Integrated Comb Laser With Active De-Multiplexer for Spectrally Sliced Coherent Receiver

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***Abstract*— Spectrally-sliced coherent receivers (SSRx) are potentially attractive for future high-speed access networks, as they allow the use of low-cost, low-bandwidth commodity components with minimal impact on performance. In this letter, we present such a receiver, and show that it is capable of detecting a single carrier, high bandwidth 100 Gb/s PDM-QPSK optical signal using two parallel coherent receivers with reduced front-end bandwidths as low as 6.5 GHz. The receivers utilize frequency separated local oscillators derived from an integrated injection-locked gain-switched comb laser assembly (iCLA) followed by an all-active 1 × 4 demultiplexer photonic integrated circuit (PIC) to derive the spectral signal slices. The high mutual coherence of the comb lines is then exploited to enable signal reconstruction in the digital domain. The use of the active demultiplexer PIC is a key advance compared to previous work using passive comb demultiplexers as it delivers sufficient local oscillator power without the need for bulky, external optical amplifiers to compensate for demultiplexer losses. Furthermore, a minimal performance penalty is observed (<1dB at the HD-FEC limit), compared to a conventional high-bandwidth receiver. Importantly, the active iCLA and demultiplexer PIC solutions demonstrated here are key building blocks required for a fully integrated spectrally-sliced coherent receiver for future coherent access networks.**

***Index Terms*— Coherent optical communication, optical frequency comb, photonic integrated circuit.**

I. INTRODUCTION

SINCE 2008, optical transceivers and communication systems have evolved to incorporate digital signal processing (DSP) technology and coherent optics to exploit advanced modulation format to carry information at 100 Gb/s and beyond per wavelength. Access to the full optical field provided by coherent detection also enabled modern digital impairment compensation beyond the capabilities of earlier intensity modulation with direct detection systems. Since then, digital coherent optics has been the dominant technology deployed in most long-haul, and more recently, metro and inter-data center interconnect applications in the telecommunication industry. One of the next frontiers of digital coherent optics is likely to be the access network to achieve higher capacity transmission and also to address the demanding link power budgets found in passive optical networks, which arise from the splitters that are used to connect multiple customers, typically up to 64, to a given central office line terminal [1]. However, this challenge requires a solution, in particular, to redesign and optimize coherent digital technology for a highly cost-sensitive application, such as an access network. In addition to the complexity of the coherent optical receiver, to capture high-baud-rate optical signals, it is generally necessary to use front-end components with wide analog bandwidth. These components are expensive and contribute significantly to the cost of the PIC [2]. Furthermore, in the context of a PON upstream burst-mode receiver, these components become increasingly difficult to realize as bandwidth and linearity requirements increase.

The SSRx allows for the coherent detection of parallel signals in the frequency domain [3], [4] and has recently been proposed as a potential solution for cost-effective coherent reception for access applications [5]. This receiver architecture, illustrated in Fig. 1, utilizes an optical frequency comb (OFC) that generates N local oscillator (LO) tones to allow the decomposition of a wideband signal into N slices, each of which is detected by a separate conventional coherent receiver channel of lower bandwidth (the N=2 case is shown by way of an example). This is followed by post-processing to reconstruct the input waveforms in the digital domain. At the design level, the most cost-effective way to implement a comb source with an SSRx is by leveraging PIC technology. The choice of gain-switching as the comb generation technique is dictated by the fact that as a direct modulation-based method, it is inexpensive, simple, and compact, allows for a flexible setting of the frequency spacing and has reasonable per comb line power when the number of comb lines is small. In previous work [5], in addition to demonstrating the feasibility of an SSRx using a gain-switched OFC, we also elucidated the crucial OFC properties required for successful signal reconstruction in spectrally sliced detection, including the impact of phase coherence, optical power per tone, linewidth, and demultiplexer imperfections such as the comb-line suppression ratio and insertion losses.

