110 km transmission of 160 Gbit/s RZ-DQPSK signals by midspan polarization-insensitive optical phase conjugation in a Ti:PPLN waveguide

Hao Hu,[1,3,*] Rahman Nouroozi,[2] Reinhold Ludwig,[1] Carsten Schmidt-Langhorst,[1] Hubertus Suche,[2] Wolfgang Sohler,[2] and Colja Schubert[1]

[1]*Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut, Einsteinufer 37, 10587 Berlin, Germany*

[2]*University of Paderborn, Faculty of Science, Applied Physics, D-33095 Paderborn, Germany*

[3]*Currently with the DTU Fotonik, Technical University of Denmark, Building 343, DK-2800 Kgs. Lyngby, Denmark*

**Corresponding author: huhao@fotonik.dtu.dk*

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We demonstrate 160 Gbit/s return-to-zero (RZ) differential quarternary phase-shift keying (DQPSK) signal transmission over a 110 km single-mode fiber by taking advantage of mid-span optical phase conjugation (OPC). The technique is based on nonlinear wavelength conversion by cascaded second harmonic and difference frequency generation in a Ti:PPLN waveguide. Error-free operation with a negligible optical signal-to-noise ratio penalty for the signal after the OPC transmission without and with polarization scrambling was achieved. The results also show the polarization insensitivity of the OPC system using a polarization diversity scheme.

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Phase-shift-keyed modulation formats, such as differential phase-shift keying (DPSK) and differential quarternary phase-shift keying (DQPSK), have become promising candidates for future long-haul transmission systems employing high-data-rate signals (100 Gbit/s or beyond). Among those advanced modulation formats, DQPSK attracts a lot of interest, because it is easier to implement compared to higher-order formats (such as 8-PSK) and shows a higher spectral efficiency and better tolerances for chromatic and polarization mode dispersion compared with on–off keying or DPSK at the same bit rate. However, DQPSK suffers from the nonlinear phase noise introduced during the transmission as a result of conversion from amplified spontaneous emission amplitude noise into phase noise through the Kerr effect (i.e., Gordon–Mollenauer phase noise).

Optical phase conjugation (OPC), which is equivalent to (midspan) spectral inversion, is a useful technique to compensate for the dispersion of a transmission link [1–5]. In addition, compared with dispersion compensation fiber (DCF) modules, the OPC technique can not only save the extra insertion loss of the DCF modules, but also cancels out nonlinear impairments resulting from the Kerr effect, such as self-phase modulation (SPM), intrachannel nonlinear effects, and nonlinear phase noise [6–8].

In this Letter, we report an experimental demonstration of error-free 160 Gbit/s return-to-zero (RZ)-DQPSK signal transmission over 110 km single-mode fiber (SMF) using OPC. The technique is based on cascaded second-harmonic generation (cSHG) and difference-frequency generation (DFG) in a periodically poled lithium niobate (PPLN) waveguide. These second-order nonlinear interactions result in ultrafast response, negligible spontaneous emission noise, and broad working bandwidth. In addition, we also demonstrate polarization-insensitive operation of the OPC using a polarization diversity scheme. To the best of our knowledge, 160 Gbit/s is the highest operation speed of an OPC transmission without dispersion and dispersion slope compensation reported to date.

As shown in Fig. 1, the key device of the OPC is the polarization-insensitive PPLN subsystem, which is a polarization-maintaining (PM) loop configuration enabling bi-directional nonlinear wavelength conversion in the Ti:PPLN waveguide to provide a polarization diversity scheme with an intrinsic equalization of the differential group delay [1,9]. The two polarization components of the signal wave λ_s are routed by the polarization beam splitter (PBS) and PM fibers contra-directionally as TM modes through the PPLN waveguide, and the corresponding components of the converted signal (idler) wave λ_i are recombined in the PBS and routed to port 3 of the circulator. Polarization-insensitive operation is optimized by adjusting the polarization of the fundamental wave λ_f at port 1 to get an equal power splitting at the PBS outputs. The total loss of the polarization-insensitive PPLN subsystem is about 9 dB, which includes ~1 dB propagation loss, ~5.5 dB coupling loss, and ~2.5 dB passive loss of the PBS and the circulator.

