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ORIGINAL PAPER

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2.38 Tbit/s, 1.49 bit/s/Hz, and (16×4×40 Gbit/s) RZ-DQPSK polarization division multiplex transmission over 273 km of fiber

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Abstract We report on transmission of a net aggregate data rate of 2.38 Tbit/s (excluding an assumed ~7% FEC overhead) over 273 km of fiber with just 16 100-GHz-spaced WDM channels. Due to polarization division multiplex and RZ-DQPSK modulation, each channel carries 160 Gbit/s (including the assumed FEC overhead) although the symbol rate is only 40 Gbaud. Polarizations are demultiplexed using automatic polarization control with a $LiNbO_3$ polarization transformer. In-phase and quadrature data are demodulated in a 1-bit interferometer.

Keywords Differential quadrature phase shift keying (DQPSK) · Polarization division multiplex (PolDM) · Wavelength division multiplex (WDM) · Chromatic dispersion (CD) compensation · Optical fiber communication.

1 Introduction

An evolutionary, cost-effective upgrading of optical fiber links requires an optical modulation format with a high spectral efficiency. This allows to keep existing erbium-doped fiber amplifiers (EDFAs) for the optical C band (1530–1561 nm wavelength) in service. Various proposals have been made in this context optical code division multiplex together with alternate polarizations of wavelength division multiplex (WDM) channels has allowed for optical fiber communication with a record 1.6 bit/s/Hz spectral efficiency [1] throughout the whole C band.

Competing conventional techniques are more polarization-mode dispersion (PMD) and chromatic dispersion tolerant, support larger amplifier spacing, allow one to re-use existing optical multiplexers and demultiplexers, and allow for a coexistence of lower bit rate and upgraded WDM channels. Polarization division multiplex [2–4] and differential quadrature phase shift keying (DQPSK) transmission [3–9] can each double fiber capacity by their increased spectral efficiencies. Both techniques together allow to transmit 4×10 Gbit/s per WDM channel [3, 4]. Interestingly, a spectral efficiency of 1.6 bit/s/Hz has also been achieved by DQPSK alone recently [10]. However, orthogonal polarizations had to be used for adjacent WDM channels. This channel-packing method suffers from PMD and is impractical to implement with today's optical multiplexers which do not maintain polarization.

We therefore see a greater potential in the inclusion of polarization division multiplex where the mentioned difficulties are relaxed or nonexistent. DQPSK combined with polarization division multiplex and automatic polarization demultiplex at the receiving end is therefore the basis for the present contribution. 4×40 Gbit/s are transmitted over each WDM channel with bit error ratios (BERs) below the forward error correction (FEC) threshold. Advanced FEC technology indeed relaxes the transmission constraints imposed on systems operating at 10 Gbit/s and beyond [11].

2 Transmission setup

Figure 1 shows a return-to-zero (RZ) DQPSK polarization division multiplex, 16×4×40 Gbit/s transmission setup, similar to Bhandare et al. [9]. Sixteen WDM signals (192.2–193.7 THz) with about 100 GHz channel spacing are combined with equal polarizations, and are modulated together. The electrical part of the transmitter features a 16:1 multiplexer that combines 16 2.5 Gbit/s sub-channels, mutually delayed by multiples of 8 bit. The resulting 2^7-1 PRBS data stream is impressed onto the optical signals in a dual-drive Mach-Zehnder modulator. This generates a nonreturn-to-zero

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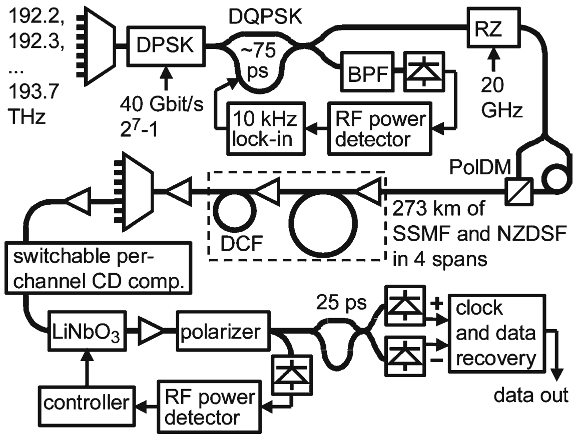

Fig. 1 16×4×40-Gbit/s per channel, RZ-DQPSK polarization division multiplex transmission

(NRZ) differential phase shift keying (DPSK) optical signal.

