PLL-free coherent optical QPSK Transmission with realtime digital phase estimation using DFB Lasers

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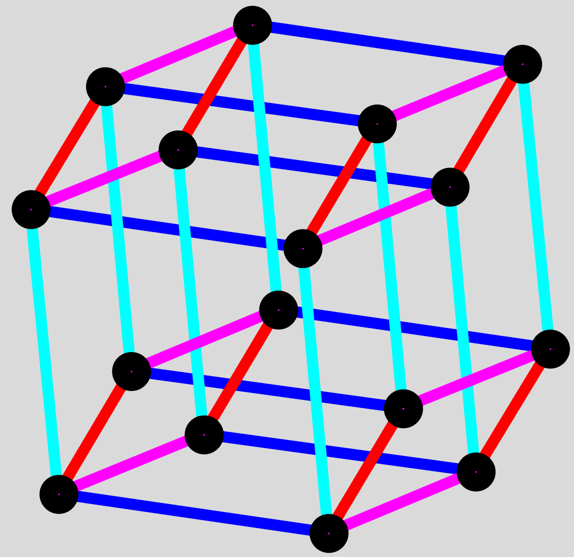
Outline

- Properties of coherent optical QPSK transmission
- Description of Receiver
- Measurement Results
- Conclusions



Properties of synchronous optical QPSK

- **4 bit/symbol** (with added polarization division multiplex)
  ► **lower cost per bit**
- Symbol rate: 40 Gbaud may suffer from nonlinear phase noise. 10 Gbaud (= 4 x 10 Gbit/s) is perfect for **evolutionary retrofitting of 40 Gbit/s transponders into existing 10 Gbit/s WDM systems**.
- Electrical received signals are proportional to optical fields: „**Optical equalization of CD and PMD in the electrical domain**“ becomes possible.
- **DFB lasers** are a must, since external cavity lasers are too costly and space-consuming.
  ► **Possible for synchronous QPSK with feed-forward carrier recovery**

Demodulation of the QPSK signal

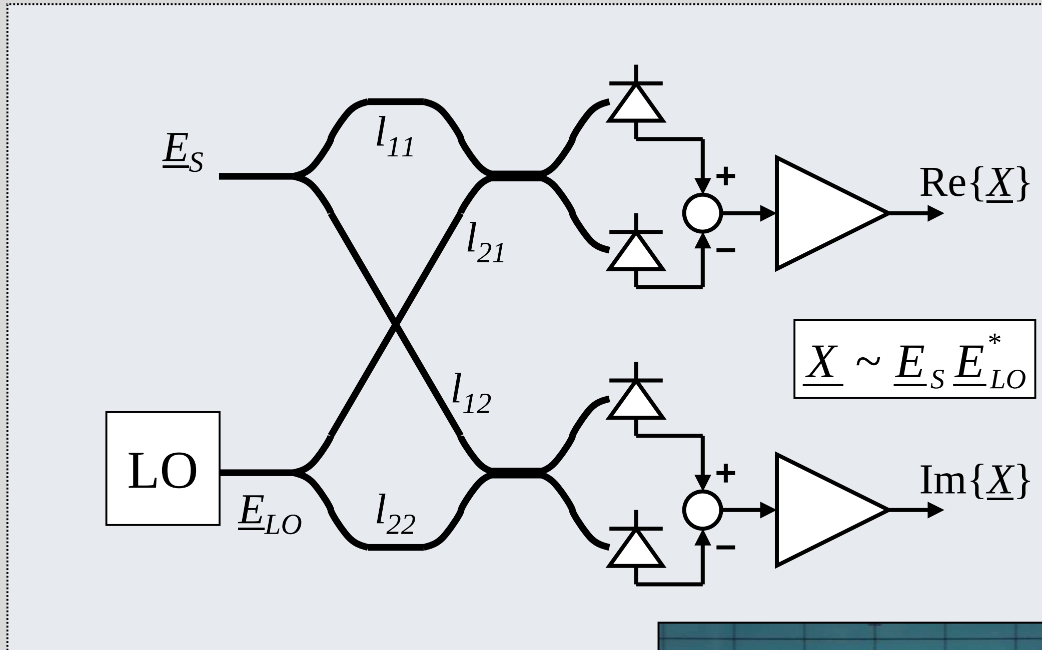
$$\underline{E}_S \propto \underline{c}e^{j(\omega_S t+\varphi_S)}$$

