200-Gb/s, 430-km PDM-RZ-DQPSK (4 bit/symbol) Transmission with 10 krad/s Endless Polarization Tracking

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Abstract: We report agile endless optical polarization demultiplex, free of polarization channel jumps, over a 475 Mrad long Poincaré sphere trajectory at 10 krad/s speed, in a 50-Gsymbol/s, 4-bit/symbol realtime data transmission over 5 fiber spans.

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1. Introduction

Polarization-multiplexed quadrature phase shift keying (PDM-QPSK) transmission with coherent technology has been developed for 46 Gb/s (gross) [1] to seemingly 56 Gb/s per optical carrier [2], with impressive performance but also substantial development effort and power consumption. Higher bitrates are accessible only with offline processing [3, 4]. On the other hand, many transmission links are chromatic dispersion (CD) compensated and have just moderate polarization mode dispersion (PMD) so that coherent technology with its electronic bottleneck is not needed. Indeed, with differential QPSK (DQPSK) and interferometric direct detection, up to 170 Gb/s have been transmitted in realtime with pure WDM technology, but polarization control was seemingly slow [5–7] or manual [8, 9]. Recently we have transmitted 112 Gb/s while tracking 800 rad/s on the Poincaré sphere [10]. Here we prove that endless optical polarization control technology [11, 12] lends itself to much faster tracking of PDM signals.

2. Setup

A 50-GHz synthesizer clocks a 50 Gbaud bit pattern generator (SHF12100B). The data signal and its complementary version drive with a mutual delay of 12 symbols a (D)QPSK transmitter (SHF46214A), with a 1553 nm, 12 dBm laser as optical source. An EDFA reamplifies the signal. The 25 GHz halfrate clock of the bit pattern generator drives a subsequent Mach-Zehnder modulator. RZ pulses with alternating polarity are thereby impressed on the DQPSK signal. Finally the 100-Gb/s RZ-DQPSK signal is passed through a 3 dB coupler. One branch signal is delayed by a couple of ns, and both are multiplexed with orthogonal polarizations. The clock frequency is fine-tuned (49.936 GHz) so that the delay is an odd number of symbols.

For testing purposes the 200-Gb/s signal is passed through a polarization scrambler. It consists of two batteries (1, 2) with 4 rotating fiberoptic quarterwave plates (QWP) each, and in between an electrooptic halfwave plate (HWP). Optionally, another QWP battery (0) and a PMD element are inserted before QWP battery 1.

The signal is transmitted in 5 spans (launch power: +3 dBm) over a total of 430 km of fiber (SSMF: 170 km, NZDSF: 260 km). Dispersion compensating fiber (DCF) modules (about –3200 ps/nm in total) are inserted in double-stage EDFAs. At the receive end the signal is attenuated to set the OSNR, and preamplified in two EDFAs. We reject noise in available cascaded DWDM channel filters with a combined bandwidth of 116 GHz. Residual CD

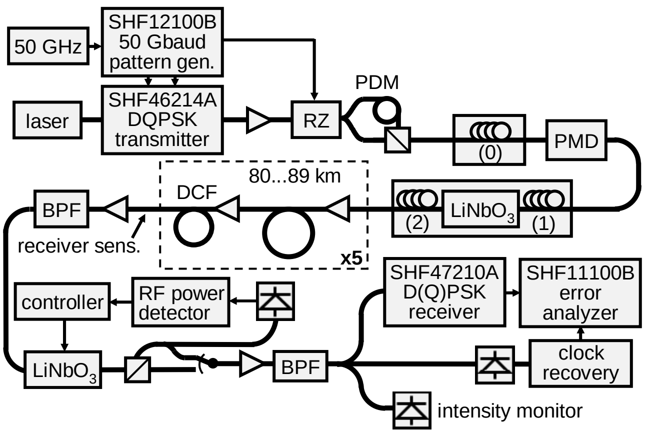

Fig. 1: 200-Gb/s PDM-RZ-DQPSK transmission setup

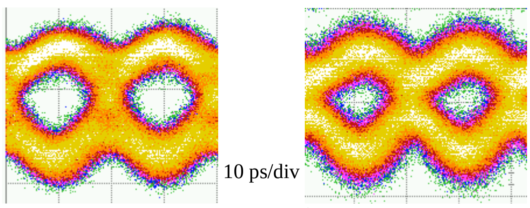

Fig. 2: DQPSK eyes back-to-back (left; by mistake recorded with 26 rather than 50 GHz scope bandwidth), after 430 km (right)

