Optical Signal Recovery for Phase-Agnostic Coherent Reception

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Abstract: Photonic signal processing is being evaluated for signal recovery in phase-agnostic coherent receivers. Taking advantage of efficient direct-drive translation of photocurrents to the optical frequency domain for subsequent signal processing, the circuit can perform at half the energy cost when compared to RF-based envelope detection.

I. Introduction

Signal processing is at the heart of telecom networks and a key ingredient to propel their advancement towards higher capacities and higher operational efficiency. As modulation formats grow more complex and sophisticated detection methods are being employed, high-bandwidth digital processors have become an undeniable necessity for optical transceivers. Most performance gains obtained in the realm of copper-based or optical communication networks during the past 2-3 decades have (at least partially) relied on digital signal processing (DSP) [1]. The offloading of a critical task such as signal processing to the digital realm comes at a great burden: it requires an efficient broadband interface between the optical and digital domains, paired with DSPs capable to handle GHz-clocked information throughputs. This bottleneck has challenged researchers to investigate all-optical alternatives. Prominent examples can be found in the domain of microwave photonics or neuromorphic processing. However, the demonstrated accomplishments primarily focus on very basic physical-layer functions such as filtering [2] or true-time delays [3], or bio-inspired processing [4] under error-tolerant neural network configurations rather than precise and flexible arithmetic units as known from traditional computing. Towards this direction, first attempts to realize general-purpose building blocks involving temporal integration or differentiation have been made [5].

This work adds to this list by shifting signal processing dedicated to coherent reception (CRX) to the optical domain, using a photonic circuit that is tasked to recover the signal after coherent detection with free-running local oscillator (LO).

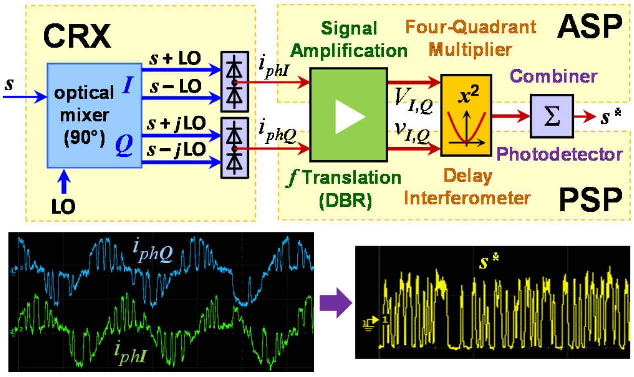

Fig. 1. PSP for phase-agnostic CRX of a signal s, photocurrents $i_{phI,Q}$ yielded by a phase-diversity CRX, and recovered data envelope s^*.

II. Photonic processing for Coherent Reception

The photonic signal processing (PSP) for the phase-agnostic coherent reception of a real-valued data signal $s(t)$ through a phase-diversity scheme relies on the spectral processing of frequency-translated photocurrents i_{ph} by computing the envelope function $s^*(t) = I(t)^2 + Q(t)^2$ in the optical domain. This scheme is introduced in Fig. 1. The envelope function is implemented through an optical circuit that is comprised of *(i)* distributed Bragg reflector (DBR) lasers as current-to-frequency translators at an independently chosen optical emission frequency ν_0, *(ii)* an optical squarer realized through a delay interferometer (DI) having an asymmetry of $\Delta T = 1/\mathrm{FSR}$ in one of its branches, biased at its spectral notch to provide a square-like transmission, and *(iii)* a photodetector acting as summing element. Under the condition that the frequency deviation of the frequency-translated photocurrents remains $\nu_\Delta < \mathrm{FSR}/2$, the processing function of the PSP circuit can be expressed as

$$s^*(t)=\sum_{I,Q}\pi^2\Delta T^2\left(\nu_0+\nu_\Delta i_{ph}\right)^2 \qquad (1)$$

III. Experimental Photonic Signal Processing

Figure 2(a) presents the experimental setup to compare the PSP approach against analogue RF-based signal processing (ASP). The CRX receives an on-off keyed (OOK) signal at 1550 nm. A phase-diversity receiver based on an optical 90° hybrid down-converts the data signal to an intermediate frequency (IF) that is governed by the frequency offset between the signal and the LO. The latter had a power of 9 dBm. Balanced receivers in the I,Q branches yield the photocurrents $i_{phI,Q}$ shown in Fig. 1, which are characterized by this IF note. This work will use balanced receivers without transimpedance amplifier (TIA) to feed the subsequent signal processing chains. This is possible due to the excellent frequency-translation efficiency of the DBR lasers in the PSP chain, which is ~18 GHz/mA. Since the bias points of the DBR sections can be independently chosen, the frequency-domain I and Q representations can share the same 10-GHz DI for the purpose of squaring signals. This is accomplished by using the complementary DI inputs, while an APD+TIA photoreceiver converts the sum of squared I and Q quadratures back to the electrical domain.

The RF-based ASP requires balanced PIN+TIA receivers to drive its four-quadrant RF multipliers dedicated to the squaring process. Further low-noise amplifier (LNA) stages have been added to pre-compensate for the RF loss of the squarer.