Figure 2 shows the experimental setup for the 160 Gbit/s RZ-DQPSK signal transmission over a 110 km SMF using cSHG/DFG-based OPC in a Ti:PPLN waveguide. It included a 160 Gbit/s RZ-DQPSK transmitter, two fiber spans consisting of a 52.8 km SMF and a 57.6 km SMF with the OPC in the middle, and a 160 Gbit/s DQPSK receiver. The RZ-DQPSK transmitter consisted of a pulse source, a 10–40 GHz phase stable pulse multiplier, a DQPSK modulator, and a 40–80 Gbaud optical time-division multiplexer. The pulse source was a tunable

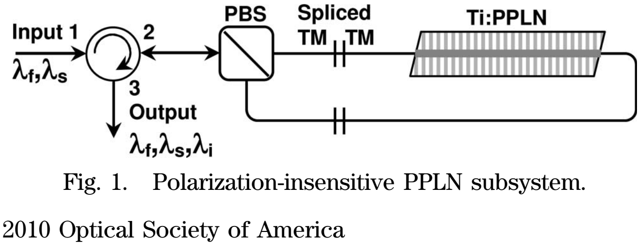

Fig. 1. Polarization-insensitive PPLN subsystem.

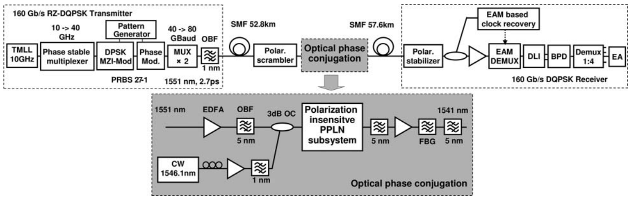

Fig. 2. Experimental setup for the 160 Gbit/s RZ-DQPSK signal transmission over 110 km SMF using OPC.

semiconductor mode-locked laser (TMLL), which produced a 1.4 ps, 10 GHz (STM-64) optical pulse train at 1551 nm, multiplied to 40 GHz by the pulse multiplexer. A two-stage modulator was used to encode the DQPSK signal. The first stage was a Mach–Zehnder $LiNbO_3$ device driven in push–pull mode by a 40 Gbit/s pseudorandom binary sequence signal (2^7-1) from a pattern generator to encode the π phase shift. The second stage was a $LiNbO_3$ phase modulator to encode the additional $\pi/2$ phase shift, driven by the same electrical signal with a sufficient delay for decorrelation. The modulated 40 Gbaud (80 Gbit/s) RZ-DQPSK signal was then multiplexed in time by a passive fiber-delay multiplexer (MUX $\times$ 2) to generate a 80 Gbaud (160 Gbit/s) RZ-DQPSK signal. The generated 160 Gbit/s RZ-DQPSK signal was filtered by a 1 nm optical bandpass filter (OBF) to have a FWHM of 2.7 ps, and then was transmitted over a 52.8 km SMF (attenuation 0.2 dB/km, dispersion 17 ps/nm/km, PMD $<$ 0.05 ps/km$^{1/2}$, where PMD is the polarization mode dispersion). The polarization of the data signal was scrambled in front of the OPC, to test the polarization insensitivity.

In the OPC system, the signal was amplified by an erbium-doped fiber amplifier (EDFA) after the 52.8 km SMF transmission line, then was filtered by a 5 nm optical bandpass filter (OBF), and was finally launched into the polarization-insensitive PPLN subsystem through a 3 dB coupler (OC). The signal power was 14.7 dBm at the input of the polarization-insensitive PPLN subsystem. The cw pump light at 1546.1 nm, acting as a fundamental wave to be frequency doubled in the PPLN waveguide, was amplified by a high-power EDFA, filtered, and launched into the polarization-insensitive PPLN subsystem through the second input of the 3 dB coupler. The fundamental power was 24.4 dBm at the input of the polarization-insensitive PPLN subsystem. The polarization controller in front of the EDFA was adjusted for optimum polarization-insensitive operation. At the output of the polarization-insensitive PPLN subsystem, the signal was launched into a filtering subsystem, which consisted of two 5 nm OBFs, an EDFA in between, and a tunable fiber Bragg grating (FBG). The FBG was used to block the fundamental wave, and the OBFs separated the phase conjugated (wavelength converted) signal at 1541 nm from the fundamental and the original signal waves. Next, the phase conjugated (wavelength converted) signal was transmitted over another SMF of 57.6 km. Since the dispersion of the SMF is lower for the converted signal compared to the unconverted signal, the length of the second span was chosen for minimum accumulated dispersion at the receiver.

