

40Gbit/s Coherent Optical Receiver Using a Costas Loop

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Abstract For the first time, a highly integrated coherent optical receiver is demonstrated using a homodyne OPLL as a Costas loop. The OPLL shows 1.1GHz loop bandwidth, 120ps effective loop delay, and $10 \times 10 \text{mm}^2$ compact size of chip integration. The receiver exhibits 40Gbit/s BPSK reception with no latency.

Introduction

Coherent optical communication has resurged due to demand for higher sensitivity, data rates, and spectral efficiency^{1,2}. Recent approaches to coherent optical receivers have adopted coherent detection using a local oscillator (LO) laser, a polarization diversity 90° optical hybrid with balanced detectors, and digital signal processing (DSP), because advanced DSPs can manage phases and polarizations without a phase lock^{1,2}. However, they require high speed analog to digital converters (ADC) and complicated signal processing algorithms. They are also limited by data processing speed, cost, and power consumption^{2,3}.

The alternative coherent optical receiver is a homodyne optical phase locked loop (OPLL) based coherent detection also known as a Costas loop^{2,3}. It restores the phase of a carrier laser, and high-speed data are demodulated by a simple phase locked loop (PLL) without ADC and DSP. However, it has been regarded as challenging because of large loop delays which lead to a narrow loop bandwidth, and therefore, the OPLL cannot maintain stability against laser phase noise and frequency drift¹⁻³.

Recently, several OPLLs have been reported including a highly integrated homodyne OPLL using a high speed HEMT based loop filter with a loop bandwidth of 300MHz⁴, a heterodyne OPLL using an exclusive-OR (XOR) as a phase detector with a loop delay of 1.8ns⁵, and a highly integrated heterodyne OPLL using an integrated single side-band mixer and a phase frequency detector (PFD) with a loop delay of 0.2ns and loop bandwidth of 550MHz⁶.

OPLL based coherent optical receivers have been improved with modified OPLL topologies such as a decision driven OPLL with sub-carrier modulation⁷ and a digital OPLL using sampled I-Q signals and slow speed DSP for homodyne reception of PSK 40Gbit/s³. However, such OPLLs may require a narrow linewidth on

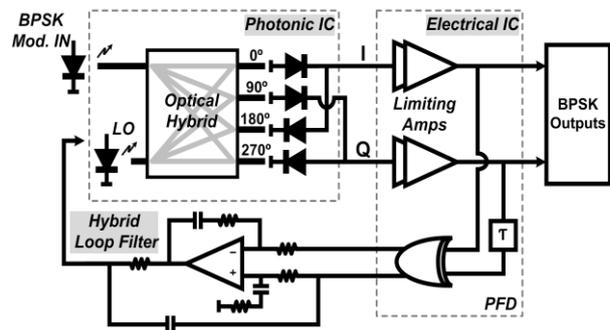


Fig. 1: A schematic of a homodyne OPLL and a BPSK receiver

transmitting and LO lasers due to a narrow loop bandwidth, and these OPLLs may need additional circuit blocks such as voltage controlled oscillators, a Mach-Zehnder modulator (MZM), an optical filter, and even ADC and DSP to recover the carrier signal.

In this paper, a highly integrated 40Gbit/s BPSK coherent optical receiver based on the homodyne OPLL and the Costas loop is demonstrated for the first time. The OPLL has achieved a large closed loop bandwidth of 1.1GHz by a significantly minimized loop delay of 120ps. In addition, digitally operating electrical circuits make the OPLL system less sensitive to external fluctuations and the PFD extends phase-lock and frequency pull-in ranges. The BPSK coherent receiver exhibits BER results of error-free ($\text{BER} < 10^{-12}$) up to 35Gbit/s and less than 10^{-7} for 40Gbit/s. The compact BPSK coherent optical receiver is integrated within $10 \times 10 \text{mm}^2$ and consumes less than 3W power.

Homodyne OPLL / Costas Loop

Design of Homodyne OPLL: The homodyne OPLL consists of three main blocks: a photonic IC (PIC), an electrical IC (EIC), and a hybrid loop filter as shown in Fig. 1. The fabricated PIC uses an InGaAsP/InP platform and integrates a widely (40nm) tunable sampled grating

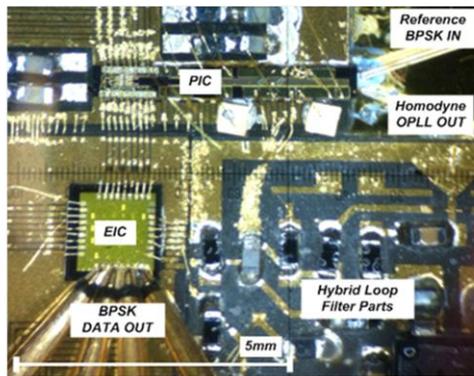


Fig. 2: A photograph of an implemented Costas loop based on a homodyne OPLL receiver

distributed Bragg reflector (SG-DBR) laser as an LO whose wavelength is tuned by current injection into front / back mirrors and a phase tuning diode. The received signal and LO laser are mixed by an integrated 90° optical hybrid and detected by uni-travelling carrier photodetectors (PD) for I-Q quadrature electrical current outputs. The optical hybrid has 48 - 52% balanced outputs, and the PDs show a 3-dB bandwidth of 30GHz and saturation currents of 18mA with -5V bias.