$$\underline{E}_{LO} \propto e^{j(\omega_{LO} t+\varphi_{LO})}$$

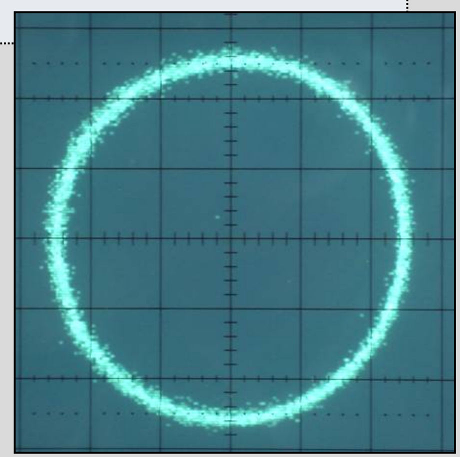
Setting of 90° hybrid:

$$(l_{11}-l_{21})-(l_{12}-l_{22})=\frac{\lambda}{4}$$

$$\underline{X}=\mathrm{Re}\{\underline{X}\}+j\,\mathrm{Im}\{\underline{X}\}=\underline{c}e^{j\varphi'}$$

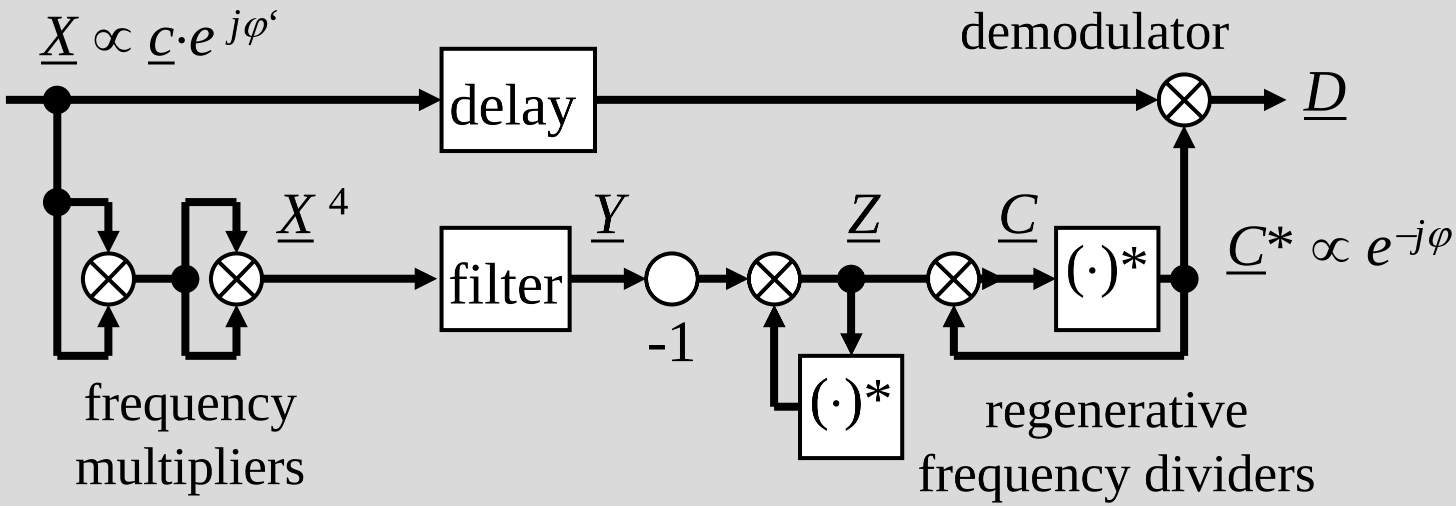


$$\varphi'=(\omega_S-\omega_{LO})t+(\varphi_S-\varphi_{LO})$$



Automatic frequency control & carrier recovery needed!

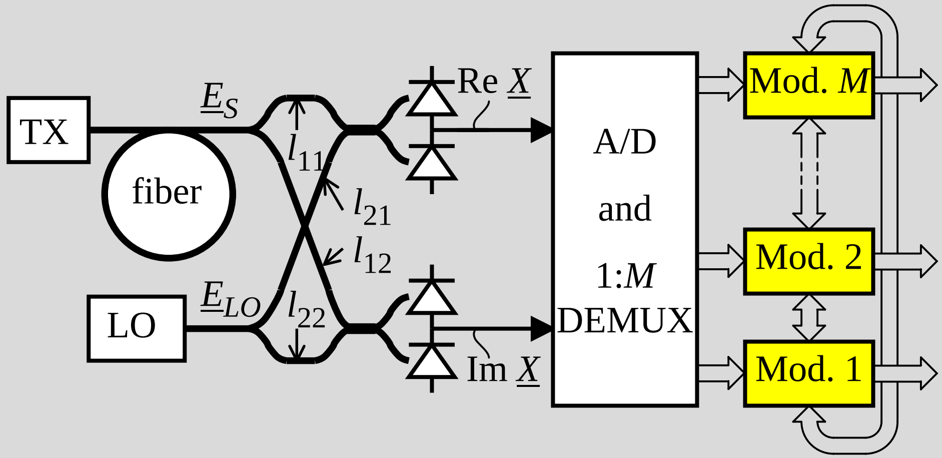
Analog carrier recovery



- Frequency multiplication by a factor of 4 removes QPSK modulation
- Lowpass filtering of frequency-quadrupled carrier: in analog mutipliers (Gilbert cells) and adders included, filter design part of circuit design
- Frequency division of baseband intradyne signals by a factor of 4, using two regenerative frequency dividers: $e^{j\omega t} = e^{j2\omega t} \cdot e^{-j\omega t}$