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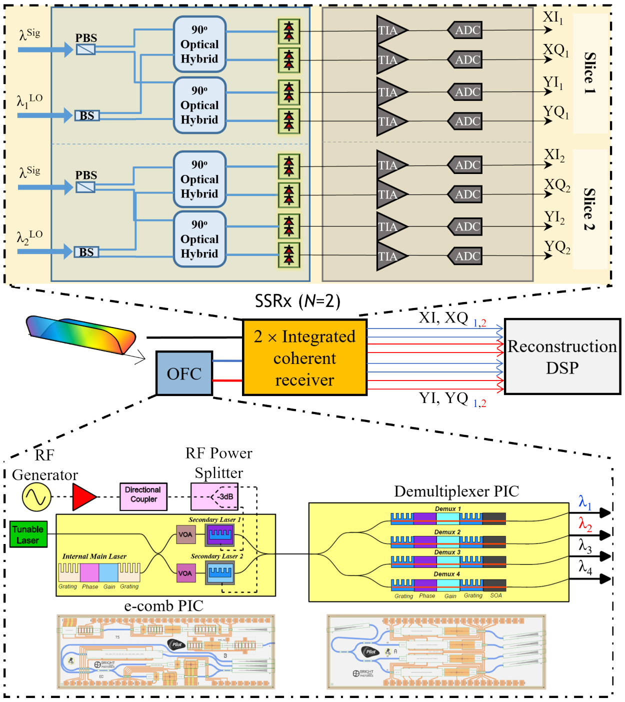

Fig. 1. Proposal architecture for the spectrally sliced optical coherent receiver with scaling of N=2, the inset above illustrates the schematic of a two-channel receiver consists of optical hybrids and balanced photodiode (BPD) in a single PIC, transimpedance amplifier (TIA)/ADC ASIC, and array optics for fiber coupling, while the inset below depicts the schematic and fabricated PIC layout of both comb source and demultiplexer respectively.

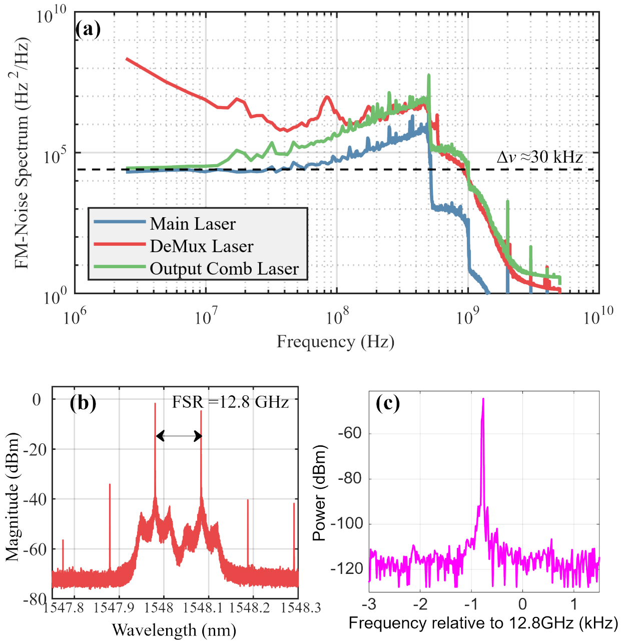

Fig. 2. (a) Phase noise measurements comparing the output comb line from iCLA with the main, and demux laser (b) optical spectrum of the output comb signals with frequency spacing of 12.8 GHz, (c) resultant beating tone between the two output tones generated at a frequency of 12.8 GHz.

Therefore, in this letter, we demonstrate the feasibility of an SSRx using a reduced front-end receiver bandwidth of 6.5 GHz and a monolithic integrated comb source with an active demultiplexer to achieve efficient slice recovery with a receiver sensitivity penalty of less than 1dB compared to a conventional intradyne coherent receiver. By improving the output power of the comb tone, the receiver's sensitivity can be reduced down to -29 dBm, thus delivering high link-budget performance for an unamplified 100 Gb/s PDM-QPSK link. To the best of our knowledge, our work represents the first spectral-slicing demonstration utilizing a comb laser PIC and a novel active demultiplexer PIC with specifications appropriate for future PON applications [5].

