Interleaved Polarization Division Multiplexing in Self-Homodyne Coherent WDM Systems

Martin Sjödin[(1)], Erik Agrell[(2)], Guo-Wei Lu[(1)], Pontus Johannisson[(1)], Magnus Karlsson[(1)], Peter Andrekson[(1)]

[(1)] Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Göteborg, Sweden martin.sjodin@chalmers.se

[(2)] Communication Systems Group, Department of Signals and Systems, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Abstract *We demonstrate increased spectral efficiency for self-homodyne coherent WDM systems by using a novel interleaved polarization division multiplexing scheme.*

Introduction

Multi-level modulation formats make it possible to increase the spectral efficiency (SE) and will be an indispensable part of future fiber-optic networks. Currently, major efforts are focused on formats that carries information in both amplitude and phase, such as 16-QAM. The main approach to extract phase information is to use a local oscillator (LO) that is mixed with the signal in the receiver. Digital signal processing is then used to track the intermediate frequency (IF) and demodulate the data. This approach, known as intradyne (ID) coherent detection, requires lasers with narrow linewidth[1] and high speed electronics[2]. Very high SE has been demonstrated using ID detection, polarization division multiplexing (PDM), 16-QAM and offline data processing[3-4].

Another possibility is to use self-homodyne (SH) coherent detection[5]. These systems are based on utilizing a polarization division multiplexed pilot tone (PT) as LO in the receiver, a scheme known to be extremely linewidth tolerant and that has been used to measure BER in real-time for 10 Gbaud 16-QAM and 5 Gbaud 64-QAM signals[6–7]. The main drawbacks are that the scheme does not permit conventional PDM and that the PT becomes deteriorated by noise in a system using EDFAs[8]. So far, the highest reported SE for an SH system is only 1.2 bit/s/Hz, which was achieved by using 10 Gbaud single polarization QPSK with 16.25 GHz channel spacing[9].

In this paper we demonstrate a novel interleaved polarization division multiplexing (IPDM) approach, which enables us to increase the SE of SH systems. We evaluate the performance back-to-back (BtB) and after transmission (200 km), both in the linear and nonlinear regime for different SE:s. We also compare with an ID system.

Interleaved Polarization Division Multiplexing

Fig. 1a shows the spectrum of a WDM signal using PDM and ID detection. The co-propagating PT in an SH system does not permit a spectrum like this. Fig.1b shows a typical signal spectrum in an SH WDM system: Only one polarization is used to transmit data. However, by placing the signals as in Fig. 1c, it is possible to enhance the SE compared to case 1b. The channel spacings are the same in both the x- and the y-polarization, but a relative wavelength shift is made that allows the PT:s to fit in between the data spectra.

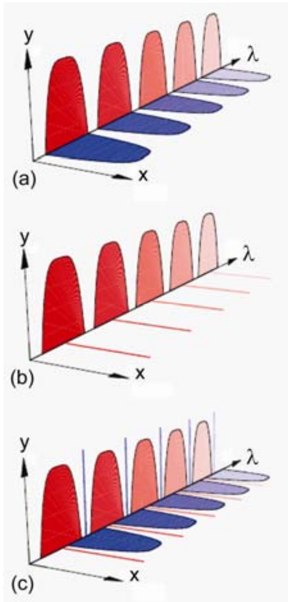

Fig. 1: Spectra for: a) a PDM ID system.
b) an SH system with data in a single polarization.
c) an SH system using IPDM.

Experimental Setup

Fig. 2a shows the transmitter for the SH system using IPDM. Five channels were used, three (the odd channels) with data in the x-polarization and two (the even channels) with data in the y-polarization. One IQ-modulator was used per polarization (IQ 1 and IQ 2) and the signals and the PT:s were combined at the transmitter output by a polarization beam-combiner (PBC), which ensured orthogonal polarizations between the odd and the even channels and between the data spectra and their corresponding PT:s. The

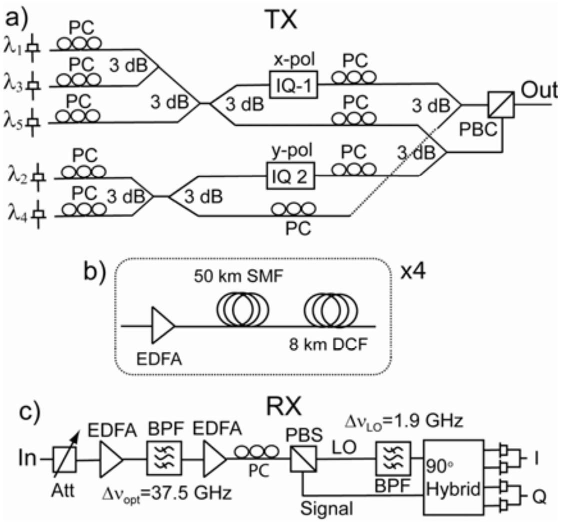

Fig. 2: The experimental setup of the SH system.

