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# Transmission of 42.8-Gbit/s RZ-DQPSK over 42x94.5-km SSMF spans using Optical Phase Conjugation and EDFA only amplification

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**Abstract** *We show that in a transmission system with terrestrial fiber spans (94.5 km) and EDFA only amplification, long-haul transmission can be realized using optical phase conjugation. In this experiment, 42.8-Gbit/s RZ-DQPSK with 0.8-bit/s/Hz spectral efficiency is transmitted over 3,970-km SSMF.*

## Introduction

Mid-link optical phase conjugation (OPC) is a method to simplify the transmission system and improve its robustness towards nonlinear impairments [1]. In such a transmission link, the phase of the signals is conjugated mid-link. At that point, the signal is severely distorted by chromatic dispersion and nonlinear impairments. As a result, the distortions that occur in the second part of the link after the OPC revert the impairments that were accumulated in the first part.

The degree in which nonlinear impairments are compensated for is dependent on the symmetry of the signal's power envelope with respect to the OPC [2]. The power symmetry of a transmission link can be increased by using Raman amplification [3, 4] or by making adjustments on the dispersion map of the transmission line [5]. So far, most long-haul OPC transmission experiments reported are conducted with Raman amplification to reduce the power asymmetry.

In this paper the transmission performance of OPC transmission is assessed in a link with only erbium-doped fiber amplifiers (EDFA) for amplification, hence creating a strongly asymmetric power profile. We report transmission of wavelength division multiplexed (WDM) 42.8-Gbit/s return-to-zero differential quadrature phase-shift-keying (RZ-DQPSK) over 3,970-km of standard single mode fiber (SSMF). This is the first long-haul 40-Gbit/s OPC transmission experiment using EDFAs only for amplification.

## Experimental setup

The experimental setup is depicted in Fig. 1. Eighteen continuous wave channels on a 50-GHz grid are modulated by two parallel modulator chains. Each modulator chain consists of a pulse carver and a parallel DQPSK modulator. The pulse carver Mach Zehnder modulator (MZM) is fed with 21.4 GHz so that a pulse with a 50% duty cycle is created. The second modulator is an integrated DQPSK modulator with two parallel MZMs within a super Mach-Zehnder structure. A 21.4-Gbit/s data stream is created by electrically multiplexing two 10.7-Gbit/s PRBS signals with a length of $2^{15}$-1 and a relative delay of 16 bits. This 21.4-Gbit/s data stream is split and fed to both inputs of the 42.8-Gbit/s DQPSK modulator with a relative delay of 10 bits of the bit sequences for de-correlation. After modulation, the even and odd channels are combined with a 50-GHz interleaver. A polarization beam splitter (PBS) ensures that all channels are co-polarized for worst-case interaction.

The transmission line consists of three 94.5-km spans of SSMF with a chromatic dispersion of ~16 ps/nm/km and an average span loss of about 20 dB. The loss of the SSMF spans is compensated for by EDFAs without mid-stage access. A loop-synchronous polarization scrambler (LSPS) is used to reduce the statistical correlation of loop-induced polarization effects. Power equalization of the WDM channels is provided by a channel based dynamic gain equalizer (DGE).

The signals are optically phase conjugated in the middle of the transmission link. In the re-entrant re-

