A 106.25 Gb/s 2ASK-DBPSK Integrated Silicon Self-Coherent Optical Receiver

Ye Gu, Tinus Pannier, Joris Lambrecht, Peter Ossieur

***Abstract*—This paper presents a 106.25 Gb/s two amplitude-shift keying differential binary phase-shift keying (2ASK-DBPSK) co-integrated self-coherent optical receiver consisting of a silicon photonic integrated circuit (PIC) and an electrical integrated circuit (EIC). The optical receiver detects the phase information of the optical signal using a delay line interferometer (DLI) on the PIC. Without any equalization, a sensitivity of -7.3 dBm at a bit-error rate (BER) of 3.8×10^{-3} was measured. Using a 9-tap feed-forward equalizer (FFE, implemented offline) a sensitivity of -7.2 dBm at a BER of 2.4×10^{-4} was measured. Unlike 4-level pulse amplitude modulation (PAM-4), the approach does not necessarily need linear electronics. In addition, no local oscillator laser is required at the receiver to detect the optical phase information.**

***Index Terms*—optical receiver, 2ASK-DBPSK, self-coherent, delay line interferometer (DLI), silicon photonics, photodiode (PD), transimpedance amplifier (TIA).**

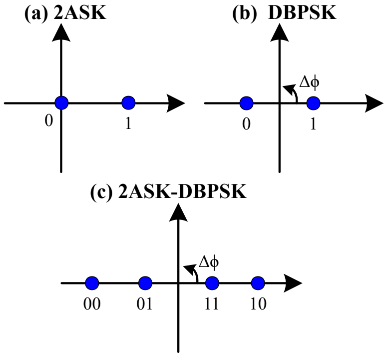

Fig. 1. Constellation of (a) 2ASK (b) DBPSK (c) 2ASK-DBPSK. For DBPSK and 2ASK-DBPSK, the polar angle represents the phase difference $\Delta\phi(t)$ between two consecutive symbols.

I. INTRODUCTION

DRIVEN by the rapid expansion of online search engines, social media, video streaming and, most recently, artificial intelligence (AI), data centers have become vital facilities for these internet applications. Optical transceivers are essential components in data centers for low power consumption and high bandwidth. Traditionally, intensity modulation-direct detection (IMDD) is used for intra-data center short-reach optical interconnections. PAM-4 [1] and non-return-to-zero (NRZ) [2] are the most popular IMDD modulation formats. Compared to NRZ, PAM-4 utilizes two bits per symbol, resulting in higher bandwidth efficiency, at the cost of more stringent linearity requirements. With industry now seeking options to scale capacity for short-reach optical interconnect beyond 200G/lane, it is interesting to consider options beyond PAM-4. Higher capacity is possible by modulating also the phase of the optical carrier: quadrature phase-shift keying (QPSK) [3] and 16-ary quadrature amplitude modulation (16-QAM) [4] are two widely used modulation formats. To demodulate such signals, typically coherent receivers are used where the incoming signal is mixed with a local oscillator (LO) signal generated by an additional laser. However, this LO increases power consumption and integration complexity at the receiver side. Moreover, carrier recovery is usually implemented in the digital domain, requiring resource-intensive digital signal processing (DSP). A more cost-effective approach to detect phase modulated signals is offered by so-called self-coherent systems. Instead of mixing the incoming signal with an LO, these systems use passive DLIs [5]–[8] to mix the incoming signal with a delayed version of itself. This approach does not require any LO or carrier recovery mechanism, resulting in low cost and lower power consumption. The supported baud rate is fixed and determined by the length of the delay line.

A few ∼25 GBd self-coherent optical receivers have been reported. A monolithic DBPSK receiver based on a multi-mode interferometer (MMI) has been demonstrated in [5], but it only demodulates 25 GBd DBPSK signals. The work presented in [6] consists of a self-coherent link demodulating differential quadrature phase-shift keying (DQPSK) signals. However, its baud rate is limited to 25 GBd. A microring-based DQPSK receiver has been demonstrated in [9], but its maximum baud rate is only 20 GBd. The microring-based DBPSK receiver reported in [10] achieves 10 Gb/s.