In the DQPSK receiver, a polarization stabilizer was used to descramble the converted data signal in order to mitigate the polarization sensitivity of the receiver. The 160 Gbit/s DQPSK receiver consisted of an optical

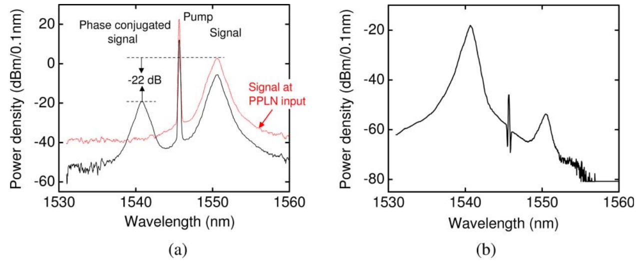

Fig. 3. (Color online) (a) Optical spectrum at the input and the output of the polarization-insensitive PPLN subsystem, (b) filtered optical spectrum at the output of the OPC.

preamplification stage, an electro-absorption-modulator (EAM)-based clock recovery, an EAM demultiplexer, a delay line interferometer (DLI), a balanced photodetector (BPD), an electrical demultiplexer (1∶4), and an error analyzer (EA). The EAM demultiplexer was synchronized to the recovered clock and used to select one of the two 80 Gbit/s (40 Gbaud) optical time-domain multiplexing (OTDM) tributaries. The DLI had a free spectral range of 40 GHz and was used to demodulate the I or Q channel from the demultiplexed 80 Gbit/s DQPSK signal. Since no DQPSK precoder was used in the transmitter, the EA was programmed to the expected bit pattern, which limited the word length in our experiments to 2^7-1. We used a variable optical attenuation at the receiver input to vary the received optical signal-to-noise ratio (OSNR).

The spectrum at the input and the output of the polarization-insensitive PPLN subsystem is shown in Fig. 3(a). The conversion efficiency for the phase conjugated (wavelength converted) 160 Gbit/s RZ-DQPSK signal is –22 dB (defined as the ratio of the output power of the phase conjugated signal to the input power of the data signal), which includes the 9 dB passive losses of the polarization-insensitive PPLN subsystem. The filtered spectrum of the phase conjugated (wavelength converted) signal is shown in Fig. 3(b). The integrated power of the remaining fundamental and input data signal was more than 30 dB lower than the power of the phase conjugated signal.

We also investigated the pulse broadening after the OPC transmission. The pulse width was broadened from 2.7 ps FWHM (measured by autocorrelation, assuming sech^2 pulses) to 3.5 ps after the 110 km OPC transmission, as shown in Fig. 4. The broadening is mainly due

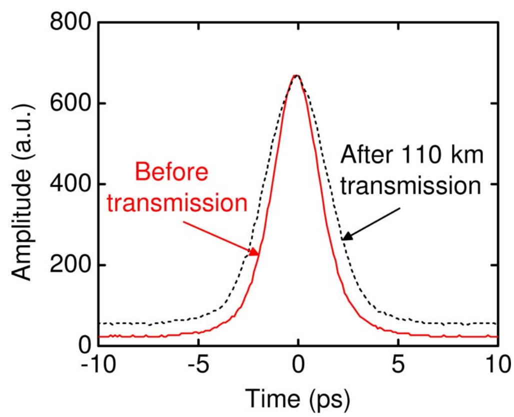

Fig. 4. (Color online) Autocorrelation trace of the data pulses before transmission and after 110 km OPC transmission.