II. THE DESIGN & CHARACTERIZATION OF iCLA FOR SPECTRALLY SLICED COHERENT RECEIVER

This demonstration uses an iCLA for downconverting the wideband optical signal for spectrally sliced detection. The iCLA is capable of generating four mutually coherent lines and routing them to the LO ports of different coherent receivers, which is shown in Fig. 1. In this version, the iCLA consists of an expanded optical frequency comb PIC (e-comb) and an all-active 4-channel demultiplexer PIC. The e-comb PIC is based on the gain-switching of two wavelength-shifted secondary lasers that are simultaneously externally injected by a single-mode main laser. This creates two mutually locked and phase-correlated combs. When these are combined, an expanded comb result is produced by the overlap and combination of the independent combs. The e-comb PIC has an on-chip low-linewidth internal main laser. However, due to the mismatch of the lasing wavelengths of the internal main laser and the secondary lasers, an external low linewidth ($<$30 kHz) C-band tunable laser is used as the main laser. The ability to use the OFC as an LO for the coherent receiver is based on the availability of the demultiplexer capable of separating closely spaced lines while introducing low insertion losses. In the context of an integrated platform, conventional demultiplexers, such as AWGs are generally difficult to fabricate with low footprint and sufficient spectral accuracy and adjacent channel crosstalk suppression in the narrow comb line spacing limit that we target. As mentioned above, a more suitable solution for this problem involves using filters based on InP or Si_4N_3. We chose to employ an InP-based active demultiplexer, as it provides the required selectivity and ultra-low noise amplification [6]. In this proposed iCLA, the expanded comb PIC is followed by a demultiplexer PIC.

The design of the demultiplexer PIC is a cascade of multimode interferometers (MMI) that split an input signal and couple it to an array of four single-mode injection-locked lasers to demultiplex the desired comb tones. The tones are then amplified and routed to four independent PIC outputs. As a result, it overcomes one of the main drawbacks of an OFC, namely, low comb-line power. As shown in Fig. 2(b), despite the power losses introduced by the 1 × 4 splitting waveguide, the power measured from the demuxed comb lines is approximately 0 dBm. Furthermore, the ability of the demultiplexer to suppress closely spaced adjacent lines is desirable in the context of an SSRx for efficient reconstruction performance [5]. As shown in Fig. 3(b), the two demultiplexed lines have a comb line suppression ratio (CLSR) of more than 30 dB, which is sufficient for negligible penalty impact on the slice reconstruction process [5].

Apart from its integration-enabled, cost-effectiveness, and stability, one of the main advantages of this comb architecture is its ability to achieve a low effective linewidth per tone, only restricted by the main laser used in the comb source. Therefore, phase noise measurements are made based on a modified delayed self-heterodyne technique to characterize the FM-noise spectrum of each tone [7]. Fig. 2(a) shows the FM noise spectrum of the output tone generated from the proposed comb source, which appears to give an effective linewidth measurement of approximately 30 kHz, similar to the linewidth measurement of the internal main laser. Subsequently, the two demultiplexed tones, which are separated by a 12.8 GHz spacing, as shown in Fig. 2(b), are then mixed to measure the phase correlation properties between the comb tones. The result is plotted in Fig. 2(c), showing the 3-dB beat linewidth of <1kHz, indicating the strong phase correlation between OFC tones even when demultiplexed. These low linewidth and high degrees of phase coherence properties across the comb tones make them highly suitable for optimized signal reconstruction in an SSRx and tolerant to phase noise, thus enabling a higher modulation format for high-bit-rate transmission.

III. EXPERIMENTAL DEMONSTRATIONS

The experimental setup is depicted in Fig. 3(a). The 25 GBaud signal, spectrally shaped with a raised cosine filter with a roll-off factor of 0.1 was generated by four channels of DAC driven at 50 GSa/s and amplified by RF amplifiers. These analog and electrical signals drive an optical coherent transmitter module comprised of a dual IQ modulator that has a specified 6-dB bandwidth of 30 GHz, hence resulting in a dual-polarization of 100 Gb/s signal. The transmitted carrier was based on an ECL used to modulate the signal and operated at 1548.035 nm with a linewidth of 30 kHz. The resulting optical spectrum of the transmitted signal is shown in Fig. 3(b). The modulated optical signal was followed by an Er-doped fiber amplifier (EDFA) before being launched either directly to the coherent receiver or to a 40 km SMF fiber spool with around 7 dB loss. The received optical power (ROP) could be swept by adjusting the VOA.

