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10,200km 22x2x10Gbit/s RZ-DQPSK Dense WDM Transmission without Inline Dispersion Compensation through Optical Phase Conjugation

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Abstract: Using optical phase conjugation with a polarization independent periodically-poled lithium-niobate subsystem, we demonstrate dense WDM 2x10Gbit/s RZ-DQPSK transmission over 10,200km of SSMF with a record accumulated dispersion, exceeding 80,000ps/nm.

OCIS codes: (060.2330) Fiber optics communications; (070.5040) Phase conjugation

1. Introduction

Optical phase conjugation (OPC) has been shown suitable for the regeneration of intra-channel impairments [1] and nonlinear phase noise [2] in systems employing a periodic dispersion map. Recently, it has been shown that return-to-zero (RZ) differential phase-shift-keying (DPSK) has a good performance in non-periodic inline dispersion maps since it can cope with large amounts of inline accumulated dispersion [3]. Mid-link OPC is an ideal method to avoid inline dispersion compensation. In a mid-link OPC based transmission system, the inline dispersion compensating modules (DCMs) can be omitted, which saves the extra loss through DCMs resulting in a higher OSNR after transmission for an equivalent transmission line. Using mid-link OPC the inline dispersion map is equal in all configurations, hence simplifying link design. When a periodically poled lithium-niobate (PPLN) waveguide is used for OPC, the link is transparent to different modulation formats and data rates [4]. This transparency is particularly appealing for network operators since existing networks can be upgraded without having to replace the equipment, or make changes in the transmission line.

In this paper, we show by using a single polarization independent PPLN subsystem, that dense wavelength-division multiplexed (DWDM) transmission of a 22x2x10Gbit/s RZ differential quadrature phase-shift-keying (DQPSK) signal in combination with mid-link optical phase conjugation is resistant against extreme inline accumulated dispersion, exceeding 80,000ps/nm. This is the first DWDM ultra long-haul transmission experiment using OPC for replacing inline dispersion compensation.

Recently strong interest has been shown in DQPSK transmission, which due to its favorable spectral width and high transmission tolerances at the same line rate as binary modulation is a suitable modulation format to increase the resilience of optical transmission links [5]. However, DQPSK transmission potentially suffers from increased influence of nonlinear phase noise degradation. In the experiments discussed in this paper we show only minor evidence of nonlinear phase noise in DQPSK transmission with mid-link OPC, enabling a record 10,200km transmission distance with this modulation format.

2. Experimental setup

The experimental setup is depicted in Fig. 1. At the transmitter, the output signals of 44 distributed feedback (DFB) lasers on a 50GHz grid are multiplexed by using an arrayed waveguide grating (AWG). The RZ-DQPSK signal is generated with a modulator cascade consisting of two external $LiNbO_3$ modulators. The first modulator is a RZ pulse carver for a 50% duty cycle. The second modulator is an integrated DQPSK modulator with two parallel DPSK modulators with a relative phase shift of $\pi/2$ within a super Mach-Zehnder structure. Two 10.7Gbit/s 2^{15}-1 PRBS sequences (one inverted: data A, one not-inverted: data B) with a relative delay of 5 bits for de-correlation of the bit sequences are used for modulation of the DQPSK signal.

The performance of the polarization-independent optical phase conjugator is tested using a re-entrant re-circulating loop [1]. The re-circulating loop consists of three 94.5km spans of standard single mode fiber (SSMF), with an average span loss of 21.5dB. At the span output a hybrid Raman/EDFA structure is used for signal amplification. The average net Raman gain is -10.3dB which is significantly below the gain required for power symmetry [6]. The total input power into the SSMF is 13.5dBm. No DCMs are used inside the re-circulating loop. The polarization-independence of the PPLN allows the use of a loop-synchronous polarization scrambler (LSPS) to reduce the statistical correlation of loop-induced polarization effects. Power equalization of the DWDM channels is provided by a channel based dynamic gain equalizer (DGE) with a bandwidth of 0.3nm, hence spectral filtering of the signals occurs with every re-circulation.

After 18 re-circulations the signals are fed through the PPLN-subsystem. In this subsystem, the 22 channels from 1532.3nm to 1540.6nm, used to balance the signal in the amplifiers, are removed using a band selection filter (BSF). Subsequently, the remaining 22 channels from 1546.1nm to 1554.5nm are phase conjugated in the PPLN subsystem. At the output of the PPLN subsystem the wavelengths of the channels range from 1532.3nm to 1540.6nm. Finally, the input channels of the PPLN subsystem (ranging from 1546.1nm to 1554.5nm) are recombined with the spectrally inverted channels to balance the signal propagating through another 18 circulations in the re-circulating loop.

