Novel real-time homodyne coherent receiver using a feed-forward based carrier extraction scheme for phase modulated signals

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Abstract: We report a novel real-time homodyne coherent receiver based on a DPSK optical-electrical-optical (OEO) regenerator used to extract a carrier from carrier-less phase modulated signals based on feed-forward based modulation stripping. The performance of this non-DSP based coherent receiver was evaluated for 10.66Gbit/s BPSK signals. Self-homodyne coherent detection and homodyne detection with an injection-locked local oscillator laser was demonstrated. The performance was evaluated by measuring the electrical signal-to-noise (SNR) and recording the eye diagrams. Using injection-locking for the LO improves the performance and enables homodyne detection with optical injection-locking to operate with carrier-less BPSK signals without the need for polarization multiplexed pilot-tones.

OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communications; (060.2920) Homodyning; (060.5060) Phase modulation.

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1. Introduction

There is an increasing demand for high transmission capacity due to the intense growth of bandwidth-hungry internet applications such as video streaming. Optical transmission systems that make use of complex modulation formats with coherent detection offer a promising solution to meet these demands because of their excellent spectral efficiency and superior optical signal-to-noise ratio (OSNR) performance [1–10]. To meet this demand, standardization bodies, such as The Optical Internetworking Forum (OIF), have adopted dual polarization quadrature phase shift keying (DP-QPSK) modulation format with a coherent receiver for 100 Gbit/s Ultra Long Haul DWDM applications [10]. Current research worldwide is geared towards coherent receivers based on digital signal processing (DSP), requiring complex and expensive electronics (i.e. high speed ADC, DSP) with relatively high power consumption. However, the original approach to coherent detection employed real time homodyne coherent receivers, relying on optical phase locked loop (OPLL) techniques without DSP. These were difficult to implement due to the requirements for low feedback loop delays and ultra-narrow linewidth lasers [4].

Self-homodyne techniques such as differential detection enable the local oscillator to be avoided. In order to enable linear field detection, the polarization multiplexed pilot tone technique has been proposed to enable self-homodyne coherent detection of phase modulated signals [11–13] without using an additional laser as a local oscillator (LO). Another self-homodyne 10Gbit/s PSK receiver has been recently reported using Brillouin amplification but requires a pump generated at the receiver side and frequency locked to the signal [14]. However, in all of these cases the phase reference suffers the same OSNR degradation as the signal. Optical injection-locking with phase locked loop control (OIPLL) has been identified as an alternative solution to DSP based and conventional optical phase locked loop based coherent receivers for ASK signals [5]. However, to enable OIPLL to operate with carrier-less modulation formats such as BPSK, alternative techniques to combine injection-locking with phase modulated signals are required. Such techniques could be based on:

- Using a polarization multiplexed [6] pilot tone to provide a carrier component for injection locking at the expense of reducing the spectral efficiency (SE).
- Using a sub-carrier multiplexed [7] optical pilot tone for injection-locking at the expense of reducing the spectral efficiency.
- Using a residual carrier [8,9] for injection-locking at the expense of a degraded OSNR.
- Using four wave mixing (FWM) as a modulation stripper [15,16] which requires the use of high power optical amplifiers.

In this paper we experimentally demonstrate the operation of a real-time self-homodyne coherent receiver for 10.66Gbit/s BPSK signals without the use of any pilot tones. This scheme is based on using a recently published carrier extraction scheme which is based on an optical-electrical-optical (OEO) DPSK regenerator [17]. The carrier is extracted by stripping off the modulation from a 10.66Gbit/s BPSK signal in a feed-forward manner by re-modulating it with a complementary data pattern. The generated carrier is then used as a LO in a homodyne receiver. The proposed technique does not require any pilot tone which enables polarization multiplexing to be used with self-homodyne coherent systems therefore making it possible to increase the spectral efficiency. A distributed-feedback (DFB) laser was also used as a local oscillator (LO) by injection-locking it to the extracted carrier. This significantly improved the OSNR and quality of the LO phase reference. The proposed technique enables self-homodyne and homodyne with injection-locking (IL) systems to be used with carrier-less BPSK signals allowing the spectral efficiency to be maximised.