For the conventional coherent detection scheme using a single integrated coherent receiver (ICR), another ECL with a wavelength close to that of the transmitter source was used as the LO. It was launched into a coherent optical receiver with microintegrated phase and polarization diversity to mix with the signal. For the SSRx detection case, two comb schemes were employed. The electro-optic modulator (EO) approach uses an MZM to generate two correlated comb lines from an ECL with linewidth of 30 kHz, power of 0 dBm each, and demultiplexed by a WSS. The second comb scheme is based on the iCLA where the associated LO tones were derived from a mutually injection-locked gain-switched laser with a line spacing of 12.8 GHz, as well as a four-channel PIC-based active demultiplexer, as described in the previous section. However, due to limited experimental resources, we were only able to demonstrate N=2 spectral slicing, despite the iCLA being capable of generating four comb lines. Fig. 3(b) shows the spectra of the generated filtered comb tones; each is then superimposed on the corresponding signal frequencies in the coherent receiver. The optical receiver is configured with a parallel structure of two integrated phases and polarization-diverse coherent receivers consisting of two optical 90-degree hybrids and two pairs of BPD and TIA. Given the modest degree of slicing motivated in this work, namely N=2 or 4, a power splitter was used to split the signal due to its implementation simplicity. The received waveforms were captured using eight-channel time-synchronous oscilloscopes operating at 50 GSa/s for offline DSP. Before post-processing, each channel was deskewed based on pre-calibrated values to compensate for the timing delay between the tributary channels.

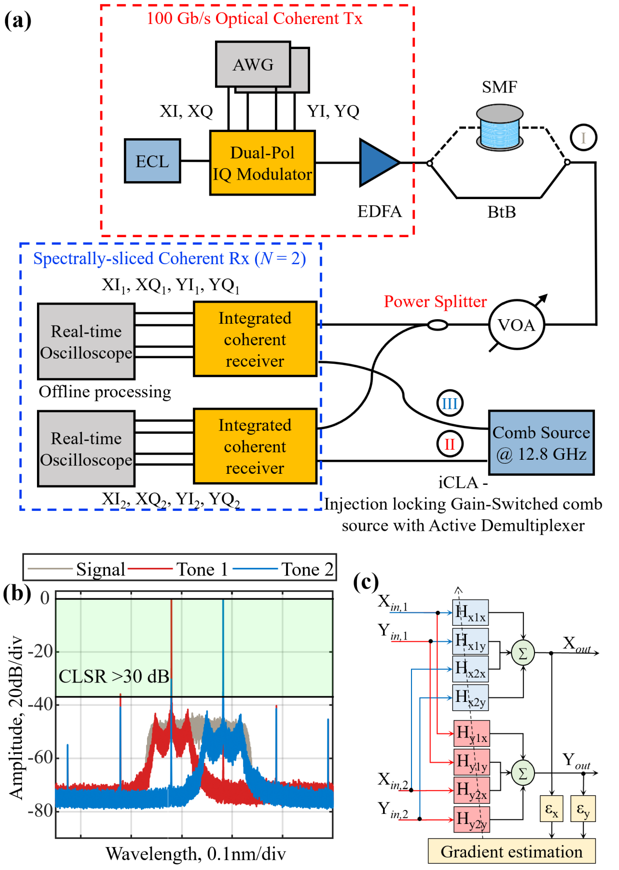

Fig. 3. (a) Experimental setup of the coherent transmission system employing a spectrally-sliced coherent receiver (N=2) utilizing an integrated comb laser with active demultiplexer, AWG: arbitrary waveform generator; SMF: single-mode optical fiber; ECL: external cavity laser; VOA: variable optical attenuator, (b) optical spectrum of the transmitted 100 Gb/s signal with two demultiplexed comb tones which each directly mixing with portion spectrum of the received signal, (c) schematic of the 4 × 2 MIMO adaptive equalizer structure for signal reconstruction.