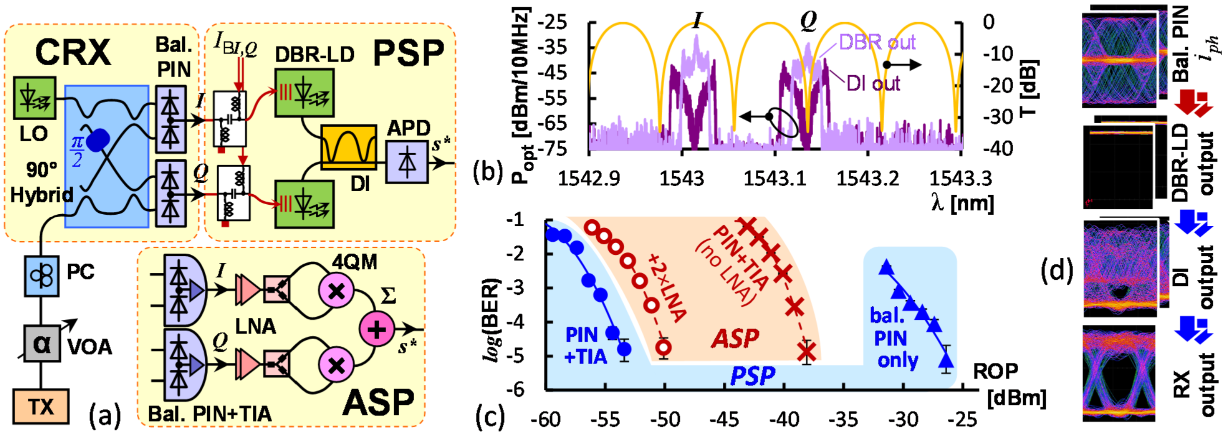

Fig. 2. (a) Experimental setup. (b) Optical spectra within the PSP unit. (c) BER performance for PSP and ASP. (d) Eye diagrams along the PSP chain.

IV. Results and Discussion

Figure 2(b) reports the optical spectra within the PSP chain. The frequency-domain representations of the photocurrents of Fig. 1 are spectrally allocated to the DI-based squarer, making them oscillate around the notches of the complementary DI ports. A peak-to-peak photocurrent swing of ~100 µA for a received optical power (ROP) of -25 dBm leads to a frequency deviation ν_Δ that pairs well with the 10-GHz FSR of the DI.

The BER performance is presented in Fig. 2(c) for PSP (▲,●) and RF-based ASP (×,○). For the most simplified receiver where the photodiode currents directly drive the DBR lasers, the PSP obtains a sensitivity of -30.1 dBm at a BER of 10^{-3} (▲). The remarkable signal integrity is evidenced by the clear eye diagram resulting from the PSP chain in Fig. 2(d). The alternative ASP approach cannot obtain a BER below 5.8×10^{-2} for this direct-drive scenario, even when raising the ROP to 3 dBm. It requires signal amplification in terms of balanced PIN+TIA receivers for the CRX to accomplish a BER of 10^{-3} at a ROP of -39.7 dBm (×). This sensitivity improves to -51.9 dBm when adding two more LNA stages with a total gain of 20 dB (○). When balanced PIN+TIA receivers are used in combination with the PSP, the reception sensitivity of the original direct-drive PSP scheme improves to -55.7 dBm (●) by virtue of the transimpedance gain. This is a clearly improved sensitivity with respect to the amplified ASP method; However, the inclusion of a TIA spoils a purely opto-electronic receiver layout for CRX+PSP (▲), suitable for photonic circuit integration.

It shall be stressed that the present experiment has been carried out for a low OOK symbol rate of 100 Mb/s since a faster electro-optic modulation of the utilized DBR lasers was restricted by their 3dB-bandwidth of 270 MHz. However, DBR lasers with a considerably wider electro-optic response supporting 10-GHz modulation have been demonstrated elsewhere [6]. This confirms that the present limitation is not fundamental roadblock for the presented PSP concept.

Moreover, the PSP evaluation has shown that an omission of electrical amplifiers is tangible. The processing chain initially includes amplified photodetectors (balanced PIN: 12 mW, with TIA: 192 mW), LNAs (95 mW/10-dB gain stage), lasers (LO: 84

mW, DBR: 45 mW), and the consumption of dedicated circuits (156 mW for the AD834 four-quadrant RF multiplier). Here, the PSP can capitalize on an efficient current-to-frequency conversion through the DBR laser, which is compatible with the direct photocurrent drive of the balanced PIN photodiodes and on the all-optical squaring function that simultaneously processes multiple input signals. Following the inventory of the setup in Fig. 2(a), the PSP (▲) can achieve a 3.3 dB lower energy consumption than the RF-based ASP without LNA (×).

V. Conclusion

An opto-electronic PSP circuit involving efficient optical frequency modulation, simultaneous squaring of multiple wavelength channels and summation has been demonstrated. The constituents of this PSP stage do not require RF circuits apart from simple bias-Ts. Through an omission of the TIA, its direct-drive scheme for the frequency translation of the received signal can greatly simplify the overall coherent receiver in links with low optical budget, boosting the energy efficiency at the same time. Scaling up the symbol rate through higher-bandwidth DBRs is left for future work.

Acknowlegement

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