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2. Experimental setup

The experimental setup of a 10.66Gbit/s BPSK real-time homodyne coherent receiver system is shown in Fig. 1. A fiber laser was used to generate a carrier signal at a wavelength of ~1553.65nm with a linewidth ~5kHz. A Mach-Zehnder modulator (MZM) biased at null-transmission was used to modulate the optical carrier with a 10.66Gbit/s electrical data stream with a pseudo random bit sequence (PRBS) length of 2^{31}-1 resulting in an optical 10.66Gbit/s BPSK signal. A variable optical attenuator (VOA) was used to vary the input power to an erbium doped fiber amplifier (EDFA) (4.6dB noise figure and 30dB small signal gain) allowing control of the OSNR that was measured at the 10% tap using an optical spectrum analyser (OSA). The EDFA was followed by an optical tuneable band pass filter with a bandwidth of ~40GHz, a second EDFA (noise Fig. 5.1dB) in automatic power control mode, and a tuneable optical filter with a bandwidth of ~30GHz. The filtered BPSK signal was then split in two paths (upper path (10%) and lower paths (90%)) using a 10:90 coupler as shown in Fig. 1. In the upper path, the filtered 10.66Gbit/s BPSK signal passed through a polarization controller, a delay line, piezo-electric fiber stretcher, and a short piece of single mode fiber before entering the signal input of a 90° hybrid. The signal in the lower path was used in a carrier extraction circuit.

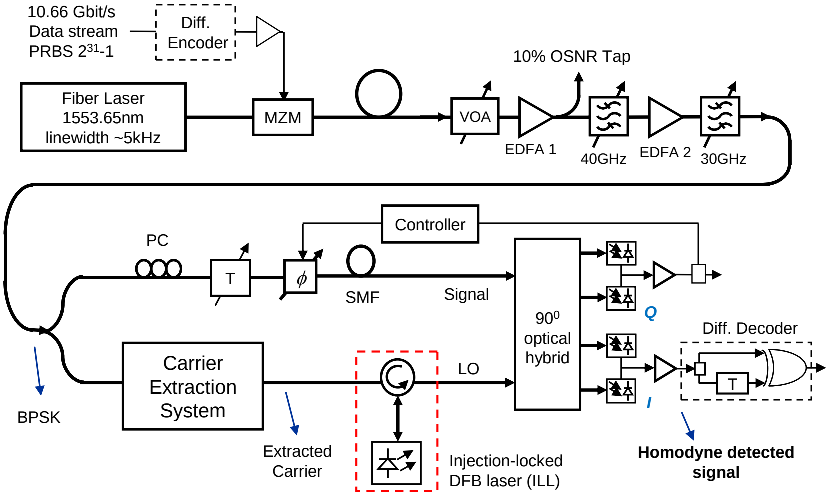

Fig. 1. Schematic of a BPSK pre-amplified coherent system based on carrier extraction with and without an IL laser.

The basic function of the carrier extraction system was to strip the data modulation off the incoming BPSK signal by re-modulating it with a complimentary data pattern. In the carrier extraction circuit the filtered 10.66Gbit/s BPSK signal was split in two paths (path (a) and path (b)) using a 3dB coupler as shown in Fig. 2. The signal in path (b) was fed to a 10.66Gbit/s DPSK demodulator consisting of a 1-bit delay asymmetric Mach-Zehnder interferometer (AMZI). Following the demodulator was a balanced photodiode that detected the differentially demodulated signal which was then amplified and reshaped using a limiting amplifier. The received electrical signal then passed to a differential encoder which restored the original logic sequence before being amplified by a modulator driver to $2V_\pi$. The amplified electrical signal was used to drive a BPSK modulator consisting of a MZM biased at null-transmission in path (a) which was used to reverse the phase modulation of the received data signal thus resulting in a continuous phase for the carrier signal. A short piece of single mode fiber and an optical delay line were used in path (a) to ensure that the delays in both paths were matched and proper carrier extraction was achieved. At the output of the MZM the extracted carrier signal contained intensity modulation at the eye crossing due to the use of MZM's for data encoding. This resulted in spectral components with a 10.66 GHz

