Real-time Synchronous QPSK Transmission with Standard DFB Lasers and Digital I&Q Receiver

Timo Pfau, Sebastian Hoffmann, Ralf Peveling, Suhas Bhandare, Selwan K. Ibrahim, Olaf Adamczyk, Mario Porrmann, Reinhold Noé
Univ. Paderborn, EIM-E, Warburger Str. 100, D-33098 Paderborn, Germany
pfau/hoffmann/suhas/ibrahim/adamczyk@ont.upb.de, peveling/porrmann@hni.upb.de, noe@upb.de

Yakoov Achiam
CeLight Israel Ltd., Rotem Industrial Park, Doar Na Arava, Israel, yachiam@celight.com

Abstract: For the first time synchronous QPSK data is transmitted in real-time with standard DFB lasers. FEC-compatible performance is reached at 400 Mbaud after 63-km of fiber. Self-homodyne operation with an ECL is error-free.

OCIS codes: (060.1660) Coherent communications; (060.2920) Homodyning

1. Introduction

The need to better utilize the available bandwidth and to cope with chromatic and polarization mode dispersion of existing optical fiber has revived the interest in coherent optical transmission, in particular QPSK transmission with polarization division multiplex for quadrupled spectral efficiency compared to standard line cards. Ultimate OSNR performance is promised by synchronous demodulation, which for QPSK outperforms the asynchronous or interferometric one by >2 dB. Ultra-narrow linewidth lasers are required to implement a phase-locked loop for carrier recovery [1], and these are widely believed to be too expensive in today's cost-sensitive economic environment. In contrast, a feedforward carrier recovery scheme [2] relaxes the sum linewidth requirement to about 0.001 times the symbol rate, which is in the reach of normal, low-cost DFB lasers. Comparable schemes have been verified offline, using oscilloscope-sampled 10 Gbaud QPSK data from coherent systems [3, 4], and online (in real-time) for PSK signals at low data rate with conventional DFB lasers [5].

For today's 10 Gbaud symbol rates, an inphase and quadrature (I&Q) or intradyne receiver with digital signal processing [6] is attractive, because it minimizes the needed analog bandwidth. It allows conducting carrier recovery, electronic polarization control (inside a polarization diversity receiver) and electronic dispersion compensation at a lower multiplex hierarchy in standard-cell CMOS circuitry. In this context we have implemented, to our knowledge, the first real-time synchronous QPSK transmission system with standard DFB lasers.

2. Experimental setup of synchronous QPSK transmission system

Up to 2x400 Mb/s PRBS data is impressed onto a DFB laser signal utilizing a QPSK modulator (see Fig. 1). Normally the I&Q data is Gray-encoded to form a quadrant number, which is modulo 4 differentially encoded to determine the quadrant of the optical phase. In our experiment, for experimental convenience, identical 2^7-1 bit PRBS are used as I&Q modulator driving data, mutually delayed by 9 or 12 symbols for decorrelation purposes, and differential quadrant encoding is not implemented.

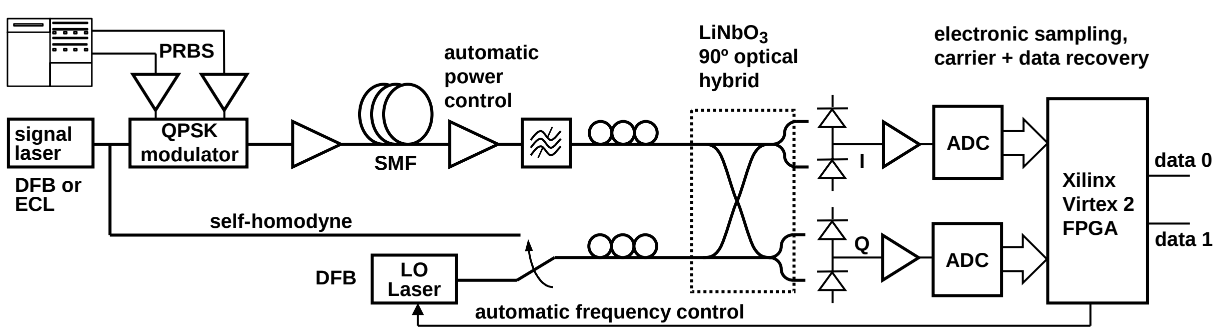

Fig. 1. 2×400 Mb/s QPSK transmission setup with a real-time synchronous coherent digital I&Q receiver, using either DFB or external cavity lasers.