A DQPSK signal is formed in a subsequent all-fiber temperature-stabilized Mach-Zehnder interferometer with a differential delay τ of about three symbol durations (~75 ps). Three symbol durations are enough to decorrelate the two quadratures while not introducing excessive phase noise due to source laser linewidth. A piezo fiber stretcher inserted into one of the interferometer arms is used to control the phase difference actively. 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 minimum interference and hence lowest RF power. A quadrature control loop based on a 10 kHz lock-in detection scheme stabilizes the interferometer phase difference by minimizing the RF power. The depth of the 10 kHz phase modulation is only ~0.01 rad (rms). In a possible variant of this stabilization scheme, an RZ modulator would have to be placed before the data modulator, and the only intensity modulation remaining after perfect DQPSK signal generation would be the clock frequency, which is outside the detection bandwidth.

The remaining laser frequencies are fine-tuned to other points of a $1/(2\tau) \approx 6.7$ GHz raster so that each WDM channel contains a proper NRZ–DQPSK signal. The channel spacing is roughly an odd multiple of the raster point spacing. As a consequence, each WDM channel has at least one neighbor where in-phase and quadrature data streams are combined with opposite polarities, hence a different optical pattern. This results in an exchange of the corresponding in-phase and quadrature data streams after delay demodulation.

In the transmitter, another dual-drive Mach-Zehnder modulator driven at half the clock rate carves 8-ps wide RZ pulses for transmission. Finally, the RZ-DQPSK signal is split and differentially delayed by 112 symbol durations (~2.8 ns) and recombined with orthogonal polarizations. Because 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 [12].

The optical signals are transmitted over four fiber spans $(81+69+60+63$ km) with a total length of 273 km, consisting of 153 km of standard single-mode fiber (SSMF) and 120 km of nonzero dispersion-shifted fiber (NZDSF). Dispersion-compensating fiber (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. No attempt was made to optimize the chromatic dispersion map of the transmission fiber. The optical spectra before and after 273 km of fiber are shown in Fig. 2.

The receiver contains optical preamplifiers and a flat top C band dense WDM demultiplexer. Per-channel chromatic dispersion compensation is applied by means of switchable short pieces of DCF. Automatic polarization control is implemented in the receiver to recover either of both orthogonal polarizations. A $LiNbO_3$ polarization controller is followed by a polarizer. The control strategy is again based on the minimization of the broadband RF interference noise. RF noise occurs when both polarizations are present after the polarizer. The interference noise is detected in another 12 GHz photoreceiver followed by an RF power detector. The measured RF power is -22 dBm in the best case (when the two polarizations are well aligned) and -8.5 dBm in the worst case (when both polarizations pass the polarizer with equal powers). Figure 3 shows the electrical interference spectra measured in a 12 GHz photoreceiver after the polarizer for the best and worst cases. Signal acquisition takes ~1 s, and this is fast enough to track occurring fiber polarization changes.

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 to either 45° or 135°, using a piezo fiber stretcher.

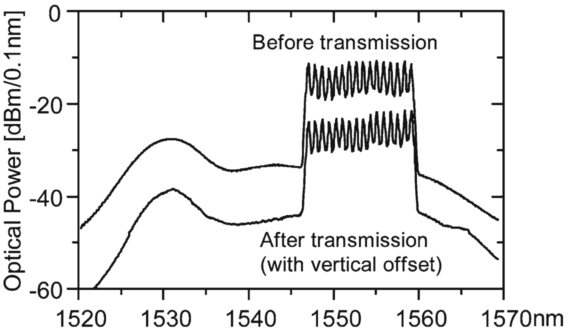

Fig. 2 Optical spectra before and after 273 km of fiber, consisting of 16×160 Gb/s RZ-DQPSK polarization division multiplex signals

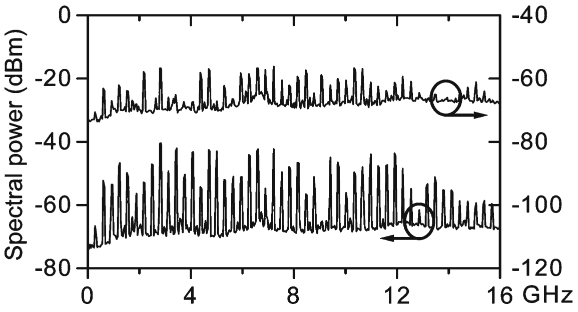

Fig. 3 Electrical interference spectra measured in the 12 GHz photoreceiver after the polarizer

The interferometer outputs are connected to two high-speed photodetectors. For balanced detection, they are directly connected to the differential inputs of a clock and data recovery with a subsequent 1:16 demultiplexer. Due to the differential demodulation, the demodulated bit patterns in the in-phase (I) and quadrature (Q) data channels differ from the transmitted ones. The half rate clock signals in the transmitter and receiver are generated by voltage-controlled oscillators (VCO).

3 Results and discussion

The receiver sensitivity for a BER $< 10^{-3}$ of each of the 16 signals was measured back to back in one quadrature and one polarization (Fig. 4 bottom). The sensitivities range from −32.3 to −28.2 dBm, these powers referring to the whole 160 Gbit/s signal. After transmission through the fiber, the channel OSNRs range from 24 to 30 dB (Fig. 4 top).