Digital carrier recovery

Differential encoding of angle quadrant number in transmitter



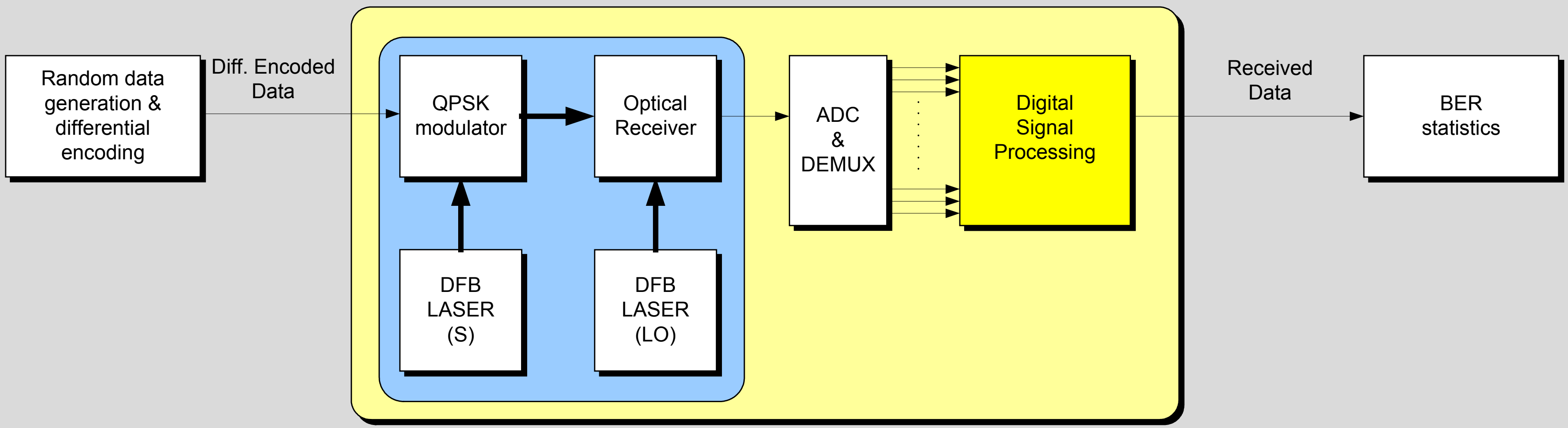
demultiplexed output data bits o_1, o_2

$\underline{X} \sim \underline{E}_{TX}\,\underline{E}_{LO}^{*}$

Content of each Module (logical unit):

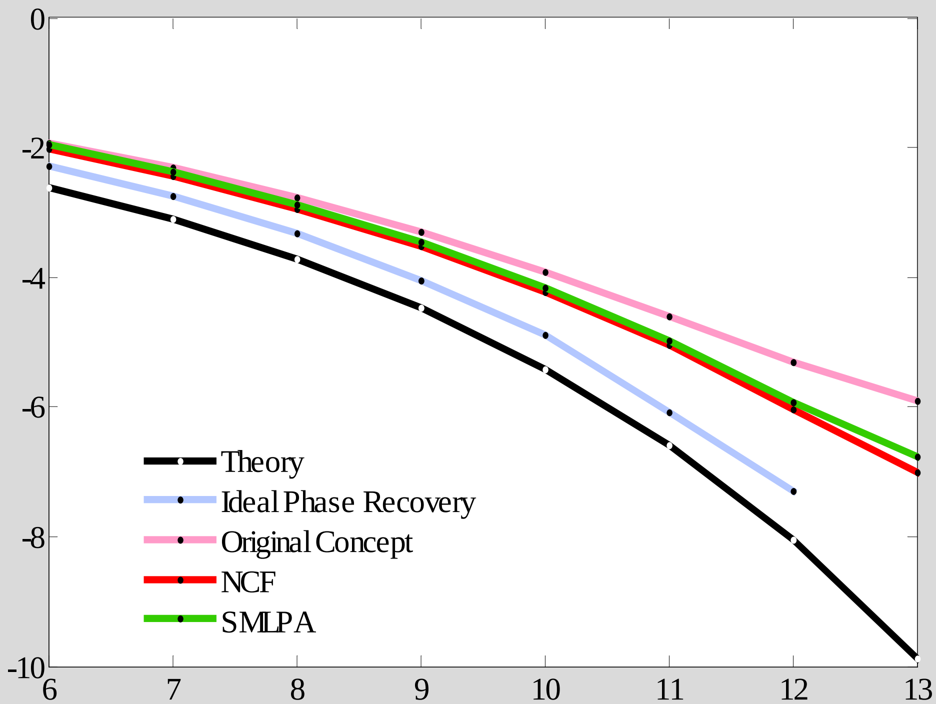
- Phase determination for the received modulated signal ψ=arc($\underline{X}$): LUT
- Estimation of phase ϕ for the unmodulated IF carrier, based on $\underline{X}$ or ψ
- Delay element for ψ that compensates for phase estimation time (feedforward approach, avoids feedback loop problems)
- Demodulation and differential decoding, based on angles ϕ , ψ and data from logical preceding module