After transmission through 2 km of standard single mode fiber, an optical preamplifier is followed by a bandpass filter with a width of ~20 GHz. The coherent receiver features a second DFB laser as its local oscillator and manual polarization control. The two optical signals are superimposed in a $LiNbO_3$ 90° optical hybrid and detected with two photodiode pairs. An optical switch before the second input of the 90° hybrid allows changing the setup between self-homodyning with the signal laser and heterodyning with an additional LO laser. The resulting electrical I&Q signals are amplified before being sampled with 5-bit analog-digital converters. The ADCs interface with a Xilinx Virtex 2 FPGA where electronic carrier and data recovery is implemented, similar to the description in [6]. The data recovery includes a differential modulo 4 decoding of the received quadrant number, to prevent occurring quadrant phase jumps of the recovered carrier from falsifying all subsequent data. Most processing occurs in parallel at a rate which is 16 times lower than the symbol rate, but the results are re-assembled to full-rate bit streams which are measured in realtime. To perform BER measurements, an appropriate bit pattern is programmed into a bit error rate tester, where the effect of the omitted differential encoding at the transmitter side is taken into consideration.

3. Measured results for self-homodyning and heterodyning

At the beginning the various bias voltages of the $LiNbO_3$ 90° hybrid, signal and LO polarizations are manually adjusted and remain stable over several hours. Fig. 2 shows measured BERs versus preamplifier input power for various configurations. All measurements turned out to be very stable and repeatable. The first test was conducted as a 400 Mbaud (2x400 Mb/s) self-homodyne experiment using an external cavity laser (ECL) with a specified linewidth of 150 kHz. I&Q channel behavior is very similar. Transmission was error-free during a 30-min test with –37 dBm of received power. Note that the applicable sum linewidth to symbol rate ratio of 0.00075 can be met by commercial DFB lasers in a 10 Gbaud system.

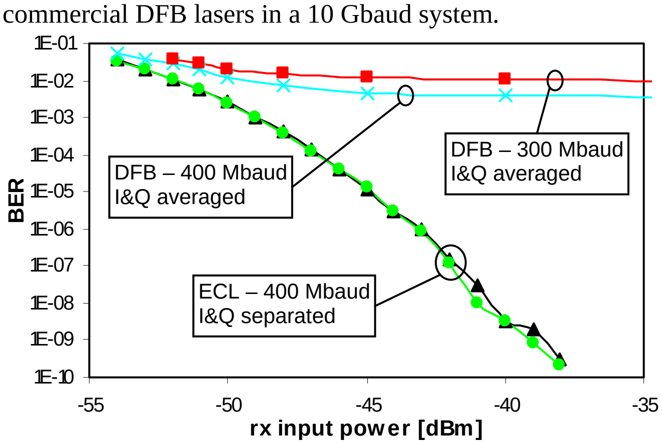

Fig. 2. Measured BER vs. optical power at preamplifier input for self-homodyne experiments using ECL and DFB lasers.

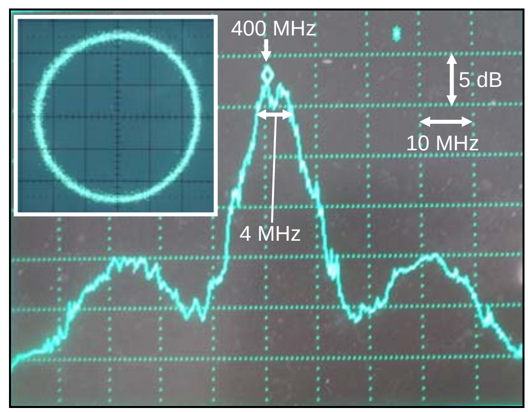

Fig. 3. Unmodulated IF spectrum and laser beating in 90° optical hybrid (inset)