First, the two complex inputs, corresponding to the slice 1 and slice 2 signals, were filtered by a 4^{th} order low-pass Bessel filter, with –3dB bandwidth of 6.5 GHz. This value was chosen to ensure that in total the slices captured the entire spectrum of the transmitted signal with minimal spectral gaps or overlaps. Then, IQ imbalances on each slice were compensated using the Gram-Schmidt Orthogonalization Procedure algorithm before the fixed equalization to compensate chromatic dispersion. Next, each slice is frequency shifted by ±6.4 GHz before the signal is reconstructed using a 4 × 2 MIMO equalization, as illustrated in Fig. 3(c); where the amplitude and phase mismatches between the two slices are compensated and the polarization of the X and Y tributaries is demultiplexed [8]. The corresponding outputs of these filters are the equalized combination of the two slices, which can be

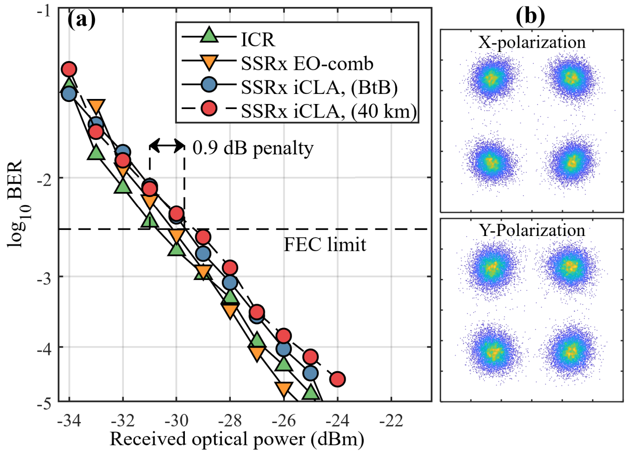

Fig. 4. (a) 100 Gb/s DP-QPSK BER versus ROP performance over 40 km transmission distance, (b) recovered 100 Gb/s DP-QPSK constellations for both polarizations at −25 dBm ROP.

computed as

$$\begin{aligned} X_{out}(n) &= H^T_{x1x}(n)X_{in,1}(n) + H^T_{x1y}(n)Y_{in,1}(n) \\ &\quad + H^T_{x2x}(n)X_{in,2}(n) + H^T_{x2y}(n)Y_{in,2}(n), \end{aligned} \tag{1}$$

$$\begin{aligned} Y_{out}(n) &= H^T_{y1y}(n)Y_{in,1}(n) + H^T_{y1x}(n)X_{in,1}(n) \\ &\quad + H^T_{y2y}(n)Y_{in,2}(n) + H^T_{y2x}(n)X_{in,2}(n), \end{aligned} \tag{2}$$

where $X_{in,N}$ and $Y_{in,N}$ denotes the complex input signal of X and Y polarization of slice N respectively, and H^T represents the conjugate transpose of the FIR filter. The filter coefficients were updated using a blind radius-directed equalization algorithm. After estimating and removing the frequency offset, a phase averaging based on the Viterbi-Viterbi algorithm was implemented to compensate for phase noise in the recovered signal. Finally, the bit error rate (BER) measurements were obtained by error counting after symbol decoding.

IV. RESULTS AND DISCUSSION

The BER performance versus received optical power comparing three receiver schemes; an ICR with bandwidth of 13 GHz (filter bandwidth is applied in the post-processing for optimum reception bandwidth.), SSRx with EO-comb, and the proposed comb (iCLA), are shown in Fig. 4(a) for the back-to-back (BtB) and 40 km SMF transmission cases. For a fair comparison, since coherent sensitivity performance is dependent on LO intensity [9], the output power per comb line in the SSRx scheme is matched to the LO output power in the ICR case, which is measured at approximately 0 dBm. The 40 km fiber transmission constellation diagrams of the SSRx with iCLA signals are shown in Fig. 4(b). BER performance is very similar in all cases. However, SSRx transmission cases based on iCLA show small sensitivity penalties of 0.9 dB in the FEC limit of 3.8×10^{-3} (HD-FEC with 7% overhead), compared to the conventional receiver. Similar performance is achieved with SSRx based on EO-comb, although the sensitivity penalty is slightly reduced to less than 0.5 dB, which we attribute to a higher degree of phase correlation of EO-comb compared to iCLA. The results for 40 km fiber and BtB transmission are very similar, indicating that the sliced signal reconstruction does not significantly affect the performance of the dispersion equalizers.

