2.56 Tbit/s, 1.6 bit/s/Hz, 40 Gbaud RZ-DQPSK polarization division multiplex transmission over 273 km of fiber

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Abstract: *We report on 16×2×2×40 Gbit/s RZ-DQPSK transmission over a 273 km fiber link with a BER < 10^{-3}. Due to polarization division multiplex each WDM channel carries 160 Gbit/s although the symbol rate is only 40 Gbaud. Polarizations are demultiplexed automatically by a LiNbO$_3$ polarization transformer.*

Introduction

The powerful tool of optical code division multiplex together with alternate WDM channel polarizations allows for a record 1.6 bit/s/Hz transmission [1] throughout the whole C band. Competing conventional techniques are more PMD and chromatic dispersion tolerant and support larger amplifier spacings. Polarization division multiplex [2-4] and DQPSK transmission [3-9] each can double fiber capacity by their increased spectral efficiencies. Both techniques have been combined to transmit 4x10 Gbit/s per WDM channel [3, 4]. Here we report for the first time to our knowledge 4x40 Gbit/s per WDM channel transmission with automatic polarization control.

Transmission setup

Fig. 1 shows the RZ-DQPSK polarization division multiplex 16×2×2×40 Gbit/s per WDM channel transmission setup, similar to [9]. 16 WDM signals (192.2 ... 193.7 THz) with about 100 GHz channel spacing are combined with equal polarizations and modulated together. The electrical part of the transmitter features a 16:1 multiplexer which processes 16 2.5 Gbit/s mutually delayed 2^7-1 PRBS data streams to form a 2^7-1 PRBS at 40 Gbit/s, and modulator drivers for a dual-drive DPSK modulator.

(D)QPSK is generated in a subsequent all-fiber temperature-stabilized Mach-Zehnder interferometer with a differential delay t of about 3-symbol durations (~75 ps) and active phase control by means of a piezo fiber stretcher in one of the arms. At one interferometer output, a 193.0 THz optical bandpass filter (BPF), a 12-GHz photoreceiver, and a subsequent RF diode detector are used to measure the RF power carried by the optical DQPSK signal. When the two optical signals are superimposed in quadrature, there is no interference and hence no RF power, except for the clock frequency that is outside the photoreceiver bandwidth. A quadrature control loop based on a 10 kHz lock-in detection scheme stabilizes the interferometer phase by minimizing the RF power. The depth of the 10 kHz phase modulation is only ~0.01 rad (rms). The laser frequencies are fine-tuned to points of a $1/(2t) \approx 6.7$ GHz raster so that each WDM channel contains a proper DQPSK signal. The channel spacing is roughly an odd multiple of the raster point spacing. This means that each WDM channel had at least one neighbor where in-phase and quadrature data streams are combined with opposite polarities, hence a different optical pattern. After a later differential interferometric demodulation in the receiver this means that in-phase and quadrature data streams are exchanged. In the transmitter a dual-drive modulator driven at half the clock rate carves 8-ps pulses and thereby completes the RZ-DQPSK signal generation.

Finally, the DQPSK signal is split, differentially delayed by 112 symbol durations (~2.8 ns) and recombined with orthogonal polarizations (PolDM). Since this particular polarization multiplexer was available, interleaving of orthogonally polarized pulses in the time domain was not tested. Anyway, pulse interleaving is not necessarily advantageous [10].

The optical signals are transmitted over 4 fiber spans (81+69+60+63 km) with a total length of 273 km, consisting of 153 km of SSMF and 120 km of NZDSF. DCF with a total dispersion of –3150 ps/nm is inserted between inline EDFAs. Fiber and DCF launch powers are +0.5 ... +5 dBm and –3 ... –1 dBm per WDM channel, respectively. EDFA input powers are –20 ... –15 dBm per WDM channel.