power ratio between PT:s and signals was set to 1 for all channels. 10 Gbaud QPSK signals were generated by applying independent $2^{10}-1$ PRBS signals to the modulators. The transmission link consisted of four sections like the one shown in Fig. 2b, with an EDFA, 50 km SMF and 8 km DCF which compensated for the SMF dispersion. In the receiver, shown in Fig. 2c, a variable attenuator (Att) and an EDFA were used to set the OSNR and the input power and a 37.5 GHz bandpass filter (BPF) to select the center channel. A polarization beam-splitter (PBS) separated the signal and the PT. The PT was filtered (1.9 GHz) and mixed with the signal in a 90° optical hybrid to generate balanced I and Q signals. After photodetection, the I and Q photocurrents were sampled with a real-time sampling oscilloscope at 50 GSample/s and BER was measured.

BER was measured for the center channel since it is the one most affected by crosstalk from the other channels and all important linear penalty sources that would exist in a real WDM system using IPDM are present. The absence of real-time BER measurements is due to a relative phase drift between the PT and the signal induced by temperature fluctuations in their different paths when they are separated. This slowly rotates the received constellation randomly in the complex plane. The problem can be avoided by using integrated components[5-7,9] or by tracking the phase drift in the receiver.

In the ID measurements, IQ 1 was used to generate 10 Gbaud QPSK. PDM was emulated by splitting the signal equally and then recombining it with a PBC with a relative delay of about 200 symbols. In the WDM case, 3x2 channels (3 wavelengths and PDM) were used since in the ID case the important linear crosstalk comes from the channels at the two nearest wavelengths. The same laser was used as both signal source and LO, 3 km of SMF in the LO path was used for phase de-correlation and feedforward carrier estimation[10] was used to estimate the phase of the IF. The equivalent noise bandwidth was 7 GHz for both the ID and the SH system. The same laser (λ_3 in Fig. 2a) was used in all BER measurements for both the SH case and the ID case. Its linewidth was about 0.7 MHz.

Results

The measured BtB BER as a function of the OSNR (0.1 nm reference bandwidth) for the SH system using IPDM with different channel spacings are shown in Fig. 3. Measured and

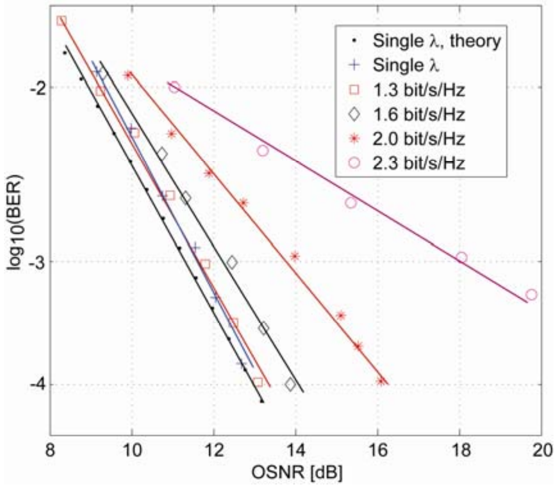

Fig. 3: BtB BER measurements for the SH IPDM system.

theoretical[8] results for a single channel are also shown. A SE of 1.3 bit/s/Hz, achieved by having a channel spacing of 30 GHz in each polarization, gives about the same performance as the single channel case while SE:s of 1.6 bit/s/Hz, 2.0 bit/s/Hz and 2.3 bit/s/Hz give penalties of 0.7 dB, 2.2 dB and 6.6 dB respectively, at a BER of 10^{-3}. We believe that the performance degradation for the cases with narrower channel spacings is mainly due to a combination of increased overlap between the PT of the center channel with the tails of the data spectra of the even channels, and that the 1.9 GHz PT filter has a quite slow roll-off which gives unsufficient suppression of the power from the data spectra of the even channels. We expect that with pre-filtering of the data spectra at the transmitter to minimize their overlap with the PT and use of a PT filter with sharper edges in the receiver, the performance should be improved and SE would be increased further. The performance of the SH system can also be improved by using a narrower PT filter in the receiver[8].

The BER was also measured for two cases (1.6 bit/s/Hz and 2.0 bit/s/Hz) after 200 km transmission with −9 dBm input power (signal and PT combined) per channel to each SMF span. Performance was the same as BtB, which is expected for moderately long links when operating in the linear regime.

The results of the BtB BER measurements for the ID system are shown in Fig. 4. As expected from the OSNR definition, there is about 3 dB difference between the cases of using a single polarization and using PDM.