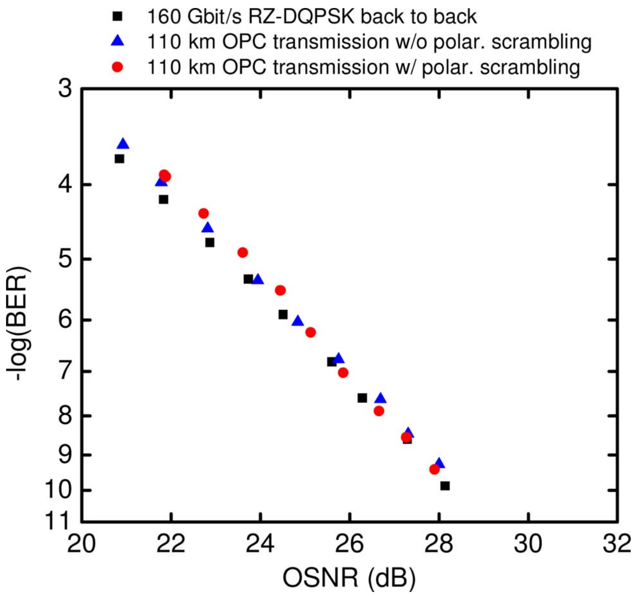

Fig. 5. (Color online) BER measurements for the 160 Gbit/s DQPSK back-to-back signal, and for the 160 Gbit/s DQPSK signal after the 110 km OPC transmission with and without polarization scrambling.

to third-order dispersion, which cannot be compensated by the OPC.

The results of the bit-error ratio (BER) measurements are shown in Fig. 5 as a function of the OSNR at the 160 Gbit/s DQPSK receiver. BER curves are plotted for the 160 Gbit/s DQPSK back-to-back signal before the OPC transmission, and for the 160 Gbit/s DQPSK signal after the 110 km OPC transmission, with and without polarization scrambling. 160 Gbit/s RZ-DQPSK phase conjugation transmission is successfully achieved with an error-free performance (BER $< 10^{-9}$). The 160 Gbit/s RZ-DQPSK signal after the 110 km OPC transmission without and with polarization scrambling shows negligible OSNR penalty at the BER of 10^{-9}, compared with the back-to-back case. The additional penalty caused by the polarization scrambling is also negligible, which demonstrates the polarization insensitivity of the optical phase conjugator. The measurements shown in Fig. 5 are made for one I/Q component of one time-domain multiplexing tributary. All tributary channels were measured, and the variation of the OSNR required for BER $= 10^{-9}$ was found to be less than 1 dB. The 40 Gbit/s eye diagrams (at BER $= 10^{-9}$) for one I/Q component after 110 km OPC transmission, demultiplexing, and demodulation, without and with polarization scrambling, are shown in Figs. 6(a) and 6(b), respectively. The eye diagrams also indicate that the signals after the 110 km OPC transmission with and without polarization scrambling have almost identical performance.

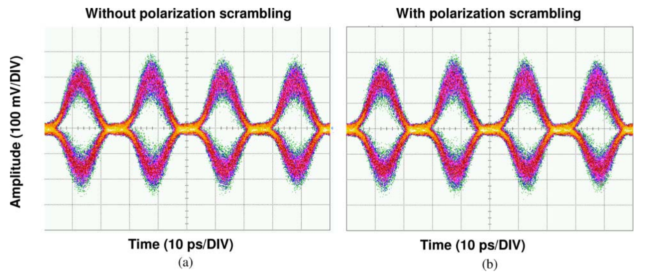

Fig. 6. (Color online) 40 Gbit/s eye diagram of the signal after 110 km OPC transmission, demultiplexing, and demodulation in the DQPSK receiver (a) without and (b) with polarization scrambling.

In conclusion, we have demonstrated OPC transmission of a 160 Gbit/s RZ-DQPSK signal over a 110 km SMF using mid span spectral inversion in a polarization-insensitive PPLN subsystem. Error-free operation with a negligible OSNR penalty for the signal after the OPC transmission was achieved. The BER measurements and eye diagrams show that the signals after the OPC transmission with and without polarization scrambling in front of the optical phase conjugator have identical performance, which demonstrates the polarization insensitivity of the optical phase conjugator.

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