In this paper, we present a 53.125 GBd 2ASK-DBPSK (Fig. 1) self-coherent optical receiver. The 2ASK-DBPSK signal is demodulated by both detecting the amplitude of the received signal and the differential optical phase using a single DLI. Compared to PAM-4, 2ASK-DBPSK has the useful property of inherently splitting the received four-level signal into two two-level signals. This allows the use of power-efficient limiting TIAs. PAM-4 requires a linear TIA and a more complex clock and data recovery (CDR) circuit or analog-to-digital converter (ADC) to recover the data from the four-level signal. DQPSK has this same advantage over PAM-4, but it requires two DLIs at the receiver and a full

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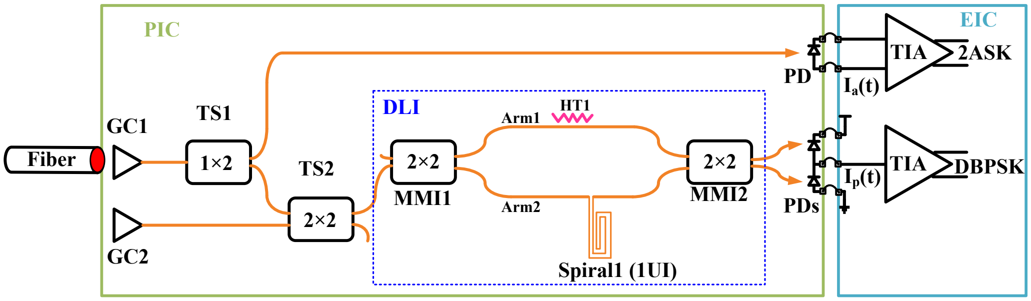

Fig. 2. Simplified schematic of the optical receiver.

IQ-modulator at the transmitter. Because the 2ASK-DBPSK constellation is located on a single axis of the IQ-plane, in theory the noise margins are smaller than for DQPSK. The optical receiver is implemented as a PIC wirebonded to an EIC. The PIC is composed of grating couplers (GCs), tunable splitters (TSs), a DLI, heaters (HTs), Ge photodiodes (PDs), and waveguides. The EIC is a four-channel TIA, of which only two channels are required for 2ASK-DBPSK detection. The optical receiver achieves a sensitivity of -7.3 dBm at a BER of 3.8×10^{-3}.

This paper is organized as follows. Section II describes the optical receiver architecture and implementation. Section III discusses the details of the measurement setup, followed by the measurement results and a comparison with the state-of-the-art in Section IV. Finally, Section V concludes the paper.

II. OPTICAL RECEIVER ARCHITECTURE AND IMPLEMENTATION

Fig. 1 shows the constellations of 2ASK, DBPSK, and 2ASK-DBPSK. 2ASK-DBPSK signals have two phase states, 0 and π, and two amplitude states. Each 2ASK-DBPSK symbol carries two bits.