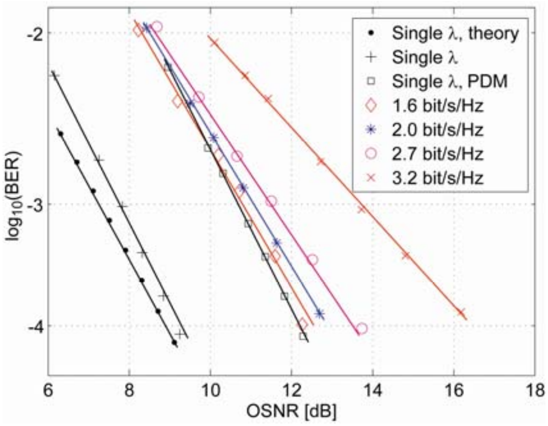

Fig. 4: BtB BER measurements for the ID system.

Fig. 5 shows plots of OSNR requirements to obtain a BER of 10^{-3} against SE for an SH system using IPDM, an SH system with data in a single polarization and for an ID system using PDM. The ID system shows best performance,

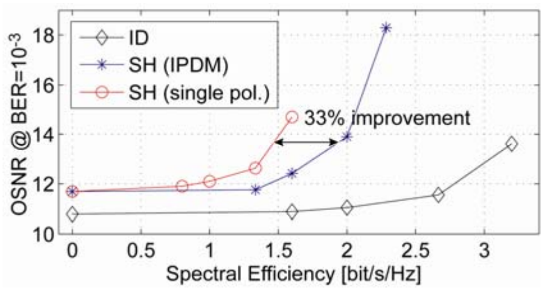

Fig. 5: OSNR required to obtain BER=10^{-3} as a function of SE.

thanks to the LO being added in the receiver instead of being co-transmitted and because of the noisy PT in the SH systems. For an OSNR penalty of 2 dB compared to the single channel case, the IPDM scheme increases SE with 33% compared to the case in which only one polarization is used to transmit data.

To investigate the tolerance of nonlinearities of the SH IPDM scheme, the input power to the link sections was varied and the required OSNR at the receiver to obtain a BER of 10^{-3} measured for both 25 GHz and 20 GHz channel separations (SE:s of 1.6 bit/s/Hz and 2.0 bit/s/Hz). The results are shown in Fig. 6. The tolerance towards nonlinearities is quite low for these channel spacings and the main reason is likely that the PT of the center channel is degraded by an increasing overlap with the

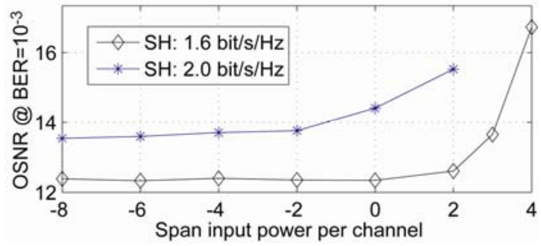

Fig. 6: OSNR required to obtain BER=10^{-3} as a function of input power to the SMF spans.

neighboring self-phase modulation-broadened data spectra of the even channels and also by cross-phase modulation from all channels in the system.

Conclusions

We have demonstrated a new PDM scheme for SH coherent systems that enable us to increase the SE compared to conventional SH systems by transmitting data in both polarizations. 33% increase was observed at 2 dB OSNR penalty. We have thus shown that the use of SH coherent detection does not necessarily imply that a factor of 2 in SE is lost due to the co-propagating PT. The scheme was validated both BtB and after 200 km transmission and has the potential to be used in real-time operation when integrated transmitter and receiver components are used. In a comparison with an ID system, it was shown that the ID scheme with PDM has advantages over the SH IPDM scheme when it comes to OSNR requirements, resilience towards nonlinearities and achievable SE. However, we believe the performance of our scheme can be further improved by optimizing the filtering in the transmitter and the receiver.

Acknowledgement

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References

1 T. Pfau et al., J. Lightw. Technol., **27**, 989 (2009).
2 K. Roberts et al., Opt. Express, **16**, 873 (2008).
3 P. Winzer et al., J. Lightw. Technol., **28**, 547 (2010).
4 A. Sano et al., OFC’10, PDPB7 (2010).
5 T. Miyazaki et al., IEEE Photon. Technol. Lett. **17**, 1334 (2005).
6 M. Nakamura et al., LEOSST’08, WC2.3 (2008).
7 M. Nakamura et al., OFC’09, OWG4 (2009).
8 M. Sjödin et al., IEEE Photon. Technol. Lett. **22**, 91 (2010).
9 T. Miyazaki, ECOC’05, We4.P.042 (2005).
10 A.J. Viterbi et al., IEEE Trans. Inf. Theory IT-29, 543 (1983).