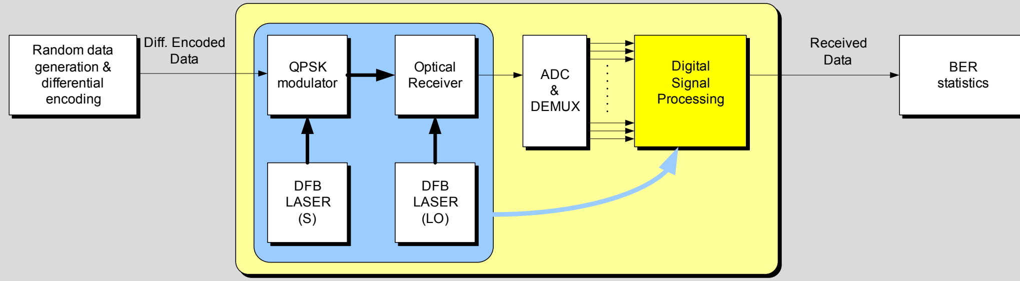
System Level Monte Carlo Simulation performed in Matalb

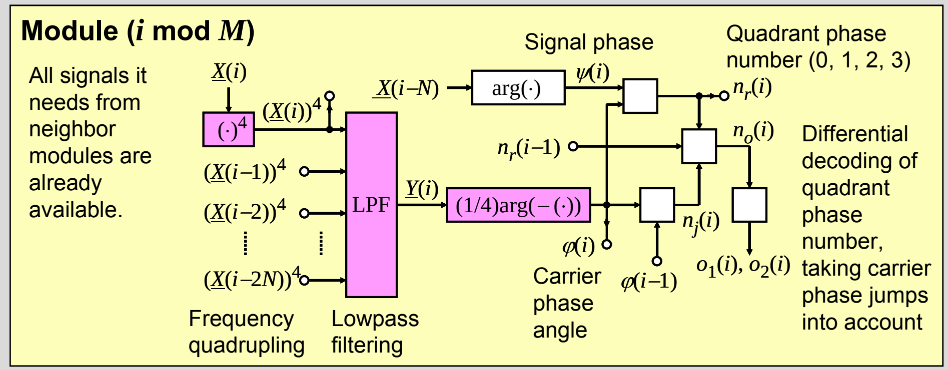


- Random QPSK Data is generated and differentially encoded
- Physical behaviour of the optical transmission subsystem is modeled
- BER statistics collected after Digital Signal Processing (DSP)
- Compare different Phase recovery concepts with identical input data

Simulation results (log BER vs. SNR curves)

