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Transmission of a Serial 5.1-Tb/s Data Signal Using 16-QAM and Coherent Detection

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Abstract: Generation, transmission and coherent detection of a 640-GBd RZ-16-QAM, polarization-multiplexed OTDM signal is demonstrated. Considering 7% hard decision FEC overhead, error-free transmission of 4.8 Tb/s is achieved over 80 km dispersion-managed fiber.
OCIS codes: (060.2330) Fiber optics communications; (320.7160) Ultrafast technology; (060.1660) Coherent communications

1. Introduction

Optical time-division multiplexing (OTDM) technique is a simple method for high-speed data generation beyond the bandwidth limitation of electronics. Here, different optical pulse streams, called tributaries, originating from the same laser (same central wavelength), are separately encoded by electrically generated data signals. Due to the low duty-cycle of their pulses the tributaries are serially bit interleaved in order to form the OTDM data signal. By using this technique, single channel transmission with a symbol rate of 640 GBd has been demonstrated in 1998 employing on-off keying (OOK) data modulation [1]. With the same symbol rate, the single channel bit rate has been increased to 1.28 Tb/s using polarization multiplexing [2], and to 2.56 Tb/s using polarization multiplexed differential quadrature phase-shift keying (DQPSK) [3]. Transmission of higher symbol rates (1.28 TBd) was reported by applying differential phase-shift keying (DPSK) [4]. Recently, 16-ary quadrature amplitude modulation (16-QAM) of a 1.28 TBd signal has been demonstrated by using an ultrafast coherent receiver with a pulsed local oscillator (LO) [5]. Despite having indicated the feasibility of 29-km transmission, this proof-of-concept experiment applied LO pulses originating from the same laser as the data signal which is not practical for transmission system applications.

In this paper, we demonstrate error-free transmission of a serial 5.1-Tb/s data signal over 80 km of dispersion-managed fiber (DMF) by using an ultrafast coherent receiver including a separate optical LO pulse source. The data signal is generated by return-to-zero (RZ) 16-QAM modulation, OTDM to a symbol rate of 640 GBd and additional polarization multiplexing. The signal is simultaneously demultiplexed and demodulated in the coherent receiver by using a pulsed LO, which is generated from a separate pulse source within the coherent OTDM receiver. Assuming 7% hard decision FEC overhead, error-free performance of the 5.1-Tb/s data signal (net 4.8 Tb/s) was achieved after 80-km transmission for all 128 OTDM tributaries (both polarizations).

2. Experimental Setup

Fig. 1 shows the experimental setup. It is composed of the 5.1-Tb/s transmitter, the 80-km DMF and the coherent receiver. At the transmitter a mode-locked solid state laser (MSSL) produces a pulse train having 1.2-ps full-width at half-maximum (FWHM), 10-GHz (STM-64) repetition rate and is centered at 1550 nm. The pulses are amplified to 21.5 dBm and injected into a 250 m long highly-nonlinear fiber with attenuation $\alpha = 0.78$ dB/km, dispersion $D = -0.49$ ps/(nm·km), slope $S = 0.0061$ ps/(nm²·km) at 1550 nm and nonlinear coefficient $\gamma = 10\ (\text{W}\cdot\text{km})^{-1}$. The optical spectrum is broadened due to self phase modulation (SPM), resulting in a broad supercontinuum exceeding 40 nm. The supercontinuum is offset filtered by a flat-top 20-nm optical band pass filter (OBPF) centered at 1555 nm and is subsequently modulated in an in-phase and quadrature modulator (IQ-Mod.).

The IQ modulator is driven by a two-channel arbitrary waveform generator which was programmed to generate a

