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1.6-b/s/Hz 160-Gb/s 230-km RZ-DQPSK Polarization Multiplex Transmission With Tunable Dispersion Compensation

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***Abstract*—A 160-Gb/s (4 × 40 Gb/s) return-to-zero differential quadrature phase-shift keying polarization-division multiplex transmission is demonstrated with $Q > 15.6$ dB in one of eight 100-GHz-spaced wavelength-division-multiplex channels after 230 km of fiber. Residual chromatic dispersion (CD) is equalized by a thermally tunable CD compensator for the 192.5-THz channel. Polarizations, in-phase and quadrature data channels are demultiplexed using a $LiNbO_3$-based automatic polarization control and a 1-bit interferometer, respectively.**

***Index Terms*—Differential quadrature phase-shift keying (DQPSK), polarization-division multiplex (PolDM), tunable chromatic dispersion (CD) compensation, wavelength-division multiplex (WDM).**

I. INTRODUCTION

DIFFERENTIAL quadrature phase-shift keying (QPSK) [1]–[6] and polarization-division multiplex (PolDM) [7] transmission each double fiber capacity by their increased spectral efficiency. Both techniques have been combined to transmit 4 × 10 Gb/s per wavelength-division multiplex (WDM) channel [8]–[10].

At 40 Gb/s, chromatic dispersion (CD) is the main limiting factor, as the system tolerance is reduced to 1/16 of that at 10 Gb/s [10]. Temperature changes can lead to variations in dispersion that may be significant enough to degrade system performance. Therefore an accurate, tunable CD compensation is often required. Among various integrated optical dispersion compensators demonstrated so far, the fiber Bragg grating (FBG)-based compensators exhibit the largest dispersion and lowest insertion loss with an associated tunability [11], [12].

In this letter, a 160-Gb/s (4 × 40 Gb/s) transmission system is realized by combining DQPSK with PolDM for the first time at a line rate of 40 Gbaud. The fiber capacity equals 1.6 b/s/Hz, which value has previously been achieved or surpassed only at 10 Gbaud [8]–[10].

II. TRANSMISSION SETUP

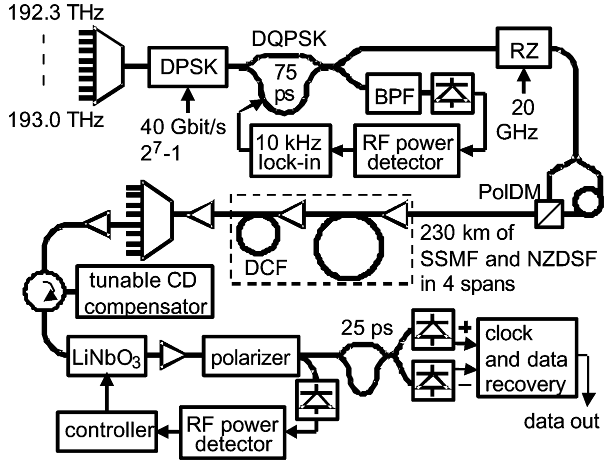

Fig. 1. 4 × 40 Gb/s per channel, RZ-DQPSK, PolDM transmission.

Fig. 1 shows the return-to-zero (RZ)-DQPSK PolDM 4 × 40 Gb/s per WDM channel transmission setup. Eight 100-GHz-spaced WDM signals $(192.3, \ldots, 193.0 \text{ THz})$ are combined with equal polarizations and are modulated together. The transmitter employs a 16 : 1 multiplexer which processes 16 2.5-Gb/s $2^7 - 1$ PRBS data streams, mutually delayed by multiples of 8 bits, and modulator drivers for a dual drive differential phase-shift keying (DPSK) modulator. There is a yet unresolved word length dependence which likewise affects amplitude shift-keying signals. The 2 × 40 Gb/s DQPSK signals are generated in a subsequent all-fiber temperature-stabilized Mach–Zehnder interferometer with a differential delay of three symbol durations. This delay is high enough for decorrelating the data streams but avoids vibration and laser linewidth-induced differential phase fluctuations. The polarization-dependent phase shift is <500 MHz and the extinction ratio is ~24 dB. A piezo fiber stretcher is included in one of the arms for active phase control. At one interferometer output, a 192.5-THz optical bandpass filter, a photoreceiver with a bandwidth of about 12 GHz, and a subsequent radio-frequency (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 10-kHz phase modulation has a depth of ~0.01 rad (root mean square). The interferometer delay is roughly a half-integer multiple of the inverse channel separation. This means that in-phase and quadrature data streams are usually combined with alternating

