# First Real-Time Data Recovery for Synchronous QPSK Transmission With Standard DFB Lasers

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*Abstract*—For the first time, synchronous quadrature phase-shift keying data is recovered in real-time after transmission with standard distributed feedback lasers using a digital inphase and quadrature receiver. Forward-error-correction-compatible performance is reached at 800 Mb/s after 63 km of fiber. Self-homodyne operation with an external cavity laser is error-free.

*Index Terms*—Heterodyning, optical fiber communication, quadrature phase-shift keying (QPSK), real-time systems, synchronous detection.

## I. INTRODUCTION

COHERENT optical transmission, in particular quadrature phase-shift keying (QPSK) transmission, allows an improved bandwidth utilization of existing optical fiber together with a robustness against chromatic and polarization-mode dispersion. Ultimate optical signal-to-noise ratio performance is promised by synchronous demodulation, which for QPSK outperforms the asynchronous or interferometric one by >2 dB. Unfortunately ultranarrow linewidth lasers are required to implement a phase-locked loop for carrier recovery [1], and these are believed to be too expensive in today's cost-sensitive economic environment. However, a feedforward carrier recovery scheme [2] can relax the sum linewidth requirement to about 0.001 times the symbol rate, which is in the reach of standard, low-cost distributed feedback (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 to perform carrier recovery, electronic polarization control (inside a polarization diversity receiver) and electronic dispersion compensation at a lower multiplex hierarchy in standard-cell complementary metal–oxide–semiconductor circuitry. In this context, we have implemented, to our knowledge,
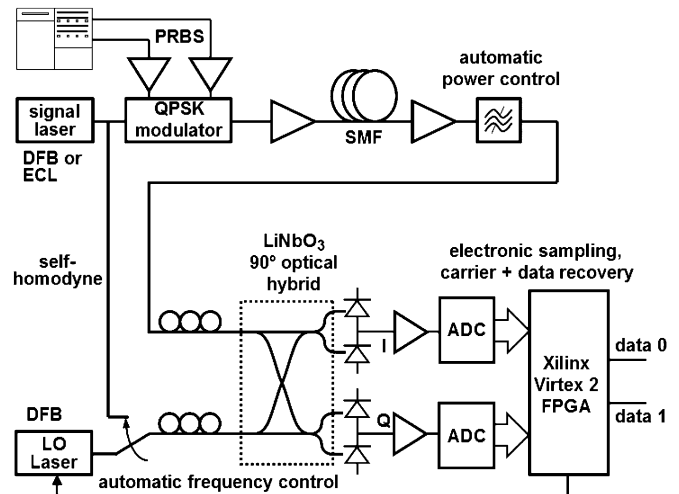
Fig. 1. A 800-Mb/s QPSK transmission setup with a real-time synchronous coherent digital I&Q receiver, using either DFB lasers or ECLs.

the first synchronous QPSK transmission system with real-time data recovery and standard DFB lasers.

## II. EXPERIMENTAL SETUP

A DFB laser signal is fed into a QPSK modulator, which is driven by up to $2 \times 400$ Mb/s pseudorandom binary sequence (PRBS) data (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. For experimental convenience, identical PRBS are used in our experiment as I&Q modulator driving data, mutually delayed by 9 or 12 symbols for decorrelation purposes, and differential quadrant encoding is not implemented.