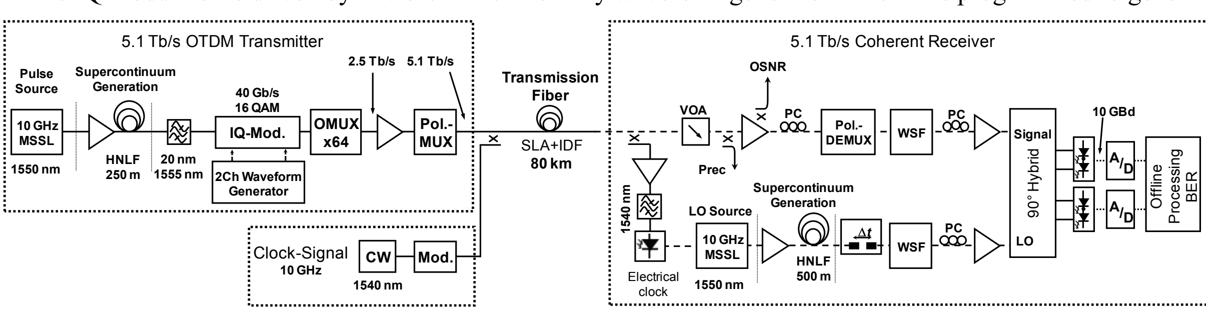

Fig. 1: Schematic depiction of the experimental setup.

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16-QAM modulation (De Bruijn sequence of 2^{15} before symbol mapping) resulting in a 40 Gb/s data signal. This data signal is time interleaved up to 640 GBd (2.5 Tb/s) in a fiber-based delay line multiplexer (OMUX). At the last stage of the transmitter, the signal passes through a polarization multiplexer, based on a polarization beam splitter to divide the signal in two branches, which are decorrelated via a fiber delay in one branch and recombined using a polarization maintaining coupler. The combination of 16-QAM and 128-fold optical multiplex enables the total data capacity of 5.1 Tb/s, with an optical signal-to-noise ratio (OSNR) at the output of the transmitter of 46 dB. The signal is then launched into an 80-km transmission link together with a 10-GHz clock signal at 1540 nm.

The 80-km DMF link (kindly provided by OFS Denmark) consists of 55.7 km super large area fiber SLA (D = 20 ps/(nm·km), S = 0.06 ps/(nm²·km)) and 23.5 km inverse-dispersion fiber IDF (D = -47.8 ps/(nm·km), S = -0.15 ps/(nm²·km)). The link has a differential group delay (DGD) of 0.3 ps and a total loss of 17.6 dB. The polarization state of the data signal was aligned with the principal polarization axes of the fiber, in order to mitigate degrading effects of polarization mode dispersion (PMD).

In the pre-amplified receiver the 10-GHz transmitted clock is extracted via a 10-dB coupler and a 1.2-nm 3-dB bandwidth OBPF. The extracted clock is detected by an optical 10-GHz receiver and then used to synchronize the separate MSSL, which is used as LO in the coherent receiver. The LO MSSL produces 10-GHz (STM-64) pulses with 1.8-ps FWHM and centered at 1550 nm. The LO is amplified to 23.4 dBm and injected in a 500 m long HNLF having the same properties as the one used to generate the supercontinuum at the transmitter. The broad spectrum resulting from SPM is subsequently reshaped by a waveshaping filter (WSF, Finisar WaveShaper 4000S). A tunable time-delay is used to align the LO pulses with any TDM tributary within the 5.1 Tb/s data signal.

The data path of the pre-amplified receiver consists of a variable optical attenuator (VOA) to vary the received signal power and OSNR, two erbium-doped fiber amplifiers (EDFA), a polarization demultiplexer, a second WSF, a 90°-hybrid, two balanced photo detectors (BPD), two analog-to-digital converters (A/D, 50-GS/s real-time sampling oscilloscope with 20 GHz bandwidth) and a computer for offline processing and BER measurement. The average optical input powers into the 90°-hybrid were 15 dBm and 12 dBm for the data signal and the LO, respectively. The data is recovered by a conventional digital signal processing block comprising resampling, relative carrier frequency offset compensation (data signal with respect to LO) and blind adaptive equalization. After pre-convergence of the equalizer using the constant modulus algorithm, it was switched to a decision-directed least-mean square filter error criterion.