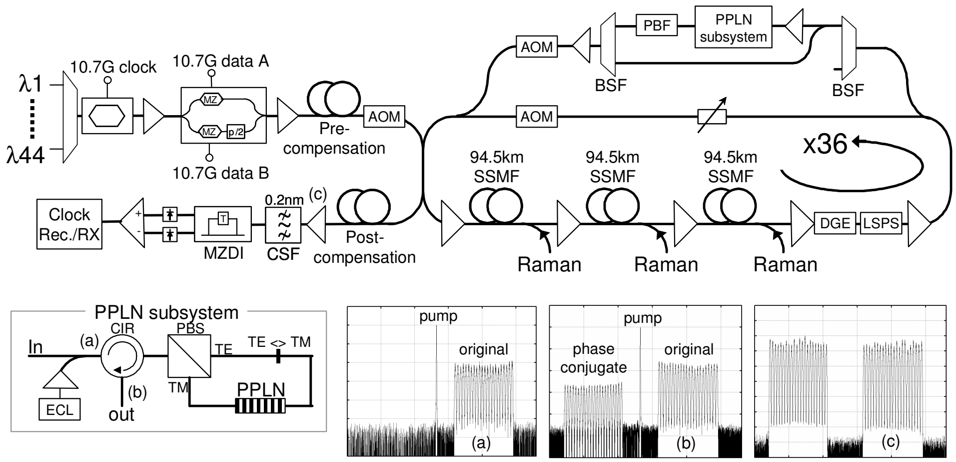

Fig. 1: Experimental setup (DGE: Dynamic gain equalizer, LSPS: Loop-synchronous polarization scrambler, BSF: Band selection filter, PBF: Pump block filter, CSF: Channel selection filter). (a) and (b) Optical spectra at the input and output of the PPLN subsystem, respectively, (c) receiver spectrum

Phase conjugation inside the PPLN waveguide is realized by two quasi phase matched χ^2 processes. A second harmonic from a pump is generated through second harmonic generation. Simultaneously, the second harmonic interacts with the incoming data signal through difference frequency mixing. At the output of the PPLN, the phase conjugated signals are present mirrored with respect to the pump. In Fig. 1 the optical spectra (res. bw. = 0.01nm) are shown before (a) and after (b) phase conjugation.

At the input of the PPLN subsystem, the channel polarizations are randomized by the transmission fiber and the LSPS, hence polarization independence is required. A polarization independent PPLN subsystem is realized by using both directions of propagation in a single PPLN [7]. The layout of the polarization independent PPLN subsystem is depicted in the inset in Fig. 1. A polarization beam splitter (PBS) splits the incoming signal into TE and TM mode independent of the polarization of the input signal. The TM mode is phase conjugated in the PPLN and subsequently rotated to TE mode by a 90 degrees splice. The TE mode is first converted from the TE to the TM mode and afterwards phase conjugated. Both counter propagating modes are recombined at the PBS to effectively create polarization independent phase conjugation. The measured polarization dependent loss of the PPLN subsystem is less then 0.4dB. A continuous wave (CW) pump signal is generated at 1543.4nm using an external cavity laser (ECL) and amplified to 388mW. In order to pump both the directions of the PPLN, the pump is split in a 50%-50% ratio at the PBS. The power of the signal is approximately 10mW per channel at the polarization beam splitter. The conversion efficiency of the PPLN with these powers is -9.2dB. The PPLN waveguide used for OPC operates at 202.3° Celsius in order to reduce the photorefractive effect. After transmission, the dispersion is optimized on a per-channel basis and the channels are filtered with a 0.2nm channel-selection filter (CSF). After a one-bit (94ps) Mach-Zehnder delay interferometer (MZDI) and a balanced detector, the performance of the signal is evaluated using a bit-error-rate test set (BERT), programmed for the expected output sequence. The BER is evaluated for the 22 phase conjugated channels. A second PPLN subsystem would be required to conjugate and measure the other 22 channels.