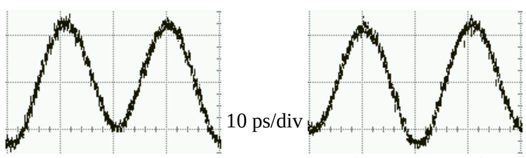

Fig. 3: Received intensity modulation (64-fold averaged) for the two polarization channels (while clock recovery PLL stays locked)

is compensated in some DCF (−40 ps/nm). For polarization demultiplexing we have developed an endless polarization controller with a commercial $LiNbO_3$ device. It is followed by a polarization beamsplitter (PBS). At its outputs the two polarization channels are available. At one output some power is tapped off for a 10 Gb/s photoreceiver. If polarization channels are not perfectly demultiplexed, they interfere. Interference is measured in an RF power detector and minimized by the control hardware [5] (A/D converter, FPGA, D/A converters, amplifiers).

The output signal is optically amplified again, then split into three equal portions (9 dBm each). One branch signal is detected in a D(Q)PSK photoreceiver (SHF47210A). Its output signal drives an error analyzer (SHF11100B). Another branch signal is detected in a 45-GHz photodiode. The RZ modulation generates a 50-GHz sinewave there. A clock recovery PLL is set up with a 4th-harmonic mixer, a 12.5-GHz VCO, a loop filter, and a frequency doubler from 12.5 to 25 GHz. The recovered 25-GHz signal is connected to the error analyzer in the halfrate clock mode. The third branch with one more 45-GHz photodiode allows to observe intensity modulation.

3. Results

The error analyzer was programmed to receive those two I&Q data streams which were expected due to DQPSK modulation with decorrelated data streams and interferometric DQPSK detection. PRBS of size 2^7-1, $2^{11}-1$, $2^{15}-1$ were transmitted, with sensitivity differences of a few 1/10 dB and a back-to-back Q^2 value of 23 dB. Both polarization channels and both quadratures were demultiplexed successfully. Back-to-back sensitivity at BER = 10^{-4} was −30.5 dBm before preamplification. Due to memory size restrictions in the realtime mode we selected $2^{11}-1$ PRBS for the following. Sequences were synchronized manually, so that unwanted slipping of the polarization channel would be indicated by an error overflow.

The received DQPSK eye diagram, back-to-back and after 430 km, is seen in Fig. 2. Fig. 3 shows the detected intensity modulation, with averaging. Two traces are shown. Between these recordings polarization control was switched off and on again while the clock recovery PLL stayed locked. Both traces show the 50 GHz RZ modulation. But they differ by the phase of the parasitic 25-GHz subharmonic, which allowed us to identify the received polarization channel. The interference spectrum of the intensity modulation is shown in Fig. 4 for worst case (manually adjusted) and best case (polarization controller switched on). The contrast is on the order of 10 dB. The periodicity is due to the 12 symbol delay between I&Q data. The 25-GHz component is also visible.

The polarization-multiplexed 200 Gb/s signal exhibited a degree-of-polarization (DOP) smaller than 0.05. Fig. 5 left shows the completely filled Poincaré sphere after the scrambler. (A display inside the sphere, reflecting the small DOP, would be more appropriate.) In contrast, the polarization-demultiplexed 100 Gb/s channel signals were re-polarized with a DOP >0.99 and stable polarization (Fig. 5 right).

The tolerance of the PDM-DQPSK system to fast polarization changes was tested with the polarization scrambler back-to-back when the BER was degraded to about 10^{-4} by noise loading, assuming the presence of a forward error correction. The BER was recorded several times with and without scrambling for each speed. BER changes are transformed into changes of Q^2 (in dB). Fig. 6 shows the penalty as a function of scrambling speed. The

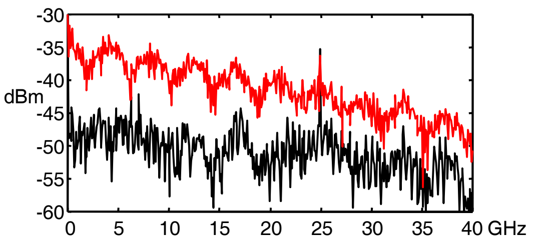

Fig. 4: Interference spectra for worst case (top) and best case (bottom)

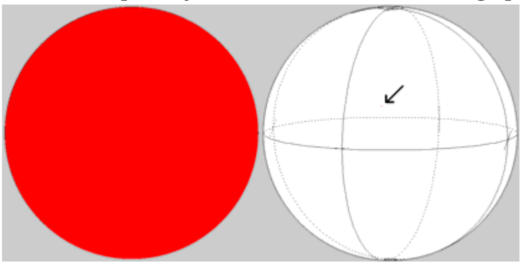

Fig. 5: Poincaré sphere behind scrambler (left; note that the DOP is <0.05) and behind polarization demultiplexer (right; the polarization is so stable that the dot is hardly visible)