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 a manual polarization controller. 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 local oscillator (LO) laser. The resulting electrical I&Q signals are amplified before being sampled with 5-bit analog–digital converters (ADCs). The ADCs interface with a Xilinx Virtex 2 field-programmable gate array (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
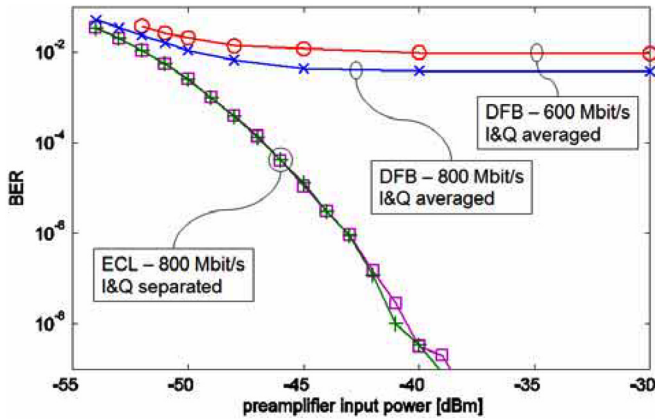
Fig. 2. Measured BER versus optical power at preamplifier input for self-homodyne experiments using ECL and DFB lasers.
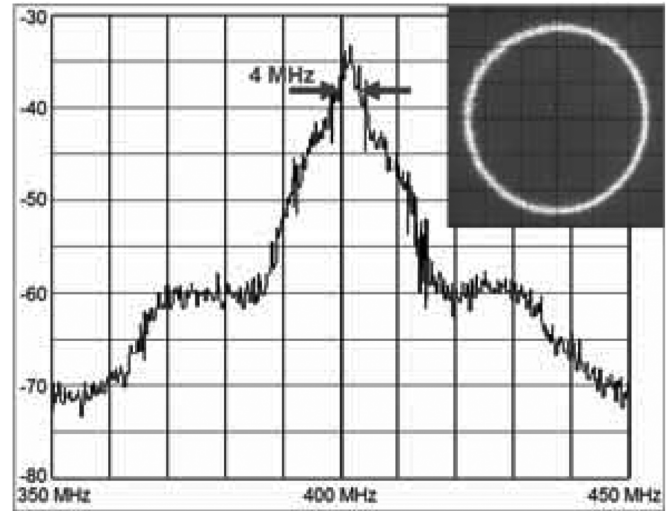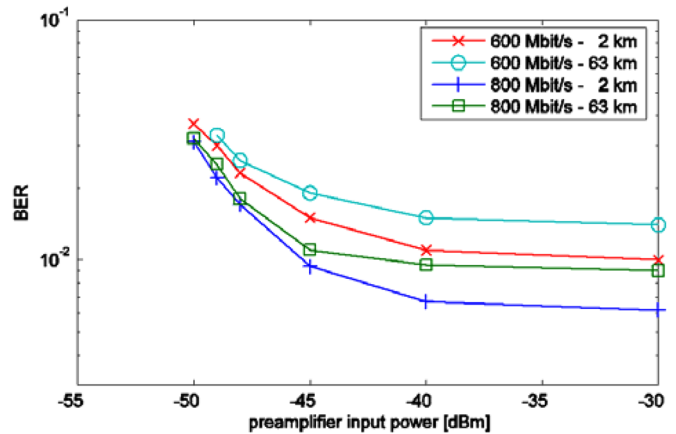


Fig. 3. Unmodulated IF spectrum and laser beating in 90° optical hybrid (inset).



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

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 real-time. To perform bit-error-rate (BER) measurements, an appropriate bit pattern is programmed into a BER tester, where the effect of the omitted differential encoding at the transmitter side is taken into consideration.

## III. MEASUREMENT RESULTS

### A. Self-Homodyne Experiments

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 with a $2^7 - 1$ PRBS as a 800-Mb/s (400 Mbaud) self-homodyne experiment using an external cavity laser (ECL) with a specified linewidth of 150 kHz. I&Q channel behavior was very similar. Sensitivity was 874 photons/bit at a BER of $10^{-9}$. Transmission was error-free during a 30-min test with $-37$ dBm of received optical power. Note that the applicable sum linewidth times symbol rate ratio of 0.00075 can be achieved with commercial DFB lasers in a 10-Gbaud system.

Next, the ECL was replaced by a DFB laser (JDS Uniphase) with a specified linewidth of 1 MHz (datasheet value). 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 600 and 800 Mb/s, 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 $1.1 \cdot 10^{-2}$ (600 Mb/s) and $3.7 \cdot 10^{-3}$ (800 Mb/s).

### B. Heterodyne Experiments

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 (IF) should be less than 1% of the symbol rate. Automatic frequency control is therefore implemented as follows: The observed carrier phase jumps between subsequent symbols are output from the FPGA and fed into an integral controller. The resulting signal controls a portion of the LO bias current. 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 sidelobes at $\pm 30$ MHz due to reflections.