3. Results and Discussion

Fig 2a shows the transmitted spectrum including the 10-GHz clock at 1540 nm and the 20-nm data spectrum, carved out from the broad transmitter supercontinuum. For optimum system performance, the supercontinua generated at the transmitter and LO have to be transformed to achieve the shortest possible pulses on the BPDs. In our setup, this transformation is mediated by the dispersion of the fiber components, the residual dispersion of the fiber link and fine tuning of spectral amplitude and phase profile of the two WSF (signal and LO path). Fig. 2b shows the optical spectra of the 10-GHz LO and the 5.1-Tb/s 16-QAM data signal at the input of the 90°-hybrid, i.e. after spectral reshaping in the WSFs. Both spectra are Gaussian with 6-nm FWHM centered at 1555 nm. The residual phase profile of the link as shown in Fig. 2b was compensated by the phase shaping ability of the WSF in the data path inside the coherent receiver. This allowed precise compensation of the residual dispersion of the link up to the fourth order dispersion (β_2, β_3, β_4) and thus to minimize pulse broadening due to chromatic dispersion (CD). Additionally,

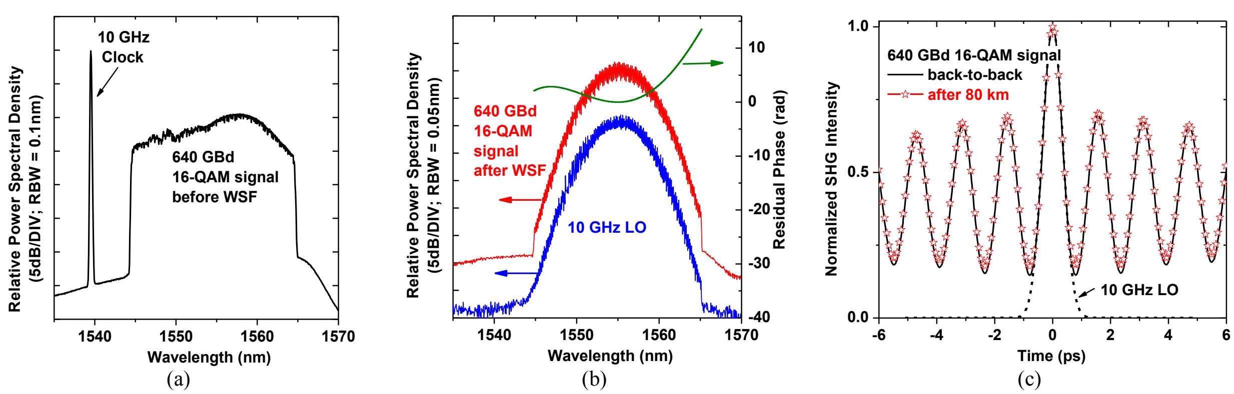
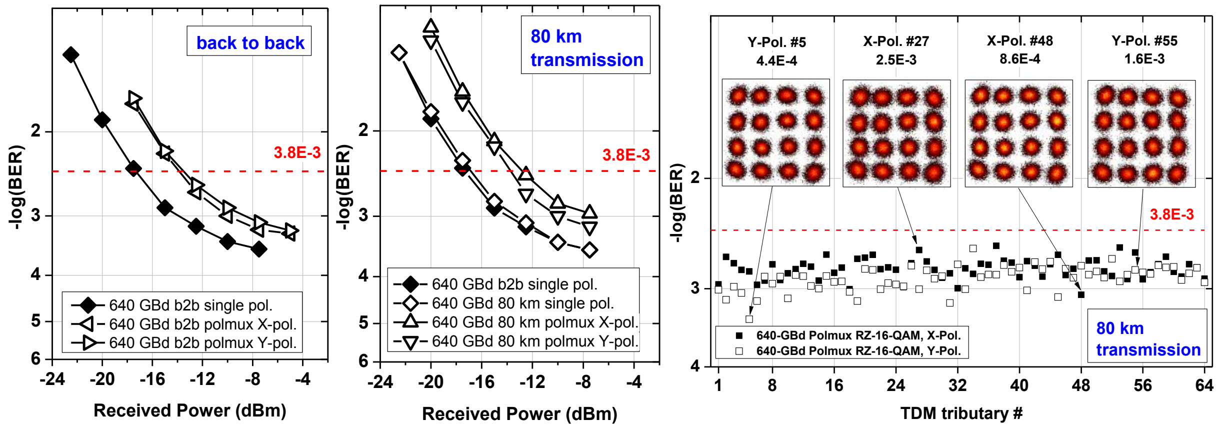


Fig. 2: a) Transmitted optical spectrum including the 10-GHz clock and the 5.1-Tb/s data signal. b) Reshaped optical spectra of the data signal (single polarization) and LO (measured at the input of the 90°-hybrid) as well as residual phase profile of the transmission link (as compensated for by the WSF in the signal path). c) Autocorrelation traces of the compressed 10 GHz LO pulse train (dashed) and of the modulated and optically multiplexed 640 GBd RZ-16-QAM data signal before and after transmission (single polarization).