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spacing appearing on the spectrum of the extracted carrier which was also degraded by the finite OSNR of the incoming BPSK signal. When using the extracted carrier as a LO phase reference for self-homodyne coherent detection without an injection locked laser, a delay line (delay line in upper path in Fig. 1) is required to align the crossing points of the received BPSK signal and extracted carrier (LO). This could be eliminated if an injection-locked laser was used at the output of the carrier extraction circuit. In Fig. 1 an injection locked DFB laser (ILL) was also used as a local oscillator for the homodyne receiver, enabling homodyne detection operation. The DFB laser used in the experiment had a self heterodyne free running linewidth of ~475kHz half width half maximum. The power of the extracted carrier applied to the packaged DFB laser was ~4dBm and the DFB laser output power was ~13dBm. The injection-locking frequency range was ~257MHz. It should be noted that the packaged DFB laser had an internal isolator. For homodyne detection with injection-locking, the frequency of the DFB LO laser was manually tuned to enable injection-locking to the extracted carrier. The injection-locking operation was stable over several hours; therefore no injection-locking stabilization circuit was required. In a practical system, a feedback control circuit would be required to maintain the injection-locking and track any frequency drifts. Such circuit could be based on the frequency control circuit reported for OIPLL in [6], or by using an injection-locking stabilization circuit as reported in [18]. The LO and signal powers at the input of the optical hybrid were ~0dBm and ~5dBm, respectively for both the self-homodyne detection without injection-locking and the homodyne detection with injection locking LO.

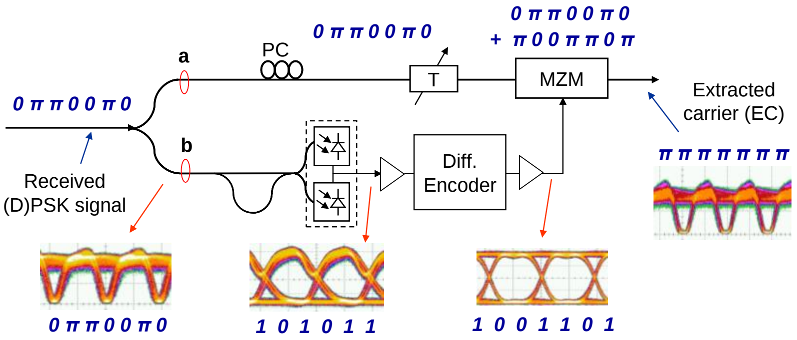

Fig. 2. Schematic of a BPSK carrier extraction system. Eye diagrams from left to right are: received BPSK signal, demodulated BPSK, differentially encoded, and extracted carrier.

The received in-phase (I) and quadrature (Q) signals were detected after the 90° hybrid using two balanced photodiodes followed by electrical amplifiers. Assuming differential encoding is used at the transmitter, an electrical differential decoder based on a 1-bit delay and an electrical logic XOR circuit can be used at the receiver to differentially decode the received data (I) in the electrical domain as shown in Fig. 1 (bottom-right). The (Q) channel was connected to a low-barrier Schottky-diode microwave detector to extract an error signal used in a feedback control circuit based on a lock-in amplifier with a 1 kHz dither frequency. The control signal was used to adjust the relative phase between the signal and recovered carrier signal by controlling a piezo-electric fiber stretcher in the upper path of the receiver shown in Fig. 1. The controller was used to compensate for any variations in the path lengths due to thermal and other environmental changes. This enabled a stable operation of the homodyne receiver which allowed quantitative eye-diagram measurements, for the homodyne detected signal on channel (I) of the hybrid.