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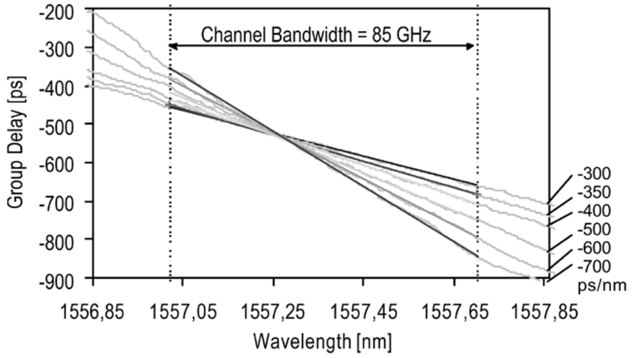

Fig. 2. Group delay versus wavelength in tunable CD compensator for various dispersion settings.

polarities from one WDM channel to the next. The channel spacing is fine-tuned so that each WDM channel contains a proper DQPSK signal. A dual-drive modulator driven at half the clock rate carves 8-ps pulses and thereby generates the RZ-DQPSK signal for transmission.

In order to increase the data rate from 80 to 160 Gb/s per channel, the DQPSK signal is split and recombined with orthogonal polarizations with a differential delay of 2.8 ns. Since this polarization multiplexer (PolDM) was available, interleaving of orthogonally polarized pulses in the time domain was not tested.

The optical signals are transmitted over four fiber spans with 81.3 km of standard single-mode fiber (SSMF), 25.1 km of SSMF, 60.1 km of nonzero dispesion-shifted fiber, and 63 km of SSMF, respectively ($\sim$230 km in total). Dispersion-compensating fiber (DCF) with dispersions of -1345, -685, and -683 ps/nm is inserted insid^{e} first t° third inline erbium-doped fiber amplifier (EDFA) pair, respectively (-2713 ps/nm in total). Fiber and DCF launch powers are $-0.5, \ldots, +4$ dBm and $-4.8, \ldots, -3$ dBm per WDM channel, respectively. EDFA input powers are $-15, \ldots, -10.5$ dBm per WDM channel.

The receiver contains optical preamplifiers and a flat top C-band dense WDM demultiplexer. To receive the 192.5-THz (1557.366 nm) channel, a thermally tunable dispersion compensator (TDC) is used. It is based on an FBG and is coupled via a circulator. It is set to -440 ps/nm, while the total tuning range is -300 to -700 ps/nm. Group delay versus wavelength for various settings is shown in Fig. 2. Other WDM channels are not compensated because only a single-channel TDC was available.

Automatic polarization control is implemented in the receiver to recover both polarizations. A $\mathrm{LiNbO_3}$ polarization controller is followed by a polarizer. The control strategy is again based on the minimization of the broad-band RF interference noise. It 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). The controller tries to minimize the interference noise by suppressing the unwanted polarization in the fiber polarizer. Signal acquisition takes $\sim$1 s, and this is fast enough to track occurring fiber polarization changes.

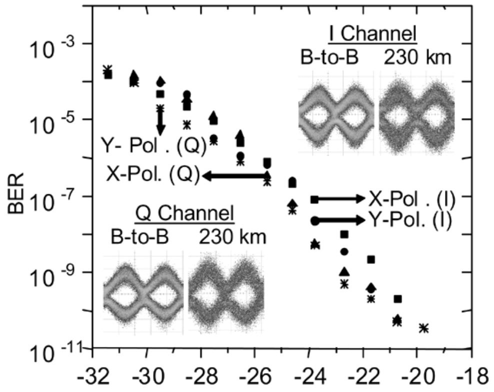

Fig. 3. Back-to-back receiver sensitivity and eye diagrams (before and after transmission) for both in-phase and quadrature data channels for one polarization. Optical power is given for aggregate 160-Gb/s signal.

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, which in turn are connected to the differential inputs of a 1 : 16 demultiplexer with standard clock and data recovery. Note that 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 voltage controlled oscillators.