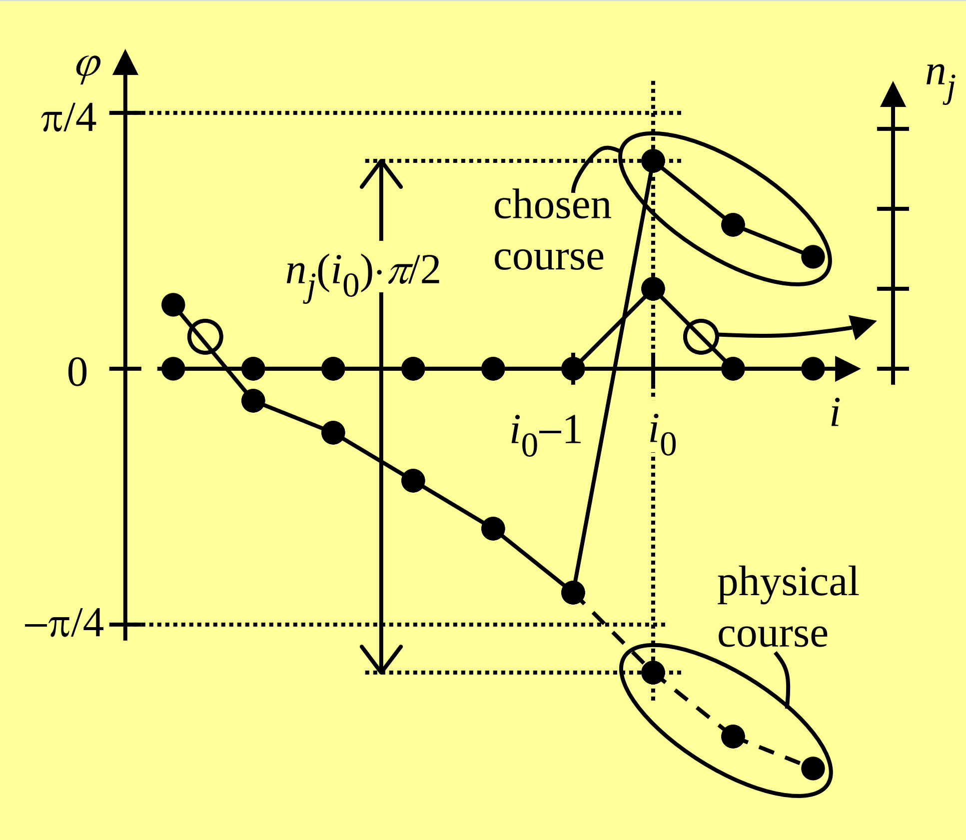






- Theory: Curve is obtained without use of the simulation model
- Ideal Phase Recovery: Use real IF phase from physical model
- Original Concept: IEEE PTL, Vol. 17, 2005, pp. 887-889
- NCF: Nonlinear Complex Filter, best results, high effort
- SMLPA: Selective Maximum Likelihood Phase Approximation, 2nd best results, low effort, **chosen for implementation**

Frequency estimation for Automatic LO frequency control

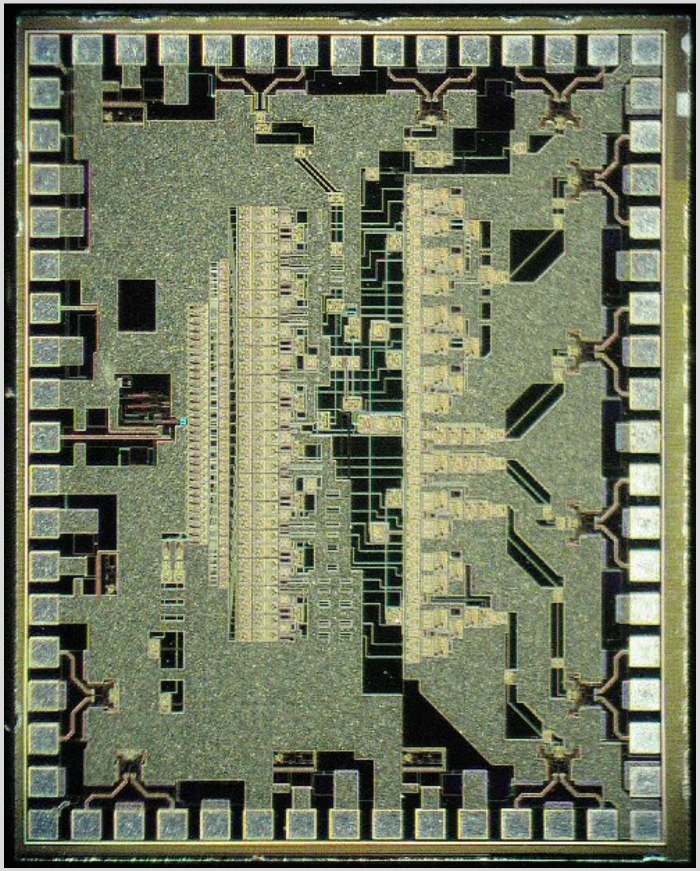


Inconsistency between estimated IF phase and (most likely) physical course is detected and encoded for differential decoding as a quadrant jump number n_j

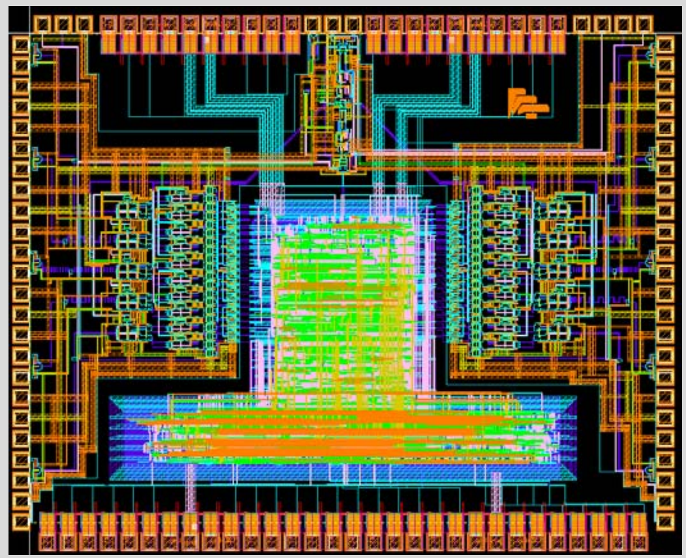
- Quadrant jump numbers are generated for each pair of subsequent estimated phase angles, necessary for correct differential decoding
- Possible values (0,1,-1) can be interpreted as a raw estimation of instantaneous phase change velocity
- Sum of quadrant jump numbers from 16 modules yields an estimated LO frequency
- Sum is PWM modulated for external automatic frequency control: single output pin
- Coarse frequency control, no OPLL