The simplified schematic of the optical receiver is shown in Fig. 2, which consists of a PIC wirebonded to an EIC. The receiver has two channels: the 2ASK channel and the DBPSK channel. The PIC is fabricated in imec's iSiPP50G process. Because the receiver is targeted towards short-reach intra-data center interconnections, all the selected optical devices were optimized for operation in the O-band. The PIC consists of two GCs, two TSs, one DLI and two groups of PDs. Optical signals can be coupled into the PIC through GC1, which is connected to TS1. TS1 is controlled by a thermo-optic heater on the PIC and connected to a PD and TS2. The cathode and anode of the PD are connected to the differential inputs of the TIA with bonding wires for 2ASK detection. The PD, with >50 GHz bandwidth and ∼0.9 A/W responsivity in the O-band, supports >50 GBd low-noise optical receivers. The TIA [2], fabricated in a 55nm BiCMOS process, achieves more than 40 GHz bandwidth. The PD current $I_a(t)$, containing the detected optical signal amplitude, is further converted into a voltage signal by the TIA. TS2 is biased by a thermo-optic heater to pass the input optical signal of TS2 to the following DLI with minimal power loss. The DLI consists of two MMIs and one delay line. The upper output Arm1 of MMI1 is routed directly to the upper input of MMI2, while the lower output Arm2 of MMI1 is routed to the lower input arm of MMI2 via a delay line. The delay line is implemented using a 1260 μm spiral waveguide with a nominal delay of ∼18.6 ps (waveguide group index $n_g = 4.43$). The spiral delay line can be made very compact because of the high-index-contrast waveguide system of the silicon photonics technology. The phase difference ϕ_{DLI} of Arm1 and Arm2 can be fine-tuned by a thermo-optic heater. MMI2 is followed by two balanced PDs. The common junction between the two PDs is connected to the input of the TIA on the EIC through a bonding wire. The PD currents $I_a(t)$ and $I_p(t)$ are given by [11]:

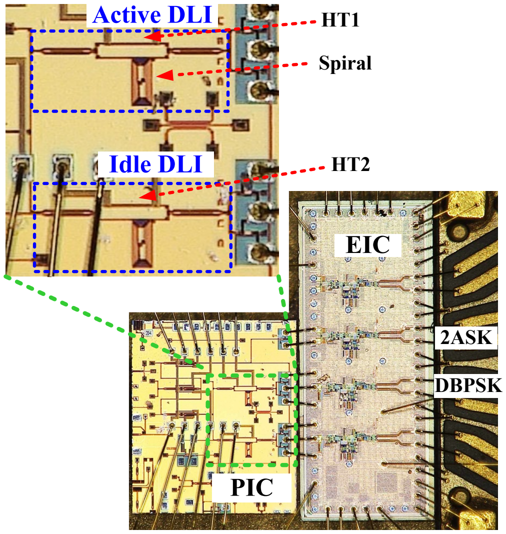

Fig. 3. Micrograph of the optical receiver. The electrical IC contains four TIA channels, of which the middle two channels are used.

$$I_a(t) = R\,P_1\,a^2(t) \tag{1}$$

$$I_p(t) = R\,P_2\,a(t)\,a(t - T_s)\,\cos[\Delta\phi(t) + \phi_{DLI}] \tag{2}$$

where R represents the responsivity of the PDs, $a(t)$ is the modulation amplitude, and T_s equals a symbol period. The average optical powers of the 2ASK and DBPSK signals are given by P_1 and P_2, respectively. The phase difference between two consecutive symbols, $\Delta\phi(t)$, is equal to 0 or π for 2ASK-DBPSK modulation. To maximize the amplitude of $I_p(t)$, ϕ_{DLI} should be equal to 0 or π.