BER versus received power is plotted in Fig. 4 for transmission of 600- and 800-Mb/s data rates over distances of 2 and 63 km, using a $2^7 - 1$ PRBS. The BER floor for transmitting 63 km is higher than for 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 800 Mb/s transmitted over 2 km. For $2^{31} - 1$ PRBS transmission over 2 km, the
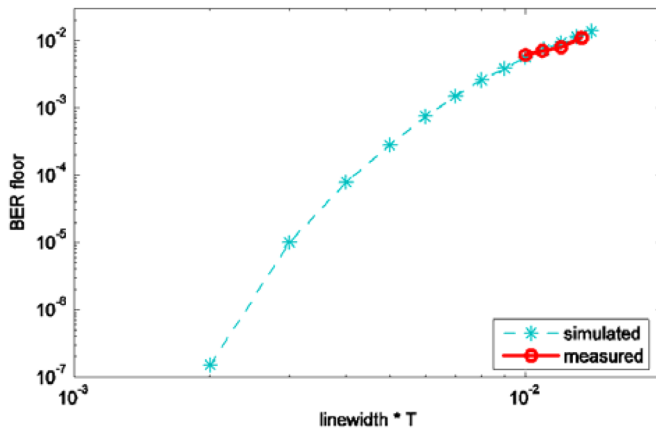
Fig. 5. BER floor for different products of linewidth times symbol duration $T$ for heterodyne configuration with DFB lasers.

measured BER floors were $6.3 \cdot 10^{-3}$ at 800 Mb/s and $1.1 \cdot 10^{-2}$ at 600 Mb/s.

## IV. DISCUSSION

A forward-error correction (FEC) coding scheme with 24.6% overhead is able to recover (quasi) error-free data for a raw BER below 2% [7]. Our 800-Mb/s QPSK transmission, therefore, corresponds to an error-free data rate of 642 Mb/s, assuming the presence of such an FEC.

A group of seven contiguous symbols is averaged to estimate the carrier phase, which is 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 additional phase noise, simply by averaging less samples. In line with this, future implementation of polarization division multiplex would result in an improved linewidth tolerance because the needed samples occur in half the time. 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. Very good performance with standard DFB lasers can be achieved at 10 Gbaud, which corresponds to 20-Gb/s data throughput, or even 40 Gb/s with additional polarization multiplex.

The surprisingly good agreement between theory and experiment is believed to result from a mutual canceling of two effects: The noise of the laser bias currents is Gaussian or even of finite amplitude, and the associated linewidth broadening is, therefore, less cumbersome than a Lorentzian one on which the simulation is based. On the other hand, the sidelobes of the heterodyne spectrum (Fig. 3) are elevated beyond a Lorentzian spectrum, which makes them more critical. A second isolator in the laser package should help in this respect.

The receiver sensitivity is currently strongly limited by the following: Thermal rather than shot noise is dominating. 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 is much stronger than the signal due to the low symbol rate and high optical filter bandwidth. The fact that there is no principal sensitivity degradation is also suggested by Figs. 2 and 4, where
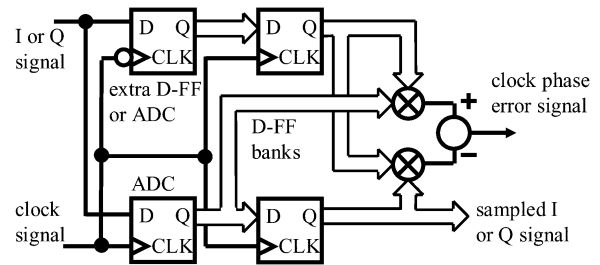


Fig. 6. Possible clock phase error signal generation.

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. Increasing the bit rate and reducing thermal frontend noise should bring the sensitivity near the quantum limit.

A shortcoming of the present experiment is the absence of a clock recovery. As a remedy, an I or Q signal can be sampled also with an inverted clock signal (top left block in Fig. 6), i.e., with a $T/2$ delay, similar to standard binary receivers. After temporal alignment in D-FF banks, this sample is correlated with the adjacent regular samples, and the results are subtracted to obtain a clock phase error signal.

## V. 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. The 800-Mb/s QPSK data was transmitted 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 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.

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