3. Results

Figure 3 (left) shows the optical spectrum (measured with a resolution bandwidth (RB) of 0.01nm) of the received BPSK signal at the input of the carrier extraction system showing no carrier component, the generated extracted carrier measured at the output of the carrier extraction system showing the 10.66GHz modulation sidebands and the injection-locked DFB laser output. The injection-locked DFB laser cleaned up the spectrum of the extracted carrier which eliminated any residual intensity modulation. Figure 3 (right) shows the performance of the carrier extraction system, which was evaluated by measuring the self heterodyned linewidth of the injection-locked laser against different levels of input OSNR measured at the 10% tap after EDFA 1 at the receiver side. Figure 3 (right) also confirms that the LO DFB laser which was injection-locked to the extracted carrier had a constant measured linewidth of ~6.5kHz for an input OSNR >11.3dB/0.1nm and a measured linewidth below 140kHz for an input OSNR > 9.4dB/0.1nm.

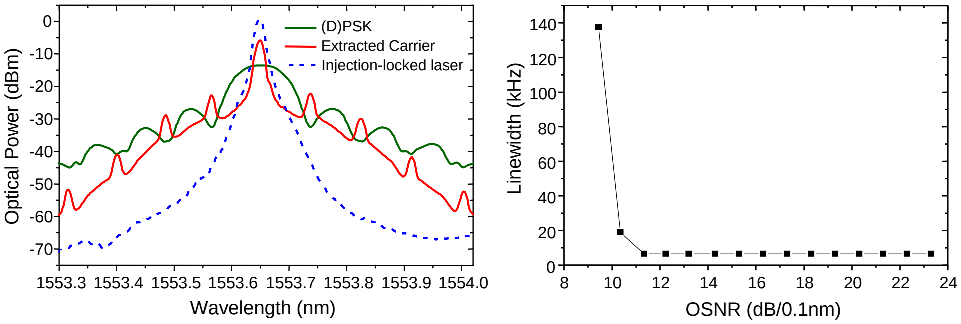

Fig. 3. Optical spectrum of received (D)PSK signal, extracted carrier and injection-locked laser (left). Measured self-heterodyned linewidth for the LO versus OSNR (right).

Figure 4 shows the captured eye-diagram of the detected signal versus different received power levels for self-homodyne detection without injection locking (top) and homodyne detection with injection-locking (bottom).

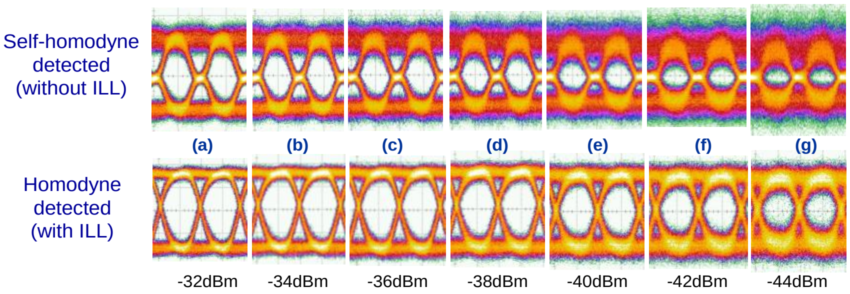

Fig. 4. Eye-diagrams of a 10.66Gbit/s for the detected signal measured at a receiver power of −32dBm, −34dBm, −36dBm, −38dBm, −40dBm, −42dBm and −44dBm for self-homodyne detection without IL (top) and homodyne detection with IL (bottom).

Without injection-locking, the impact of the amplitude nulls owing to the use of a MZM to demodulate the signal phase is clearly visible, resulting in a significant broadening of the low region at the eye crossing. The observed electrical signal-to-noise-ratio (SNR) reflects the reproduction of the signal OSNR on the modulation-stripped self-homodyne local oscillator. Both of these degradations are eliminated via injection locking, therefore resulting in an improved SNR. This is confirmed in Fig. 5 (left) which shows the SNR of the received self-homodyne signal as a function of received power without IL and homodyne detection with IL as shown in the red circles and black squares respectively. The SNR is measured using the built in measurement function of an Agilent 86100C high speed oscilloscope (12.4GHz BW plug-in) in eye diagram mode. It should be noted that the SNR is typically underestimated for non-standard eye shapes, in this case showing an abnormally wide crossing region due to the dips that existed in the extracted carrier as shown in Fig. 4 (top). For self-homodyne without IL, a BER of 10^{-9} was achieved for a received power of −39dBm which corresponds to a measured OSNR of ~14.8dB/0.1nm, and electrical SNR of ~12.7dB. Below −39dBm open eye-diagrams and SNR measurements were still obtained but phase jumps were introduced in