III. TRANSMISSION RESULTS AND DISCUSSION

Fig. 3 shows the recorded back-to-back sensitivities of the 4×40 Gb/s 192.5-THz signal, for which the TDC was operational. For a bit-error rate (BER) of 10^{-9}, the sensitivity is about -22 dBm. At the forward error correction (FEC) threshold, say for a BER of 10^{-3}, it is about -32 dBm.

The eye diagrams corresponding to back-to-back configuration and after transmission over 230 km of fiber are also shown in Fig. 3. The other polarization is very similar. The eye diagrams before and after transmission have identical shapes, which indicates a clean transmission with effective CD compensation. This is remarkable because an extrapolation of the results in [8], and our own experience, tells that DQPSK tolerates less CD than DPSK at the same symbol rate. This can be understood from the smaller distance of the transmitted states in the complex plane.

Fig. 4 shows Q-factors, directly calculated from the measured BER values, for the back-to-back case against the optical signal-to-noise ratio (OSNR). The OSNR is determined in an 0.1-nm bandwidth by comparing the spectral peak against the surrounding noise. To reach $Q = 15.6$ dB, the required OSNR is about 33 dB. At the FEC threshold, the required OSNR is about 22 dB.

Fig. 5 shows measured back-to-back Q-factors, calculated from BER measurements, for I and Q data streams for all eight WDM channels. A $Q \geq 15.6$ dB or BER $\leq 10^{-9}$ is achieved for all channels, polarizations, and quadratures. After 230 km of fiber, a BER $\leq 10^{-9}$ is obtained for the 192.5-THz channel with CD compensation. Corresponding data, expressed

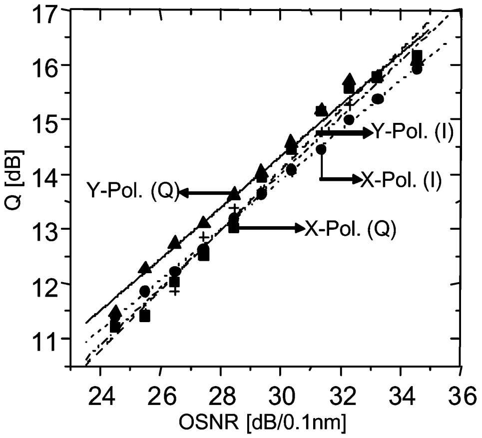

Fig. 4. Back-to-back performance of 4 × 40 Gb/s system.

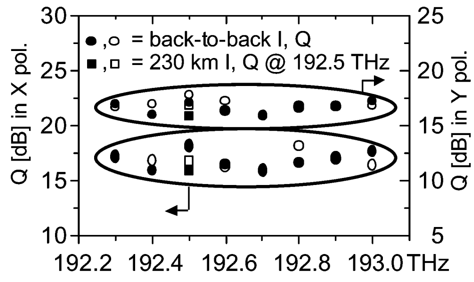

Fig. 5. Measured Q-factors for I and Q data channels in both polarizations back-to-back for eight WDM channels, and after transmission over 230-km fiber for the CD-compensated 192.5-THz channel.

as Q-factors, is also given in Fig. 5. The presence of the other WDM channels confirms that the capacity is 1.6 b/s/Hz. Simultaneous BER measurement of all WDM channels would require a broad-band dispersion compensator [10]. If FEC is available, amplifier spacing and/or WDM channel number are expected to be expandable. System stability was limited to $\sim$1 min due to insufficient thermal isolation of the receiver interferometer. Recently, the receiver interferometer has been packaged with styrofoam, which has drastically improved the system stability. However, long-term stability has not yet been assessed.

By only using a 100-GHz channel spacing, a 1.6-b/s/Hz spectral efficiency is achieved. In [4], a 70-GHz spacing was used for 2 × 42.7 Gb/s DQPSK transmission. Combining such a channel spacing with PolDM should make spectral efficiencies beyond 2 b/s/Hz possible.

IV. CONCLUSION

We have transmitted 160 Gb/s (4×40 Gb/s) on each of eight 100-GHz-spaced WDM channels. Data is carried in two polarizations and differentially encoded in two quadratures. Fiber capacity per WDM channel is, therefore, quadrupled. A 1.6-b/s/Hz transmission over 230 km of fiber is achieved with $Q > 15.6$ dB for one of the eight WDM channels for which the TDC is operational.

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