitters and LO injection locked to 25 GHz spaced optical frequency comb is proposed. The proposed system, with its performance comparable to the ECL-based system, significantly reduces the number of high-cost ECLs within the optical transceivers and features bi-direction transmission of coherent optical signals at the same wavelength over up to 80-km fiber. The functionality and performance of the system have been evaluated in transmission experiments over 32-GBd dual polarization (DP)-quadrature phase shift keying (QPSK) and DP-16 quadrature amplitude modulation (QAM) testbed. With QPSK modulation, full-duplex operation introduces a small penalty of 0.3-0.4 dB at both the hard-decision forward-error-correction (HD-FEC) threshold and the soft-decision (SD) FEC threshold. When using 16QAM, full-duplex operation can introduce 2 dB penalty at the HD-FEC threshold, and 1 dB penalty at the SD-FEC threshold.

2. Experimental Setup and Operation Principles

The schematic of the proposed full-duplex P2P optical link is shown in Fig. 1. On the Hub (left) side of the link, a 50 KHz linewidth ECL output signal (15dBm,1560.606nm) is modulated by a phase modulator followed by a Mach-Zehnder modulator, both driven with a 25 GHz RF signal to generate an optical frequency comb. The generated comb is first amplified by an erbium doped fiber amplifier (EDFA), then separated into multiple tones via a wavelength selective switch (WSS) with 25 GHz channel spacing. Each tone is sent to a corresponding full-duplex transceiver. In each transceiver, a comb tone with its narrow spectral linewidth inherited from the ECL, is then split in two: one is utilized as a master seed light to drive an OIL setup in transmitter TX1a for downlink (DL) signal transmission; the other is sent to receiver RX1b to generate the local oscillator (LO) via another OIL setup for uplink (UL) signal detection. A polarization controller (PC) is included in each OIL setup to control the polarization of the seed light. The OIL slave laser is a Fabry-Perot laser diode (FP-LD), with seed light injected into its cavity via a three-port optical circulator. The insets of Fig. 1 show optical spectrum of the FP-LD before (a) and after (b) injection locking.

For DL testing, the output from the FP-LD in TX1a is then fed into an external $LiNbO_3$ DP in-phase and quadrature (I/Q) modulator (35 GHz 3-dB bandwidth) to generate downlink signals. The symbols are resampled to match the sampling rate of 80-GSa/s for the DAC and oscilloscope. The skews among the four channels are also pre-compensated before sending the data to the DAC. To achieve full-duplex transmission, an optical circulator is connected to both the TX1a output and the RX1b input. A comb tone that shares the same wavelength with the ECL pump light is filtered and amplified to +10 dBm. This seed tone is combined with signals from full-duplex transceivers via an optical coupler (OC) and sent downlink through the 80 km single mode fiber (SMF) link.

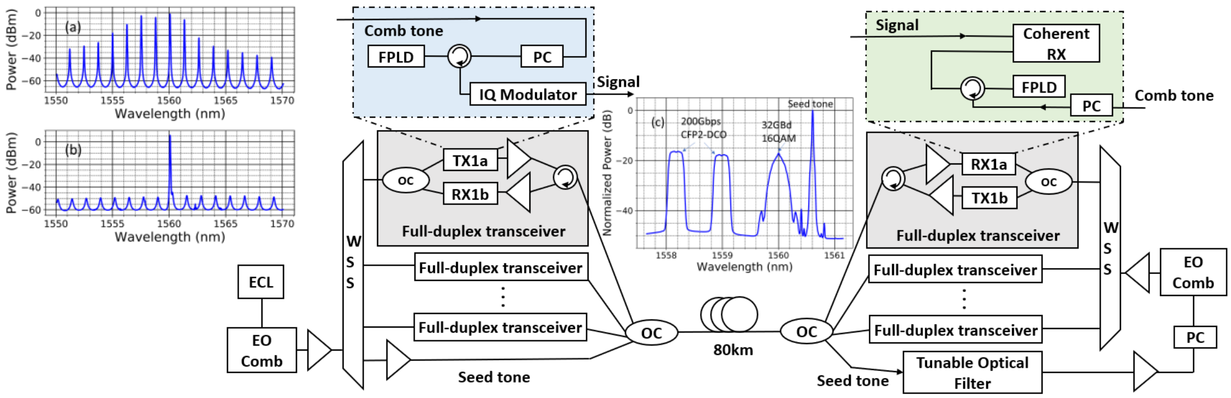

Fig. 1. Experimental system diagram for the full-duplex P2P coherent link.