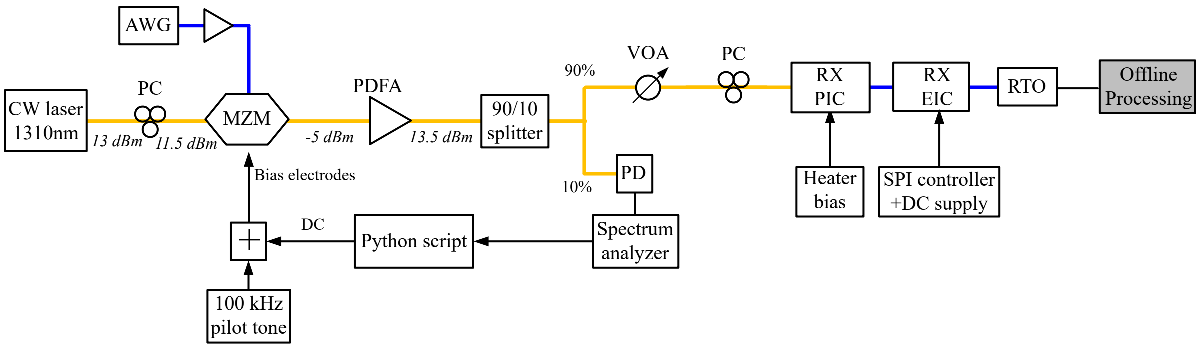

Fig. 4. Measurement setup of the optical receiver

The micrograph of the optical receiver is shown in Fig. 3. The PIC contains two DLIs, of which only one DLI is active and the other DLI is idle. The EIC contains four TIA channels, of which the middle two channels are used for 2ASK and DBPSK detection. The PIC and the EIC are connected by wirebonds. The PIC is thinned to the same thickness as the EIC and placed as close as possible to the EIC to minimize bondwire length. The outputs of the EIC are wirebonded to transmission lines on a PCB for measurement. Finally, the receiver in its current form was designed to support a single polarization. A polarization diversity receiver can be constructed using either a 2D grating coupler [6], or an edge coupler combined with polarization splitter-rotators (PSRs).

III. MEASUREMENT SETUP

The measurement setup is shown in Fig. 4. At the transmitter side, a 13 dBm 1310 nm (O-band) continuous wave (CW) laser is modulated by a commercial off-the-shelve $\mathrm{LiNbO_3}$ Mach-Zehnder modulator (MZM) with $4\,\mathrm{V}$-V_π, biased at minimal transmission point. The electrical RF signals generated by a 92 GSa/s arbitrary waveform generator (AWG) (Keysight M8196A) are further amplified by an RF amplifier to $3.5\,\mathrm{V_{pp}}$ to drive the MZM. A praseodymium-doped fiber amplifier (PDFA) is used to increase the optical power of the MZM output signal. This signal is fed to a power splitter, with 90% of the optical power being transmitted to the optical receiver and the other 10% being coupled into a commercial PD. Before data measurement, a 100 kHz pilot tone is added to a DC voltage to find the minimal transmission point of the MZM [12]. The DC voltage is controlled by a Python script which captures the spectrum of the output signal of the commercial PD from a spectrum analyzer. The 100 kHz pilot tone and the control loop are turned off during data capture. The average optical powers at the transmitter side in the measurement setup have been annotated in Fig. 4.

At the receiver side, a variable optical attenuator (VOA) is used to control the optical power coupled into the receiver. Since the PIC is polarization dependent, an external polarization controller (PC) is required to align the polarization with the TE mode of the grating coupler GC1. The heaters on the PIC are controlled by DC voltages. The high-speed PDs on the PIC are biased by a single DC voltage and their combined currents are measured to calculate the received optical power, using the reported PD responsivity. The single-ended outputs of the 2ASK channel and DBPSK channel are connected to a real-time oscilloscope (RTO) (Keysight Z634A) through a TR70 connector. The RTO features a 160 GSa/s sampling rate and an analog bandwidth of 63 GHz. Based on the data captured by the RTO, eye diagrams and BERs are obtained using offline data processing in Matlab.

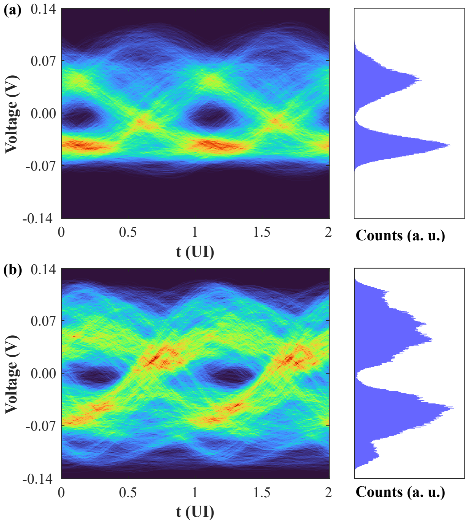

Fig. 5. 53.125 GBd eye diagrams measured by the RTO and histograms at the optimum sampling point (a) 2ASK channel (b) DBPSK channel