While the receiver sensitivity performance is mainly influenced by the power of the LO-demuxed comb line [9], it is worth mentioning that even a typical Class C 50G-PON link budget requirement (32 dB) can be met [10]. Taking this into account, the system would require a modest launched power (≈+3 dBm) for 100G operation.

V. CONCLUSION

In this work, we demonstrate the potential for unamplified coherent transmission using SSRx with a monolithically integrable comb source and active demultiplexer schemes to deliver high-quality reconstruction performance in spectrally sliced applications. A BER below the HD-FEC limit is achieved after 40 km of SMF transmission at a received power of −29 dBm, which can promise a reduction in the requirements for coherent receiver bandwidth for wide-band signal detection. The research demonstrates two key building blocks, the comb source and active demultiplexer, in the context of an SSRx with specifications suitable for future coherent PON applications. Future work will focus on integrating these elements, including the coherent receiver front-end [11] paving the way towards the ultimate goal of a fully integrated receiver SSRx for PON.

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REFERENCES

[1] J. Zhang and Z. Jia, “Coherent passive optical networks for 100G/λ-and-beyond fiber access: Recent progress and outlook,” *IEEE Netw.*, vol. 36, no. 2, pp. 116–123, Mar. 2022.

[2] W. Shieh, C. Sun, and H. Ji, “Carrier-assisted differential detection,” *Light, Sci. Appl.*, vol. 9, no. 1, p. 18, Feb. 2020. [Online]. Available: https://www.nature.com/articles/s41377-020-0253-8

[3] N. K. Fontaine, R. P. Scott, L. Zhou, F. M. Soares, J. P. Heritage, and S. J. B. Yoo, “Real-time full-field arbitrary optical waveform measurement,” *Nature Photon.*, vol. 4, no. 4, pp. 248–254, Feb. 2010. [Online]. Available: https://www.nature.com/articles/nphoton.2010.28

[4] B. Nebendahl, “Optical bandwidth interleaving,” U.S. Patent 10 389 450 B2, Aug. 20, 2019.

[5] H. Othman, X. Ouyang, C. Antony, F. Smyth, and P. D. Townsend, “Spectrally-sliced coherent receiver utilizing a gain-switched optical frequency comb,” *J. Lightw. Technol.*, vol. 41, no. 16, pp. 5262–5274, Aug. 15, 2023.

[6] A. Kaszubowska-Anandarajah et al., “Reconfigurable photonic integrated transmitter for metro-access networks,” *J. Opt. Commun. Netw.*, vol. 15, no. 3, pp. A92–A102, Mar. 2023.

[7] T. N. Huynh, L. Nguyen, and L. P. Barry, “Phase noise characterization of SGDBR lasers using phase modulation detection method with delayed self-heterodyne measurements,” *J. Lightw. Technol.*, vol. 31, no. 8, pp. 1300–1308, Apr. 15, 2013.

[8] J. C. M. Diniz et al., “Digital signal processing for spectrally-sliced coherent optical receivers,” in *Proc. Eur. Conf. Opt. Commun. (ECOC)*, Sep. 2015, pp. 1–3.

[9] K. Kikuchi and S. Tsukamoto, “Evaluation of sensitivity of the digital coherent receiver,” *J. Lightw. Technol.*, vol. 26, no. 13, pp. 1817–1822, Jul. 1, 2008.

[10] *50-Gigabit-Capable Passive Optical Networks (50G-PON): Physical Media Dependent (PMD) Layer Specification*, document G.9804.3, Recommendation ITU-T, 2021.

[11] X. Yi, N. K. Fontaine, R. P. Scott, and S. J. B. Yoo, “Tb/s coherent optical OFDM systems enabled by optical frequency combs,” *J. Lightw. Technol.*, vol. 28, no. 14, pp. 2054–2061, Jul. 15. 2010. [Online]. Available: http://ieeexplore.ieee.org/document/5491055