Signal processing component development

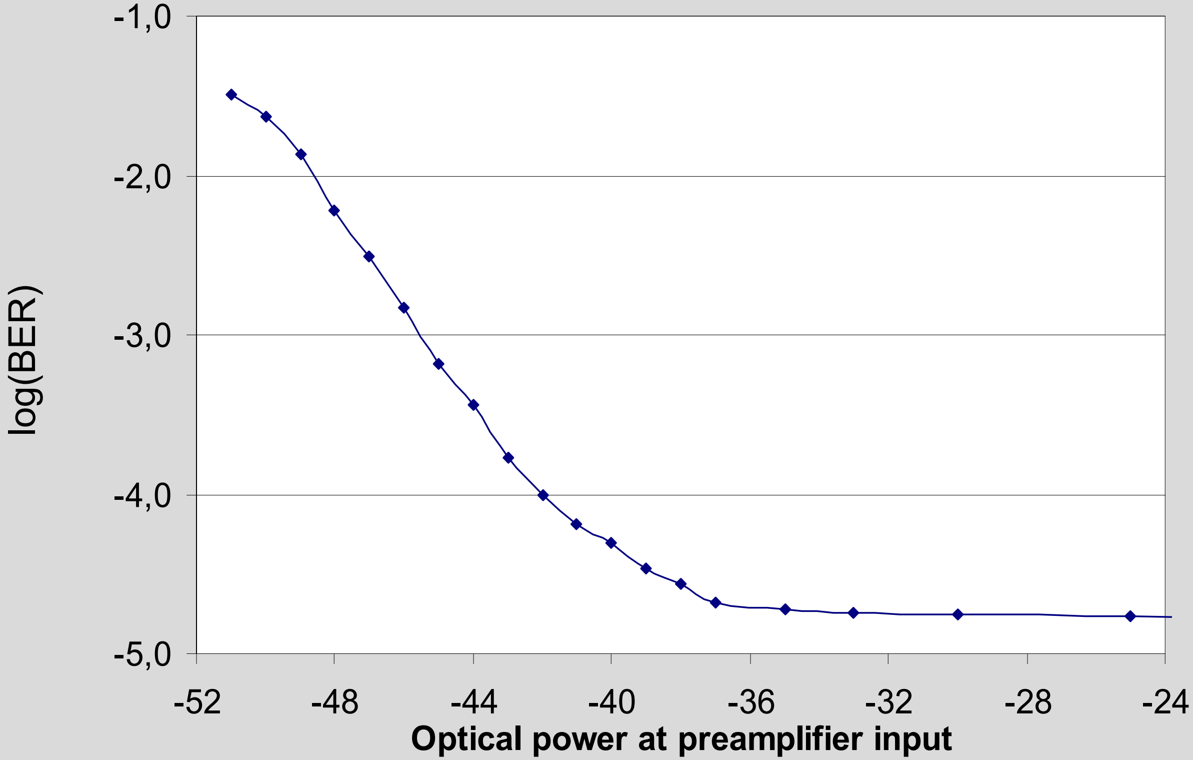
- 10 Gsps analog digital converter
- 0.25µm SiGe technology
- 5 bit Gray coded differential outputs



- Digital signal processing ASIC
- 120 nm CMOS technology
- Divide 10 GHz clock from ADC down to CMOS clock of 625 MHz
- 1:8 demultiplexer (full custom design)
- 8:16 demultiplexer, carrier and data recovery with standard cells, VHDL code verified on FPGA in experiment