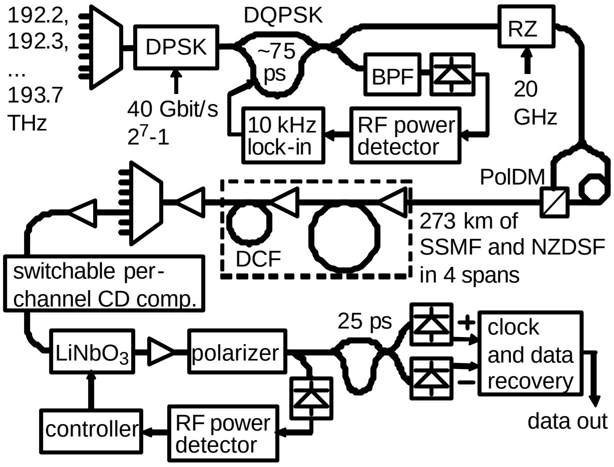

Fig. 1: 16´2´2´40 Gbit/s transmission setup

The receiver contains optical preamplifiers and a flat top C band DWDM DEMUX. A per-channel chromatic dispersion compensation is applied by switchable short pieces of DCF. A LiNbO$_3$ polarization controller transforms the selected WDM signal so that the unwanted polarization is supressed in a subsequent fiber polarizer. Another 12-GHz photoreceiver and a subsequent RF diode detector detect broadband interference between both polarization channels. A controller automatically minimizes this interference by properly setting the voltages of the LiNbO$_3$ polarization controller. At optimum polarization setting interference is minimum.

Another Mach-Zehnder interferometer, with a delay of one symbol duration, demodulates the signal. For proper reception of in-phase and quadrature data channels, the phase difference of the delay demodulator is set either to 45° or 135°, using a piezo fiber stretcher. The demodulator outputs are connected to two high-speed photodetectors. They are connected to the differential inputs of a 1:16 demultiplexer with standard clock and data recovery. Due to the differential demodulation the demodulated bit patterns in in-phase and quadrature data channels differ from the transmitted ones. The half rate clock signals in transmitter and receiver are generated by VCOs.

Results

The optical spectra before and after 273 km of fiber are shown in Fig. 2. The receiver sensitivity for a BER < 10^{-3} of each of the 16 signals was measured back-to-back in one quadrature in one polarization (Fig. 3 bottom). The sensitivities of the complete 160 Gbit/s signals range between –32.3 and –28.2 dBm. After transmission through the fiber the OSNR ranges between 24 and 30 dB (Fig. 3 top).

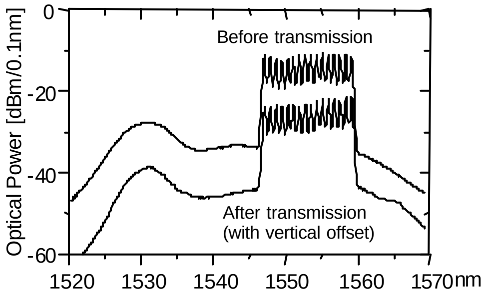

Fig. 2: Optical spectra before and after 273 km of fiber

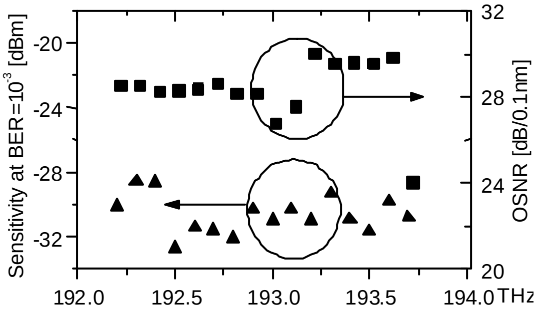

Fig. 3: 160 Gbit/s receiver sensitivity at FEC limit (bottom), and OSNR after transmission (top)

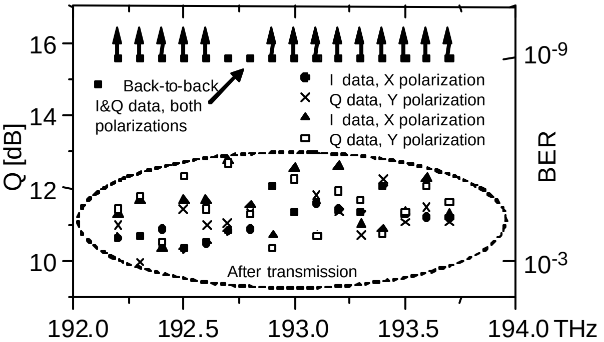

Fig. 4: Measured BERs, expressed as Q factors, for I and Q data channels in both polarizations, before and after transmission.