The EIC includes limiting amplifiers (LAs) and a PFD. It has been fabricated using Teledyne's 500nm InP HBT processes which have $300\text{GHz } f_t / f_{\max}$, respectively. The LAs amplify the photocurrents to 0.3Vp-p digitized signals which contain only phase / frequency error information, and thus, the OPLL is more insensitive against photocurrent intensity variations. The PFD has been designed using XOR as a multiplier, and 10ps delay lines on the Q-path for 50GHz frequency pull-in ranges [8]. Integrating the LAs and PFD, the EIC has an operation bandwidth of larger than 50GHz and an extremely small electrical delay of $\sim 50\text{ps}$.

The loop filter has been designed using a feed-forward technique consisting of an integrator for a main path and a differentiator for a feed-forward path. A bulk operational amplifier (OPA) has been used to obtain high gain at DC and low frequencies, but the OPA has long propagation delays and could limit the OPLL's bandwidth performance. In order to minimize the delay effects and extend the loop bandwidth, the feed-forward path using a passive capacitor component has been applied. As a result, the effective loop delay of the loop filter becomes negligible and the loop bandwidth of the OPLL is only limited by delays from the PIC (40ps), EIC (50ps), and interconnections (30ps).

With a loop delay of 120ps, the targeted loop bandwidth of OPLL can be wider than 1GHz. A second order loop has been chosen to track the laser frequency drift, and the PFD has been

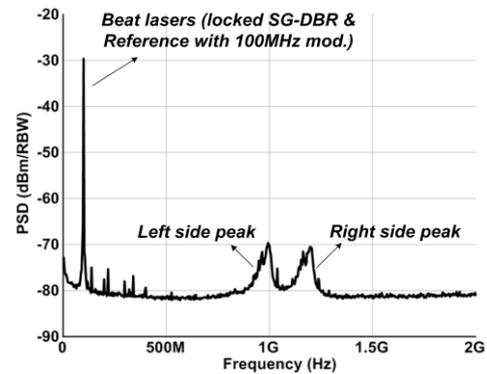


Fig. 3: A beat spectrum between a homodyne OPLL and a ref. laser with 100MHz mod. (RBW: 100kHz)

applied to extend frequency / phase acquisition performances. Loop characteristics of the PIC and EIC have been fully characterized, and parasitic effects have also been considered in the homodyne OPLL design.

Finally, the homodyne OPLL and the Costas loop have been implemented as shown in Fig. 2 within the compact size of $10 \times 10\text{mm}^2$.

Costas Loop / BPSK Receiver: A homodyne OPLL can be used in an optical carrier phase recovery circuit as the Costas Loop. I and Q signals are mixed in the PFD and the PFD output has two stable lock conditions of 0 and π in one period. Therefore, the Costas loop can keep the lock for the BPSK modulated signals. The locked SG-DBR laser down-converts the modulated data. As a result, the homodyne OPLL can be used for the BPSK receiver without post digital signal processing. In the BPSK receiver, the down-converted data outputs from PDs are amplified / limited by the EIC blocks and the signals are split to the feedback loop and BPSK data detector.

Tests and experiment results

Homodyne OPLL tests: The homodyne OPLL for a coherent optical receiver has been realized as shown in Fig. 2. A Koshin Kogaku tunable laser has been used for a 1550nm external reference laser which has a linewidth of 100kHz. The SG-DBR laser has been locked to the reference laser and beat with the reference laser with a 100MHz acousto-optic modulator (AOM). The spectrum of the beat signals has been obtained using an electrical spectrum analyzer (ESA) as shown in Fig. 3 – peak tone at 100MHz, right side peak at 1.2GHz, and left side peak at 1.0GHz as an image frequency. From the spectral results, a closed loop bandwidth of 1.1GHz is observed. The homodyne OPLL can suppress wide frequency ranges of the SG-DBR laser phase noise and hold lock against laser frequency drift.