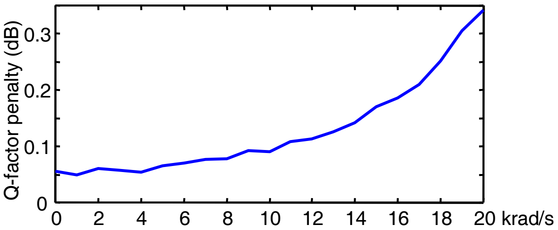

Fig. 6: Penalty @ BER = 10^{-4} as a function of scrambling speed

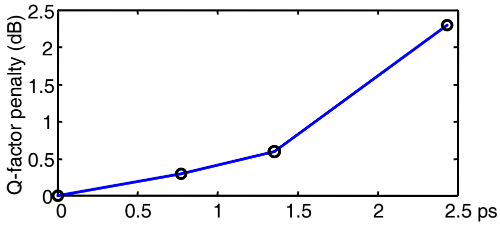

Fig. 7: Worst-case PMD penalty @ BER = 10^{-4} as a function of DGD

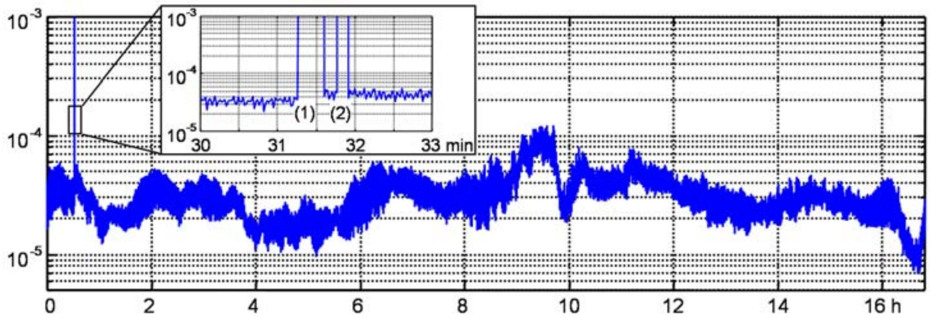

Fig. 8: BER performance while transmitting over 430 km during ~17 hours. Inserted close-up: Polarization controller is halted for a few seconds (1), then locks to the other channel with slightly worse BER, is halted again (2) and locks to the worse channel again.

0-dB reference holds for manual polarization adjustment. Up to 10 krad/s the scrambling penalty was about 0.05 dB. From 12 krad/s on, polarization channel jumps were observed. Next, QWP battery 0 and diverse PMD elements were inserted. The worst-case penalty is depicted in Fig. 6. It reaches 2.3 dB for a differential group delay of 2.4 ps.

Then the system was operated during almost 17 h at 10 krad/s maximum (7.9 krad/s average) scrambling speed. A total of 475 Mrad on the Poincaré sphere was tracked in this time. BER was monitored in 1-s intervals (Fig. 8). We deactivated automatic pattern re-synchronization in order to detect any polarization channel jumps. After 31 min we manually swapped channels and re-synchronized. Apart from this, no BER peaks were observed. The intensity monitor (in infinite persistance mode) also showed no unwanted polarization channel jump during the whole measurement. BER fluctuated within about a decade, presumably due to PMD. Indeed, if fibers between the spans were bent or moved to change link PMD, the BER changed within the same range. The BER stayed well below an FEC limit. It did not matter much whether DQPSK and interference detection receivers were connected to the same PBS output port or to different ones. So, one polarization control system sufficed to demultiplex both polarization channels. This indicates that polarization-dependent loss was small. Surprisingly, BER performance was sometimes better by half a decade when DQPSK and interference detection receivers were connected to different PBS output ports. This seemed to depend on polarization settings inside the transmission link, hence on link PMD.

4. Discussion and conclusions

We have transmitted 200-Gb/s, 4-bit/symbol data in realtime on a single optical carrier with fast endless polarization control. This rate is ~3.5 times as large as the value 56 Gb/s, which to the best of our knowledge is the highest gross bitrate where all this – and more – has been achieved before [2]. In our 430-km link with 5 fiber spans, 10 krad/s polarization changes were tracked successfully, free of polarization channel swaps, over a 475 Mrad long trajectory on the Poincaré sphere. A polarization splitter allowed to recover both polarization channels even though there was only one polarization controller. Polarization channel identification is no more complicated than I&Q channel identification, and can be accomplished by appropriate framing information. Endless polarization control technology enables transmission of 4 bit/symbol at essentially any symbol rate at which modulation, photodetection and binary data regeneration [13] is possible. An NRZ clock recovery [13] will allow to use more narrow optical filters.

5. References

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