On the Node (right) side of the link, after another OC and a tunable optical filter, the remotely delivered seed light is then amplified to 15dBm to generate a second comb. The generated comb tones are further amplified through a semiconductor optical amplifier to ensure enough optical power (around -5 dBm) for stable OIL. The comb tones, through a second WSS, are delivered to each full-duplex transceiver for UL signal generation and DL signal detection through OIL process. The inset (c) of Fig. 1 shows optical spectrum of our DL signal (32-GBd 16QAM) coupled with the seed tone and two of the 200 Gbit/s signals from commercial CFP2-DCO modules.

3. Experimental Results and Discussion

The OIL process is studied first using an ECL master laser under various injection ratio (power ratio between ECL and FP-LD) and detuning frequency, as shown in Fig. 2 (a) and (b). The injection ratio is varied by adjusting the master ECL output power, while the slave FP laser power remains at +5 dBm unchanged. The blue dots in Fig. 2 (a) indicate the OIL process occurs under corresponding injection ratio and frequency detuning. Under higher injection ratio, the injection locking process is more forgiving to frequency detuning. The results are in good agreement with the data reported in reference [9] and [10]. Under 10 dB injection ratio, the side-mode suppression ratio (SMSR) of the locked FP-LD under various frequency detuning is extracted in Fig. 2(b). Under positive frequency detuning, the SMSR tends to decrease with increasing detuning. Whereas under negative frequency detuning, the SMSR improves first, then starts to decrease. This mainly attributes to the fact that the linewidth enhancement factor of the master laser introduces carrier variation which will induce shift of the slave FP-LD laser gain towards longer wavelengths [10]. Fig. 2 (c) shows the normalized optical spectrum of an OIL FP-LD versus an amplified comb tone. The OIL process is done by injecting the same comb tone into the FP-LD. Compared with directly using the comb tone, OIL light source offers better OSNR and decent output power (+12 dBm here) without requiring additional amplification.

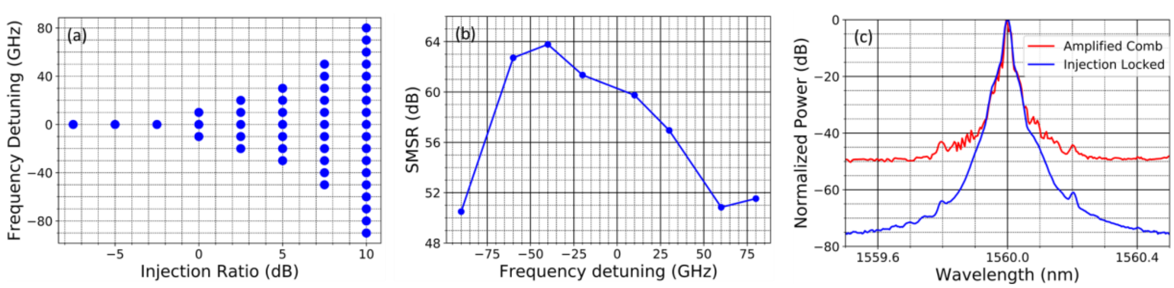

Fig. 2. (a) OIL map under various injection ratio and frequency detuning; (b) SMSR vs. frequency detuning; (c) OIL vs. amplified comb tone.

Fig. 3 shows bit-error-rate performance versus OSNR test results with constellation diagrams for the full-duplex P2P optical link. Over the 80km SMF link, DL BER vs. OSNR using 32-GBd DP-QPSK (Fig. 3 (a)) modulation format, DL BER vs. OSNR using 32-GBd DP-16QAM (Fig. 3(b)), and UL BER vs. OSNR using 32-GBd DP-QPSK (Fig. 3 (c)), UL BER vs. OSNR using 32-GBd DP-16QAM (Fig. 3(d)) are plotted separately. The results include both full-duplex operation and non- full-duplex operation for comparison in performance. OIL lasers are utilized for both transmitter and LO light sources. For reference purpose, back-to-back (B2B) BER vs. OSNR results using either ECL as both transmitter and LO light sources, or OIL as both transmitter and LO light sources are included in each plot. When using QPSK modulation format, full-duplex operation over 80km SMF link introduces a small penalty of 0.3-0.4 dB at both the HD-FEC threshold and the SD-FEC threshold. When using 16QAM modulation format, full-duplex operation can introduce around 2 dB penalty at the HD-FEC threshold, and around 1 dB penalty at the SD-FEC threshold. The full-duplex penalty mainly comes from fiber scattering and back-reflection of both the fiber link and the components used in the system.