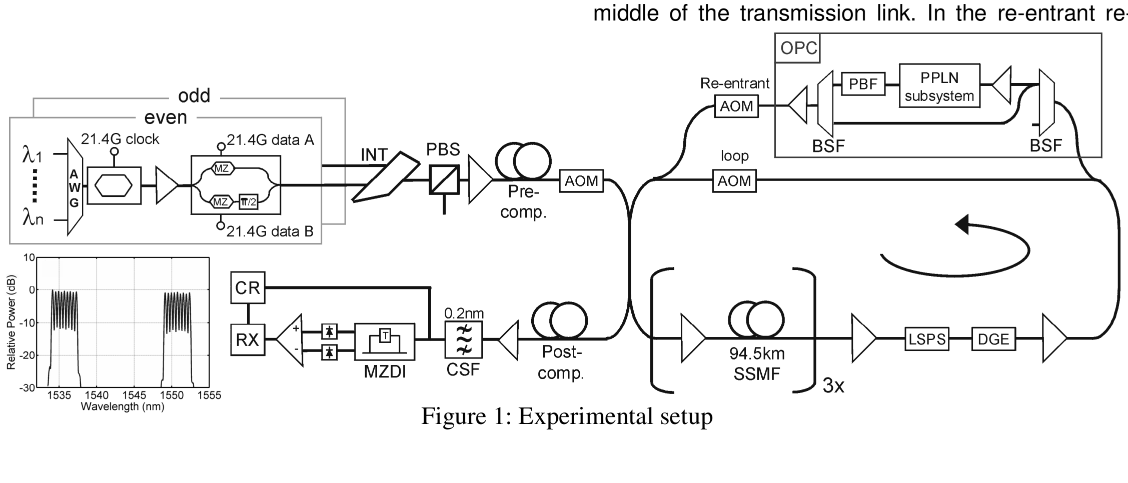


Figure 1: Experimental setup

circulating loop structure this is realized after half the re-circulations by opening the loop acousto-optic modulator (AOM) and closing the re-entrant AOM for one re-circulation. Hereby the signals are fed through the OPC subsystem. In this subsystem, the nine channels from 1534.25 nm to 1537.40 nm, used to balance the signal in the amplifiers, are removed using a BSF. Subsequently, the remaining nine channels from 1549.32 nm to 1552.52 nm are phase conjugated in the periodically-poled lithium-niobate (PPLN) subsystem. At the output of the PPLN, the phase conjugated signals are present mirrored with respect to the pump and range from 1534.25 nm to 1537.40 nm.

After transmission, the residual dispersion is optimized on a per-channel basis with a 10 ps/nm granularity. Subsequently a narrowband 0.2-nm CSF is used to select the desired channel. After the CSF, the signal is split and one part is used for clock recovery. The other part is fed to the two-bit (94 ps) MZDI followed by a balanced detector. After the balanced detector, the signal is de-multiplexed from 21.4 Gbit/s to 10.7 Gbit/s and evaluated using a BER-tester programmed for the expected bit sequence. The de-multiplexer is automatically reset every loop re-circulation, hence the measured BER corresponds to the average BER of both 10.7-Gbit/s tributaries.

**Experimental results**

The optimal launch power into the SSMF is determined by varying the launch power per channel from -6 dBm to +4 dBm after 1,700-km transmission (6 circulations through the re-circulating loop). The Q-factor as a function of the launch power is depicted in Fig. 2 for the center channel (1535.8 nm after conjugation). The optimal launch power is found to be 0 dBm, which is ~3 dB higher than the input power used in the same transmission experiment with 10-dB Raman gain per span (described in [6]).

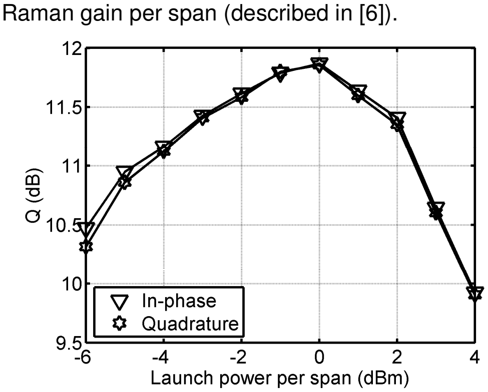


Fig. 2: Q-factor as a function of the launch power per channel into the SSMF

The Q-factor of the center channel (1535.8 nm after conjugation) as a function of the transmission distance is depicted in Fig. 3. As a reference, the performance with Raman amplification is depicted as well. The input power of the EDFA only system is ~3 dB higher than the input power used in the transmission link with Raman amplification. Furthermore, the power envelope in the EDFA only scheme is significantly less symmetric than the Raman aided configuration. However, both configurations show a linear decrease of the Q-factor with exponential increase of the transmission distance.

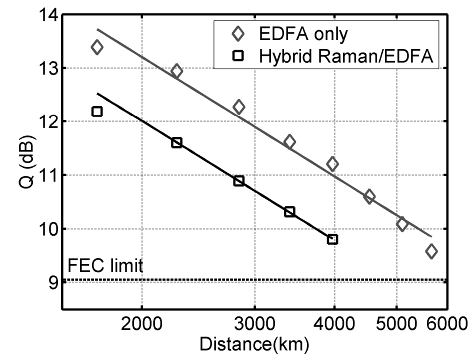


Fig. 3: Q-factor as a function of the transmission distance

After 3,970 km transmission, a Q-factor of 9.8 dB is obtained in the EDFA only configuration. Through Raman amplification, the OSNR after transmission is improved and the power symmetry of the transmission link is increased. With Raman amplification a Q-factor of 9.8 dB is obtained after approximately 5,500-km of transmission. Hence through Raman amplification an improvement in transmission distance of only 1.4-dB is obtained. It can thus be concluded that even in the asymmetric power configuration of the EDFA only transmission system, long-haul transmission can be realized through mid-link OPC with a limited penalty.

**Conclusions**

In a transmission link with a strongly asymmetric power profile, transmission of 42.8-Gbit/s RZ-DQPSK is realized over 3,970 km. When Raman amplification is employed to increase the power symmetry of the transmission link, the maximum feasible transmission distance is 5,500 km. Through Raman amplification, the maximum attainable transmission distance is improved by only 1.4 dB.

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