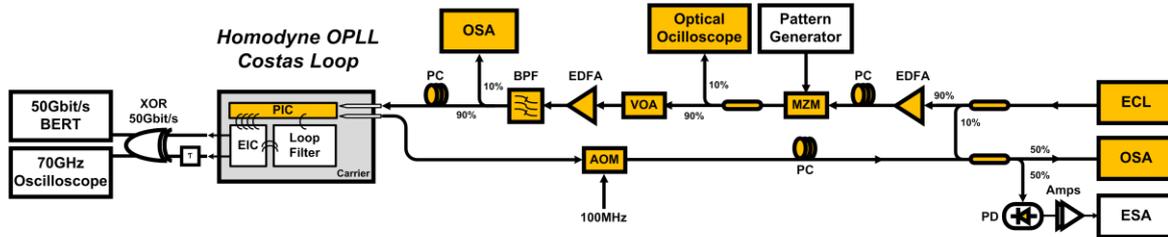


Fig. 4: A test setup of BER vs. OSNR for a Costas loop receiver (ECL: external cavity laser, PC: polarization controller, and OSA: optical spectrum analyzer)

BPSK Data Reception: To prove the BPSK coherent optical receiver performance, BER vs. OSNR has been measured using a test setup as shown in Fig. 4. A PRBS ($2^{31}-1$) pulse pattern generator and MZM have been used for BPSK optical data modulations up to 40Gbit/s, and OSNR has been controlled by a variable optical attenuator (VOA) before the Erbium doped fiber amplifier (EDFA) and 0.95nm optical band pass filter (BPF). Only I-differential outputs from the EIC are connected to 50Gbit/s BERT measurement through an external differential decoder using a 50Gbit/s XOR and 1bit-delay by phase shifters to solve the phase ambiguity of the Costas loop. At the same time, lock status of the SG-DBR has been monitored with an ESA.

A BER vs. OSNR has been measured for 25G to 40Gbit/s as shown in Fig. 5, and the BPSK receiver exhibits error-free ($BER < 10^{-12}$) up to 35Gbit/s and $BER < 10^{-7}$ for 40Gbit/s. Open received eye outputs for 25Gbit/s and 40Gbit/s are measured using a 70GHz sampled oscilloscope without the differential decoder. In addition, the linewidths of the locked SG-DBR laser with 25Gbit/s BPSK data and without the data are measured as shown in Fig. 6 using a self-heterodyne technique with a 25km fiber, and all locked SG-DBR lasers show the same linewidth of 100kHz as the reference laser. This means that the Costas loop with a 25Gbit/s BPSK data modulation can restore the carrier laser without degrading the linewidth and data reception performance.

This BPSK receiver consumes less than 3W (PIC < 0.5W, EIC < 2.2W, and loop filter < 0.1W).

Conclusions

A highly integrated coherent optical receiver has been demonstrated for the first time using the concept of a homodyne OPLL and a Costas loop. A stable homodyne OPLL has been designed with a PIC, a digitally operating EIC, and a feed-forward loop filter, achieving total effective loop delays of 120ps and a closed loop bandwidth of 1.1GHz. The coherent optical BPSK receiver exhibits error-free up to 35Gbit/s and less than 10^{-7} for 40Gbit/s with no latency and less than 3W power consumption.

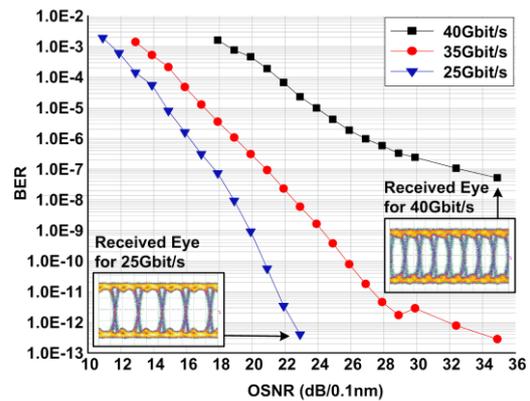


Fig. 5: BER vs. OSNR for 25G to 40Gbit/s and received eye outputs for 25G and 40Gbit/s

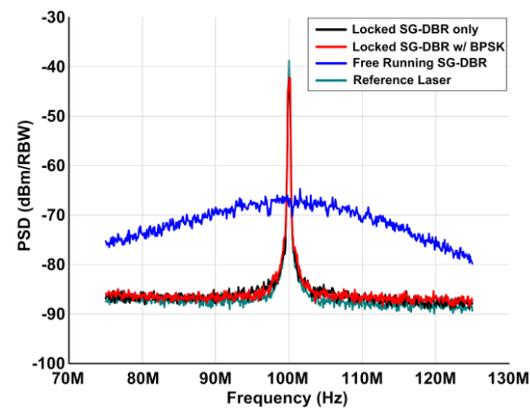


Fig. 6: Self-heterodyne linewidth measurements for locked SG-DBR w/o and w/ 25Gbit/s BPSK, free-running SG-DBR, and ref. lasers (RBW: 50kHz)

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