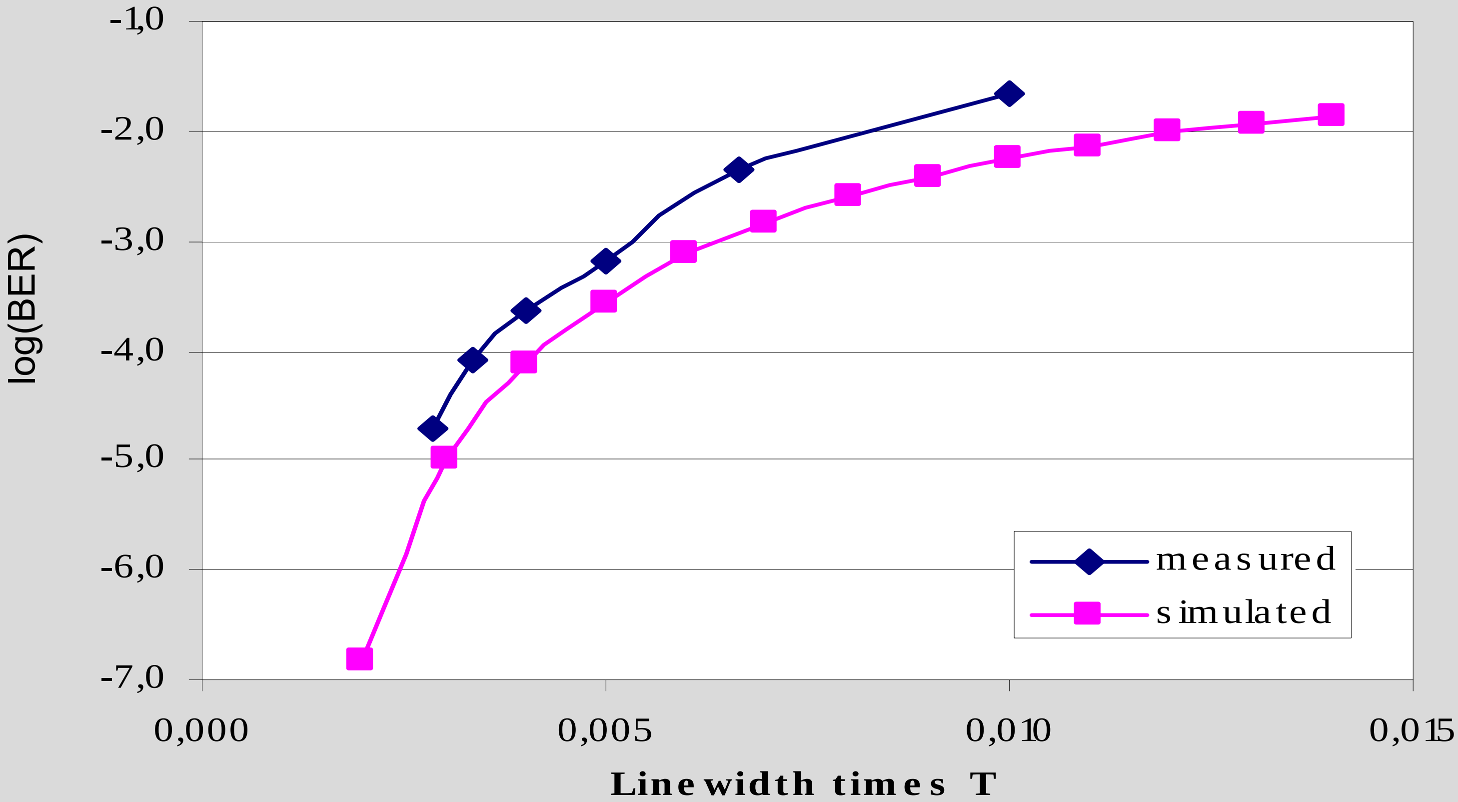


Intradyne transmission results, using DFB lasers with Δf<2 MHz (specified)