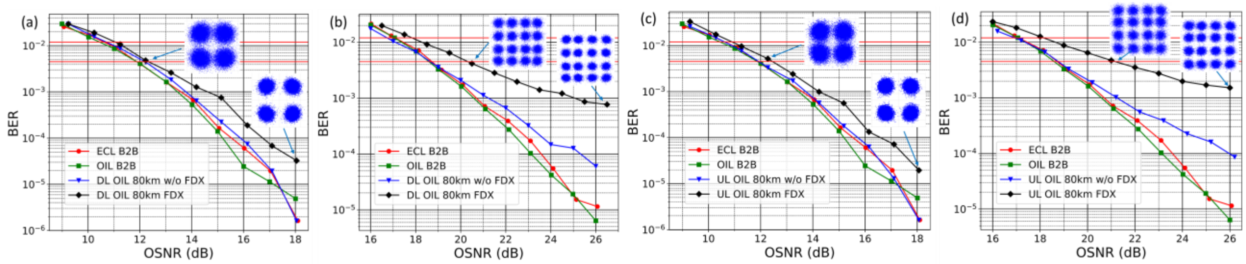

Fig. 3. (a) DL BER vs. OSNR using 32-GBd DP-QPSK; (b) DL BER vs. OSNR using 32-GBd DP-16QAM; (c) UL BER vs. OSNR using 32-GBd DP-QPSK; and (d) UL BER vs. OSNR using 32-GBd DP-16QAM.

Under full-duplex operation with DP-QPSK, BER performance vs. optical power launched into the fiber for DL and UL are tested, as shown Fig. 4(a). The BER increases with decreasing optical power, no clear sign of nonlinear impairments was observed. BER is also tested under various wavelengths by tuning the seed ECL wavelength of the comb sources and adjusting corresponding WSS and optical filter channels. For DL and UL transmission using both DP-QPSK (Fig. 4(b)) and DP-16QAM (Fig. 4(c)), no significant variation in BER performance was observed.

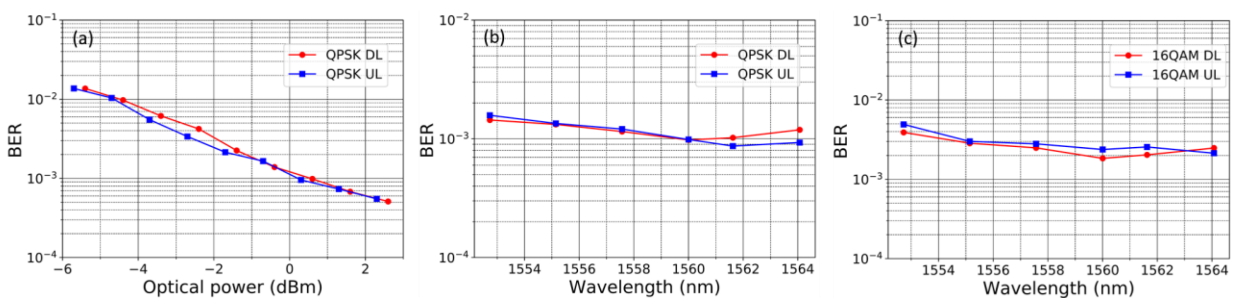

Fig. 4. (a) BER performance (DP-QPSK) vs. optical power launched into the SMF; (b) BER performance vs. wavelength (DP-QPSK); (c) BER performance vs. wavelength (DP-16QAM).

4. Conclusion

We propose, for the first time, a P2P coherent link based on optical frequency comb and OIL, that features WDM and single wavelength full-duplex through 80km SMF. OIL process and its application in coherent transmitters and receivers were studied. DL and UL full-duplex operations have been demonstrated using TX light source and RX LO that are injection locked to the comb tones, along with 32-GBd DP-QPSK and DP-16QAM coherent signal transmission, which corresponds to total bit rates of 128 and 256 Gbit/s. When using QPSK, full-duplex operation introduces 0.3-0.4 dB penalty at both the HD-FEC and the SD-FEC threshold. When using 16QAM, full-duplex operation introduces 2 dB penalty at the HD-FEC threshold, and 1 dB penalty at the SD-FEC threshold.

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