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the system causing the polarity of the received data to be flipped, therefore BER measurements were not possible without using an extra electrical differential decoder at the receiver assuming the transmitted data was differentially encoded. The origin of the phase jumps are due to the errors caused in the optical differential detection circuit used in the carrier extraction system. These errors when introduced at the input of the electrical differential encoder resulted in the polarity of the received signal driving the MZM to be flipped, therefore causing π phase jumps of the extracted carrier. It should be noted that the performance of this scheme shows a 5dB improvement in the received optical power required for a BER of 10^{-9} over previous reported real-time 10Gbit/s self-homodyne PSK systems using a polarization multiplexed pilot tone and no injection-locking [12].

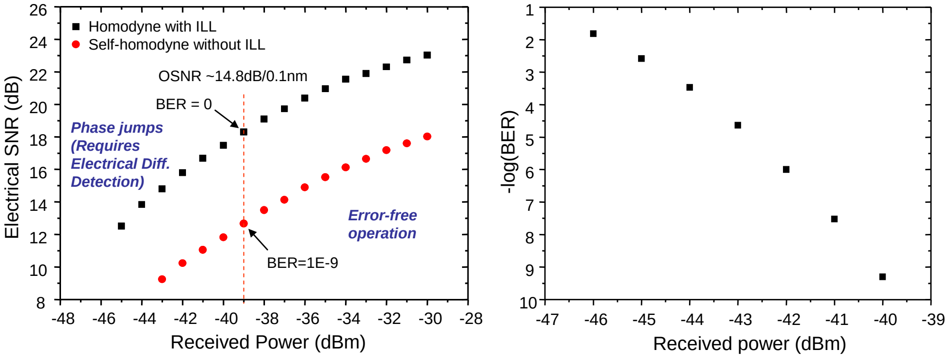

Fig. 5. Measured electrical SNR versus received power (left). BER versus received power for homodyne detection with IL using electrical differential decoding (right).

For the homodyne detected signal with IL a clear improvement in SNR and eye diagrams are shown in Fig. 4 (bottom) and Fig. 5 (left). However, at low BER the IL LO laser tends to track the phase jumps, and so polarity switches are also observed. In order to measure the BER curve for the self-homodyne signal with IL, an electrical differential decoder as shown in Fig. 1 (bottom-right) was used to decode the signal at the receiver. Since PRBS data was used, differential encoding can be assumed at the transmitter. For homodyne detection with IL, the required received optical power and OSNR to achieve a BER of 10^{-9} was measured to be ~40.2dBm and ~13.5dB/0.1nm, respectively. This indicates more than 1dB performance improvement was achieved when compared to the self-homodyne case with no IL. When compared to the theoretical calculated OSNR required to achieve a BER of 10^{-9} for an ideal LO-ASE limited 10Gbit/s BPSK coherent receiver assuming matched filters, a 5dB OSNR penalty was observed. This extra penalty could be due to the errors occurring from using differential detection resulting in ~2dB penalty. The other ~3dB penalty is expected to be due to the non-ideal filter and BW of the receiver, non-zero linewidth, non-ideal signal-LO power ratio and imbalance in the optical hybrid.

4. Conclusions

We have reported for the first time a real-time homodyne coherent receiver system for 10.66Gbit/s BPSK signals based on a novel carrier extraction scheme which is used to strip off the modulation of a BPSK signal in a feed-forward operation to generate the reference local oscillator. The performance was evaluated in terms of electrical eye-diagram SNR measurements and error free operation was obtained for received powers above −39dBm for self-homodyne without injection-locking and above −40dBm for homodyne detection with injection-locking. The proposed carrier extraction system enables homodyne detection with injection-locking to operate with carrier-less BPSK signals without the need for any pilot tones. It also guarantees a stable low linewidth ~6.5kHz for an input OSNR > 11.3dB/0.1nm.

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