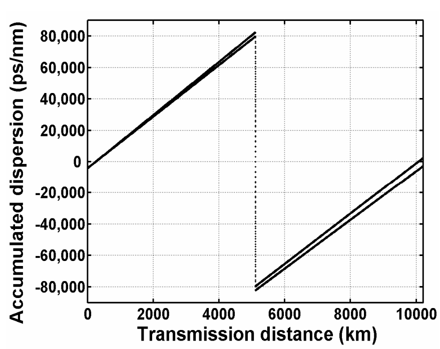

Fig. 2: Dispersion map for channel 1 and 22 of the transmission line.

3. Dispersion map

In Fig. 2 the dispersion map of the 10,200km transmission line for the 22 evaluated channels is depicted. In the first 5,100km, before the OPC, the accumulated dispersion of the signals increases to 79,600ps/nm and 82,400ps/nm for channels 1 (1546.1nm) 22 (1554.5nm), respectively. At the optical phase conjugator, all signals are mirrored with respect to the pump and the sign of the accumulated dispersion is inverted. Due to the SSMF slope of 0.063ps/nm^2/km the channels experience a different dispersion in the second half than in the first half of the link. As a result, after 10,206km, the difference in accumulated dispersion between channel 1 and channel 22 is 5206ps/nm. The amount of pre-compensation (-4082ps/nm) is chosen such that the required post compensation is centered around 0ps/nm for all channels.

4. Experimental results

Fig. 3 shows the measured Q-factor of a typical channel (in-phase at 1535.1nm) as a function of the transmission distance. Q values are measured from 1,700km up to 10,770km by adjusting the number of loop re-circulations. Eye diagrams of the balanced receiver are inserted for 2,835km, 7,940km and 10,200km. Fig. 4 depicts the Q-factor of both the in-phase and quadrature channels after 28 (7,940km) and 36 (10,200km) circulations through the re-circulating loop.

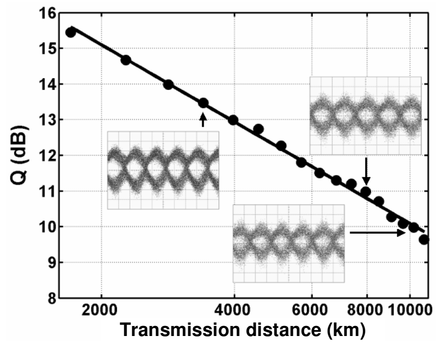

Fig. 3: Q-factor of a typical channel (1531.1nm) as a function of the transmission distance

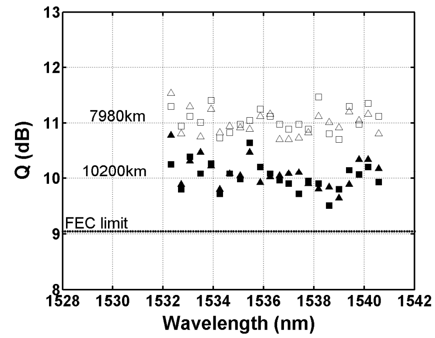

Fig. 4: In-phase and quadrature Q-factors of all 22 channels
After 7,940km I/Q: □/△ after 10,200km I/Q: ■/▲

The worst Q-factors are 10.7dB and 9.5dB after 7,940km and 10,200km transmission, respectively. Both in-phase and quadrature components show similar BER performance. For the 7,940km transmission experiment a 1.5dB margin is measured with respect to a forward error correction (FEC) threshold of a concatenated code with a 7% redundancy, for which a Q of 9dB corresponds to performance after FEC with a Q-factor of >16.9 [8]. When the transmission distance is increased to 10,200km, the measured Q-factors of all channels are still well above the FEC limit. The received OSNR of all channels after 10,200km transmission is 13.5dB on average, which corresponds to a 4dB OSNR penalty compared with back-to-back performance. For DQPSK transmission this is a small penalty due to nonlinear signal distortions and nonlinear phase noise [5]. We conjecture that the nonlinear phase noise is reduced in the experiment through mid-link OPC, as further studied in [2].

4. Conclusion

In this paper we show with a single polarization-independent PPLN subsystem successful 22x2x10.7Gbit/s RZ-DQPSK DWDM transmission without inline dispersion compensation over 10,200km. The 4dB OSNR penalty after transmission compared with back-to-back is an acceptable penalty due to signal distortions and nonlinear phase noise, which indicates a reduction of nonlinear phase noise through mid-link OPC. This transmission experiment is the longest OPC transmission experiment to date, compensating for a record accumulated dispersion exceeding 80,000ps/nm.

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