Figure 5 shows measured BERs, expressed as Q factors

$$\left(\mathrm{BER} = 1/2\,\mathrm{erfc}\left(Q/\sqrt{2}\right)\right)$$

in dB (Q[dB] = 20 log Q), for in-phase and quadrature data channels in both polarizations. Back-to-back most channels are (quasi) error-free but some yield BER ~ 10^{-9}, most likely due to large laser linewidths in the order of 10 MHz. After 273 km a BER $< 10^{-3}$ is reached in all cases. The corresponding Q factors of at least 10 dB exceed the threshold of a concatenated FEC RS(255,247) + RS(255,239) code with ~7% redundancy, necessary to achieve a decoded BER better than 10^{-13} [11]. The corresponding net data rate is 149 Gbit/s per WDM channel, and the spectral efficiency or information density is 1.49 bit/s/Hz.

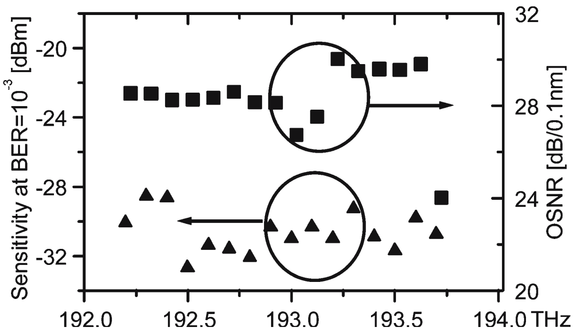

Fig. 4 160 Gbit/s receiver sensitivity at BER = 10^{-3} (*bottom*), and OSNRs after transmission (*top*)

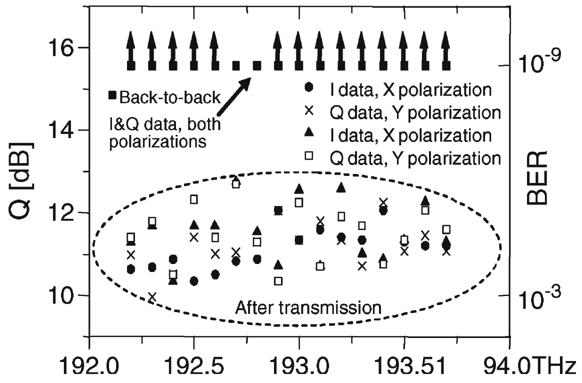

Fig. 5 Measured BERs, expressed as Q factors, for I and Q data channels in both polarizations, before and after transmission

As the single-channel BER in a similar experiment [9] was $< 10^{-9}$, the observed WDM BER performance is believed to be influenced by channel interaction. Raman gain, which is not available, could relieve the optical power constraints, in order to allow for transmission over longer spans.

Figure 6 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 disconnected from the receiver, and only the transmitter clock was therefore available for triggering.

As the signal is transmitted, the in-phase part of the optical amplifier noise modulates the pulse amplitudes. Self phase modulation converts this into a random phase modulation, which limits permissible link lengths. This nonlinear phase noise is described in Ref. [13]. It scales with the square of the length and linearly with the symbol rate (taking into account that the linewidth

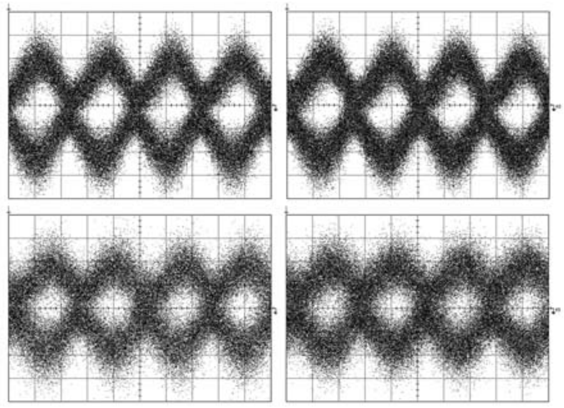

Fig. 6 40 Gbit/s RZ-DQPSK eye patterns of one quadrature in both polarizations, back-to-back (*top*) and after transmission (*bottom*)

tolerance also scales linearly with the symbol rate). In practice, the use of FEC relaxes this problem.

Separate modulation and optical filtering at the transmitter side could probably result in a yet reduced optical channel spacing, hence an increased spectral efficiency; however, this was not tried.

3.1 Conclusion

We have transmitted a net 2.38 Tbit/s data rate on 16 100-GHz-spaced WDM channels. Data are carried in two polarizations and are differentially encoded in two quadratures per WDM channel; fiber capacity is thereby roughly quadrupled. The line rate is only 40 Gbaud (including an assumed 7% FEC overhead), which is advantageous for a high dispersion tolerance.

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