Fig. 4 shows measured BERs, expressed as *Q* factors, for I and Q data channels in both polarizations. Back-to-back most channels were (quasi) error-free but some yielded BER = 10^{-9}, most likely due to large linewidths on the order of 10 MHz. After 273 km a BER < 10^{-3} was reached in all cases. This is sufficient for FEC-assisted transmission. Since single-channel BER in a similar experiment [9] was < 10^{-9}, the observed WDM BER performance is believed to be influenced by channel interaction. More channels have not been tried because available EDFA output power is limited. Raman gain, which was not available here, could relieve the optical power constraints, in order to allow for transmission over more spans.

Fig. 5 shows exemplary measured eye diagrams before and after transmission at 193.0 THz. The chosen persistence time is short because after transmission the photodiodes had to be connected from the receiver, and only the transmitter clock was therefore available for triggering.

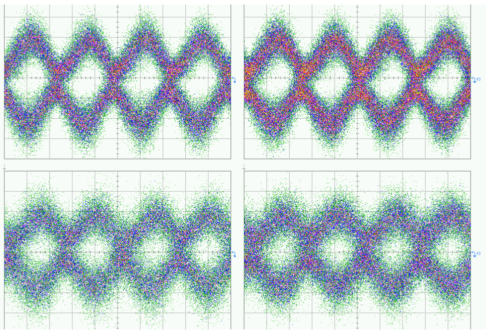

Fig. 5: 40 Gbit/s RZ-DQPSK eye patterns of one quadrature in both polarizations, back-to-back (top) and after transmission (bottom).

Conclusion

We have transmitted 2.56 Tbit/s on 16 100-GHz-spaced WDM channels at the FEC limit. Data is sent in two polarizations and differentially encoded in two quadratures per WDM channel. Fiber capacity is thereby quadrupled. The line rate is only 40 Gbaud, which is advantageous for dispersion tolerance.

References

[1] H. Sotobayashi et al, “Highly spectral-efficient optical code-division multiplexing transmission system”, *IEEE J. Selected Topics in Quantum Electronics*, 10, (2004), 250-258

[2] D. Sandel et al., “Standard (NRZ 1×40Gbit/s, 210km) and polarization multiplex (CS-RZ, 2×40Gbit/s, 212km) transmissions with PMD compensation”, *IEEE PTL* **14**, (2002), 1181-1183

[3] C. Wree, et al, “High Spectral Efficiency 1.6-b/s/Hz Transmission (8 x 40 Gb/s With 25-GHz Grid) Over 200km SSMF Using RZ-DQPSK and polarization multiplexing”, *IEEE PTL* **15**, (2003), 1303-1305.

[4] Y. Zhu et al., ”1.6 bit/s/Hz orthogonally polarized CSRZ-DQPSK transmission of 8x40 Gb/s over 80 km NDSF”, OFC2004, TuF1

[5] R. A. Griffin et al, “Optical Differential Quadrature Phase Shift Key (oDQPSK) for High capacity Optical Transmission”, in Proc. OFC’02, Atlanta, GA (2002), WX6.

[6] P. S. Chao et al, “Transmission of 25-Gb/s RZ-DQPSK Signals with 25 GHz Channel Spacing over 1000 Km of SMF-28 Fiber”, *IEEE PTL* **15**, (2003), 473-475.

[7] H. Kim et al, “Transmission of 8x20 Gb/s DQPSK Signals with 25 GHz Channel Spacing Over 310km SMF with 0.8-b/s/Hz Spectral Efficiency”, *IEEE PTL* **15**, (2003), 769-771.

[8] N. Yoshikane and I. Morita, “1.14 b/s/Hz spectral efficiency 50 x 85.4 Gb/s transmission over 300 km using co-polarized CS-RZ DQPSK signals”, OFC2004, PDP38.

[9] D. Sandel et al, “2×40 Gbit/s RZ-DQPSK transmission over 263 km of fiber with tunable chromatic dispersion compensator”, OECC/COIN2004, 16C2-3

[10] S. Hinz et al., “PMD tolerance of polarization division multiplex transmission using return-to-zero coding”, Optics Express, Optical Society of America, July 30, 2001, p. 136, Abstract 34862