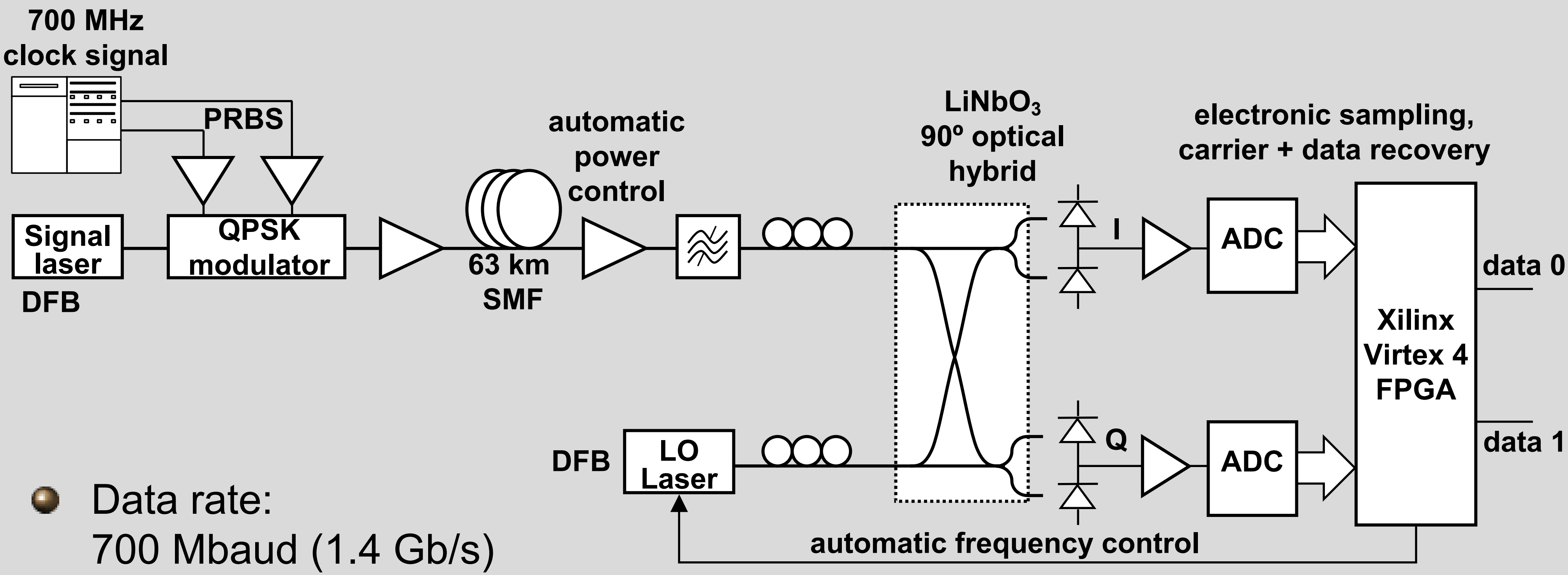
- Measured BER (I &Q averaged): $1.7 \cdot 10^{-5}$ floor
- Constant for preamplifier input power >-37 dBm
- Detection (PRBS synchronization) possible up to –51 dBm
- BER floor within capability of FEC (7%) ⇒ 1.3 Gb/s net data rate

Bit error ratio floor vs. linewidth times symbol duration product



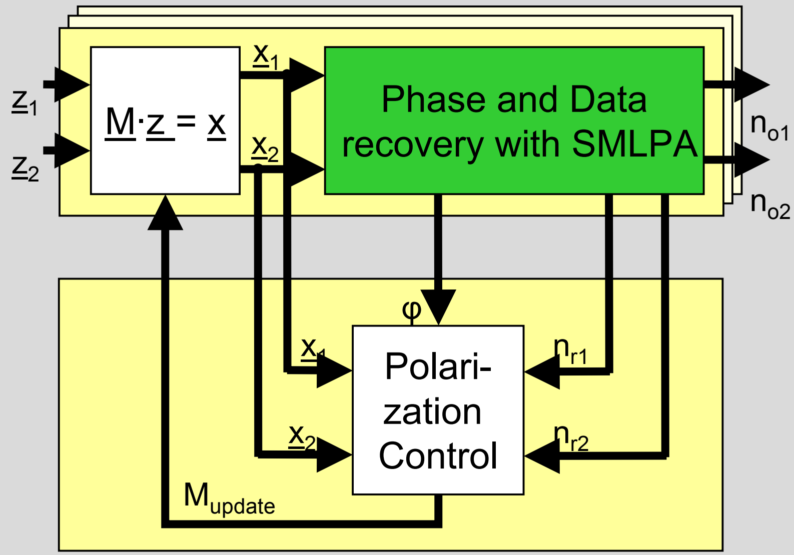
- A BER of $1.7 \cdot 10^{-5}$ was achieved, which is the lowest BER ever reported for real-time synchronous QPSK transmission with DFB lasers.
- Additional phase noise tolerance (factor 2) applies for polarization division multiplex.

Realtime coherent QPSK transmission setup with FPGA



- Data rate:
  700 Mbaud (1.4 Gb/s)
- Manual polarization control
- Commercial 5 bit ADCs, clocked at 700 MHz
- Automatic LO frequency control implemented
- Noisy optical front ends, much too wide optical filter (~20 GHz)

Outlook: Polarization multiplex, polarization control



- Combination of Phase and Data recovery based on Selective Maximum Likelihood Phase Approximation (SMLPA) with Polarization Control successfully simulated
- VHDL implementation on FPGA ready for subsequent experiments in extended testbed

Conclusions

- **Realtime coherent QPSK transmission with DFB lasers**
- BER floor of $1.7 \cdot 10^{-5}$ at 700 Mbaud (1.4 Gb/s)
- Phase noise should be unproblematic at 10 Gbaud.
- 4×10 Gb/s synchronous QPSK transmission systems with polarization division multiplex can be developed, using DFB lasers.

Acknowledgement

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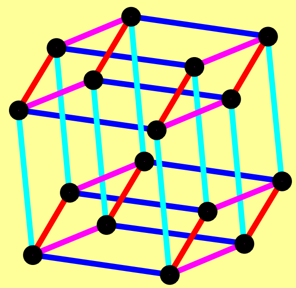
http://ont.upb.de/synQPSK



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