(a) (b) (c)

Fig. 3: BER measurements. a) Back-to-back BER for one TDM tributary for 640-GBd (2.5 Tb/s) single polarization data signal and after polarization multiplexing (5.1 Tb/s). b) BER for one TDM tributary after 80-km transmission. c) BER for all 128 tributaries (X and Y polarization) of the 5.1-Tb/s data signal after 80-km transmission. The insets show constellation diagrams with BER for selected tributaries.

the data polarization was aligned with the principal axes of the link to minimize pulse broadening due to PMD. The measured degree of polarization (DOP) after transmission over 80-km DMF was found to be 98% (for the single polarization 640-GBd data signal). After full compensation and spectral reshaping as described above, autocorrelation measurements (Fig. 2c) yielded pulse widths of 580-fs FWHM at the BPDs for both, the LO and data signal pulses, assuming Gaussian shapes in the time domain. Besides the compressed 10-GHz LO pulses Fig. 2c also shows the autocorrelation traces of the 640-GBd 16-QAM data signal (single polarization) for the back-to-back case and after 80-km transmission. The traces show negligible pulse broadening due to transmission indicating proper compensation of CD and mitigation of PMD.

Fig. 3a shows the bit-error ratio (BER) as a function of the received optical power (excluding the power in the transmitted clock signal) for the back-to-back case for one of the OTDM tributaries. The required OSNR for a BER = $3.8\cdot10^{-3}$ was 36 dB (at -17.5 dBm) for the single polarization and 40 dB (at -13.7 dBm) for the polarization multiplexed signal. Please note that the OSNR values were measured before spectral shaping of the data signal in the WSF. Fig. 3b shows the BER performance of one OTDM-tributary after 80-km transmission. The input power into the 80-km DMF span was 12.5 dBm. Due to the high symbol rate of the data signal this power did not induce a significant nonlinear penalty for the transmission. Although the required OSNR values were close to the maximum available transmitter OSNR of 46 dB, we attribute the observed error-floor mainly to deterministic relative timing jitter between the two MSSLs used as data and LO source. Fig. 3c shows the measured BER for all 128 OTDM tributaries (both polarizations: X-Pol., Y-Pol.) after 80-km transmission. All tributaries perform below the BER limit of $3.8\cdot10^{-3}$ for hard decision FEC with 7% overhead, thus representing error-free transmission of 4.8-Tb/s net data rate. Examples of constellation diagrams together with the corresponding BER values are shown as insets in Fig. 3c for selected tributaries.

4. Conclusion

We demonstrated error-free transmission over 80 km of dispersion-managed fiber at 5.1-Tb/s serial line rate. The data signal was generated by 16-QAM modulation and 64-fold optical time division multiplexing to a symbol rate of 640 GBd per polarization. The data signal was simultaneously demultiplexed and demodulated in a coherent receiver by using a separate LO pulse source. The BER of all 128 OTDM-tributaries (both polarizations) was found to be below the FEC-threshold of $3.8\cdot10^{-3}$ after 80-km transmission corresponding to an error-free net data rate of 4.8 Tb/s.

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5. References

[1] M. Nakazawa et al., “TDM single channel 640 Gbit/s tranmission experiment over 60 km using 400fs pulse train and walk-off free, dispersion flattened nonlinear optical loop mirror”, El. Lett., Vol. 34, No. 9, pp. 907-908, (1998).
[2] M. Nakazawa et al., “1.28Tbit/s-70km OTDM transmission using third- and fourth-order simultaneous dispersion compensation with a phase modulator”, El. Lett., Vol. 36, No. 24, pp. 2027-2029, (2000).
[3] H. G. Weber et al., “Single Channel 1.28 Tbit/s and 2.56 Tbit/s DQPSK transmission”, El. Lett., Vol. 42, No. 3, pp. 178-179, (2006).
[4] H. Hu et al., “Error-free Transmission of Serial 1.28 Tbaud RZ-DPSK Signal”, ECOC 2010, P4.18
[5] T. Richter et al., “Single Wavelength Channel 10.2 Tb/s TDM-Data Capacity using 16-QAM and Coherent Detection”, OCF 2011, PDPA9