In the measurement, the bias voltages of the heaters on the PIC are used to fine-tune ϕ_{DLI} to obtain maximum signal amplitude at the DBPSK channel. Due to the thermal crosstalk of HT1 (Arm1) to Spiral1 (Arm2) and the high thermal sensitivity of optical spiral delay lines, a large part of the heat produced by HT1 results in a common phase shift in Arm1 and Arm2 and does not effectively tune ϕ_{DLI}. By relying on the difference in waveguide length (and therefore thermal crosstalk sensitivity) between Arm1 and Arm2, HT2 was found to be more efficient to tune ϕ_{DLI}. HT1 could be placed close to Spiral1 (Arm2) rather than Arm1 in a future redesign to reduce the effect of thermal crosstalk.

IV. MEASUREMENT RESULTS AND DISCUSSION

The waveforms recorded by the RTO are processed offline to calculate the BER by counting. Fig. 5 shows the 53.125 GBd

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TABLE I
COMPARISON WITH CURRENT STATE-OF-THE-ART SELF-COHERENT OPTICAL RECEIVERS.

ref.	Year	Modulation format	Bits/symbol	Baud rate (GBd)	Demodulation structure	Platform
[5]	2015	DBPSK	1	25	DLI	Silicon
[6]	2014	DQPSK	2	25	DLI	Silicon
[8]	2012	DQPSK[1]	2	25	DLI	Silicon/InGaAs
[9]	2015	DQPSK	2	20	Microring	Silicon
This work	2025	2ASK-DBPSK	2	53.125	DLI	Silicon

[1] Only DBPSK has been measured.

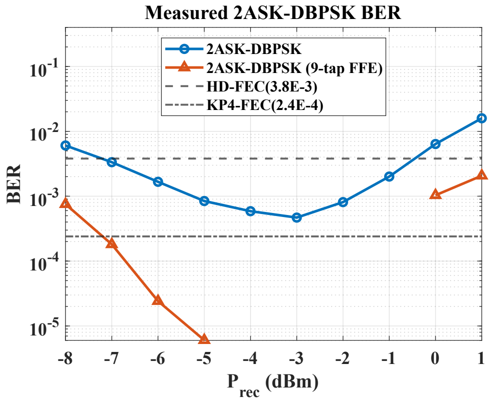

Fig. 6. Measured 53.125 GBd 2ASK-DBPSK BER vs. $\mathrm{P_{rec}(dBm)}$.

eye diagrams measured by the RTO at the outputs and the histograms at the optimum sampling point of the 2ASK and DBPSK channels at -3 dBm received optical power at the PDs. The input tunable splitter, TS1, is controlled to achieve similar eye opening between the 2ASK and DBPSK signals, to achieve the best overall BER performance. The measured 53.125 GBd 2ASK-DBPSK BER vs. $\mathrm{P_{rec}(dBm)}$ curves are shown in Fig. 6. Each BER point is obtained from the captured waveform of 3.3×10^5 symbol periods. The receiver achieves -7.3 dBm sensitivity at HD-FEC (3.8×10^{-3}) threshold and a minimum BER of 4.7×10^{-4} without any equalization in the data processing. After applying a 9-tap FFE, the receiver achieves -7.2 dBm sensitivity at KP4-FEC (2.4×10^{-4}) threshold and the minimum BER is limited by the finite length of the recorded waveforms ranging from -4 dBm to -1 dBm.

A comparison with current state-of-the-art self-coherent optical receivers is shown in Table I. The 2ASK-DBPSK optical receiver reported in this paper achieves the highest baud rate of 53.125 GBd, corresponding to 106.25 Gb/s.

V. CONCLUSION

A 106.25 Gb/s 2ASK-DBPSK integrated self-coherent optical receiver has been presented in this paper. The PIC with all the optical devices was fabricated in a silicon photonics process (imec iSiPP50G). The phase detection was based on a DLI with a waveguide delay line. The PIC has been integrated with a four-channel TIA. The optical receiver achieves -7.3 dBm sensitivity at HD-FEC without equalization and -7.2 dBm sensitivity at KP4-FEC with 9-tap FFE.

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