Next, the ECL was replaced by a DFB laser (JDS Uniphase) with a specified linewidth of 1 MHz. For simplicity only averaged I&Q channel BERs are plotted (Fig. 2). Because of the larger linewidth there are BER floors at 10^{-2} and $3.5 \cdot 10^{-3}$ for tested symbol rates of 300 and 400 Mbaud, respectively. High BERs could not be measured with long PRBS due to synchronization issues in the test set. However, transmitting 2^{31}-1 PRBS over 2 km resulted in a BER floor of $1.1 \cdot 10^{-3}$ (300 Mbaud) and $3.7 \cdot 10^{-3}$ (400 Mbaud) before synchronization loss at low optical power levels.

Finally, an identical second DFB laser was added and used as the LO source. Without modulation, the I&Q beat signals detected at the 90° hybrid outputs were displayed as a circle on an x-y-mode oscilloscope (inset of Fig. 3). The intermediate frequency should be less than 1% of the symbol rate. Therefore an automatic frequency control for the LO laser is implemented inside the FPGA. Using a 400 MHz clock frequency, the IF was once stabilized to 400 MHz rather than 0 MHz in order to measure the IF linewidth (Fig. 3). The –3 dB linewidth was 4 MHz. The broadening beyond the expected 2 MHz value is most likely caused by insufficient filtering of the laser bias currents. There are also side lobes at ±30 MHz.

BER vs. received power is plotted in Fig. 4 for transmission of 300 and 400 Mbaud symbol rates over distances of 2 and 63 km. The BER floor for 63 km distance is higher than over 2 km. This is probably due to the lack of a clock recovery circuit at the receiver and the resulting usage of the transmitter clock, which contained much phase noise. The best measured BER result is $6 \cdot 10^{-3}$ for 400 Mbaud transmitted over 2 km. For 2^{31}-1 PRBS the measured BER floors were $6.3 \cdot 10^{-3}$ at 400 Mbaud and $1.1 \cdot 10^{-2}$ at 300 Mbaud for transmission over 2 km.

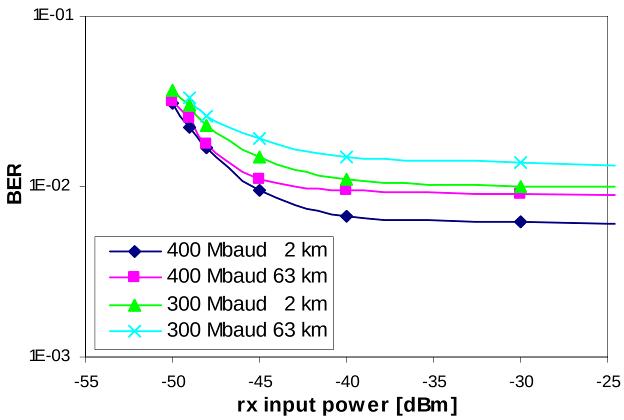

Fig. 4. Measured BER vs. optical power at preamplifier input for heterodyne configuration with DFB lasers.

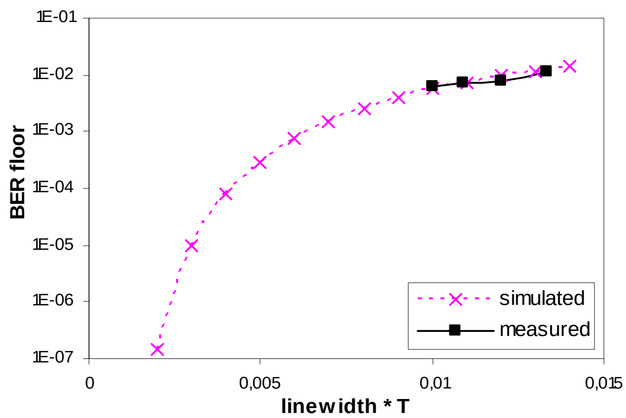

Fig. 5: BER floor for different products of linewidth times symbol daration T for heterodyne configuration with DFB lasers

3. Discussion

A FEC with 24.6% overhead is able to recover (quasi) error-free data for a raw BER below 2% [7]. Our 400 Mbaud QPSK transmission therefore corresponds to an error-free data rate of 642 Mb/s, assuming the presence of such a state-of-the-art FEC.

The carrier recovery bandwidth was chosen by previous simulations to be optimum for a single-polarization QPSK system with good receiver sensitivity and phase noise tolerance. This is important because a high received power would always allow tolerating much phase noise, simply by increasing the carrier recovery bandwidth. In line with this, future implementation of polarization division multiplex would result in an improved linewidth tolerance because the carrier recovery bandwidth could be doubled. Using the measured –3 dB linewidth, the BER floor values are plotted as a function of the sum linewidth times symbol duration T (Fig. 5). The floor drastically drops with the symbol duration. Sufficiently good performance with standard DFB lasers can be achieved at 10 Gbaud.

The sensitivity is presently limited by the following: Thermal rather than shot noise dominates in the receiver, and the signal power at the photodiodes is therefore chosen so high that imperfect receiver balance can result in significant direct detection of signal and amplified spontaneous emission, the latter being much stronger than the signal. The fact that there is no principal sensitivity degradation is also suggested by Figs. 2 and 4, where the symbol rate increase from 300 to 400 Mbaud actually improves the BER performance equivalent to 1 dB even at an optical power at the preamplifier input of -50 dBm, while the opposite would be true near the quantum limit.

5. Summary

We have demonstrated for the first time the implementation of a synchronous QPSK transmission system using commercially available DFB lasers and a real-time digital receiver for data recovery. 400 Mbaud QPSK data was transmitted quasi error-free in a self-homodyne configuration utilizing a low linewidth ECL, and with FEC-compatible performance in heterodyne configuration utilizing standard DFB lasers. Their sum linewidth times symbol duration T product equals 0.01, more than ever reported. The results show the outstanding potential of this scheme in a future 10 Gbaud QPSK transmission system with normal, low-cost DFB lasers.

6. References

[1] F. Derr, Coherent optical QPSK intradyne system: Concept and digital receiver realization, *IEEE J. Lightwave Technology* Vol. 10, 1290-1296, (1992).

[2] R. Noé, Phase Noise Tolerant Synchronous QPSK/BPSK Baseband-Type Intradyne Receiver Concept with Feedforward Carrier Recovery, IEEE J. Lightwave Technology, Vol. 23, 2005, pp. 802-808

[3] M.G. Taylor: Coherent detection method using DSP to demodulate signal and for subsequent equalization of propagation impairments. Proc. ECOC-IOOC 2003, We4.P.111, Sept. 21-25, 2003, Rimini, Italy.

[4] S. Tsukamoto, D.-S. Ly-Gagnon, K. Katoh, K. Kikuchi: Coherent Demodulation of 40-Gbit/s Polarization-Multiplexed QPSK signals with 16-GHz Spacing after 200-km Transmission. Proc. OFC/NFOEC2005, PDP29, March 6-11, 2005, Anaheim, CA, USA.

[5] R. Noé, E. Meissner, B. Borchert, H. Rodler: Direct modulation 565 Mb/s PSK experiment with solitary SL-QW-DFB lasers and novel suppression of the phase transition periods in the carrier recovery. Proc. ECOC '92, Th PD I.5, Vol. 3, pp. 867-870

[6] R. Noé, PLL-Free Synchronous QPSK Polarization Multiplex/Diversity Receiver Concept with Digital I&Q Baseband Processing, IEEE Photon. Technol. Lett., Vol. 17, 2005, pp. 887-889

[7] T. Mizuochi, et al: Forward Error Correction Based on Block Turbo Code With 3-Bit Soft Decision for 10-Gb/s Optical Communication Systems, IEEE Journal of Sel. Top. in Quant. Electr., Vol. 10, NO 2, 2004, pp. 376-386