All-optical Combination of DPSK and OOK to 320-Gb/s DQPSK Signal Using Fiber-based Signal Processors

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Abstract *All-optical combination of 160-Gb/s DPSK and OOK signals into a 320-Gb/s DQPSK signal is demonstrated using highly-nonlinear fibers. A polarization-insensitive optical parametric limiter enabled error-free combination operation midway in a 200 km fiber link.*

Introduction

The use of various types of optical modulation formats has enabled to increase spectral efficiency and improve system performance [1]. In future high speed photonic networks different modulation formats will coexist to guarantee simplicity, high spectral efficiency and flexibility. To maintain a high transparency of photonic networks, all-optical format conversion and combination of different modulation format will be desirable. Previously, we investigated the conversion from OOK to DPSK signal and vice versa at 160 Gb/s [2] and the combination of DPSK and OOK signals to a 160 Gb/s DQPSK signal [3].

In this paper we report on all-optical combination of DPSK and OOK signals into a DQPSK signal by cross-phase modulation (XPM) in a highly-nonlinear fiber (HNLF). We employ a polarization-independent optical limiter using gain-saturated optical parametric amplifiers (OPAs) [4] for amplitude equalization of the transmitted DPSK signal and successfully demonstrate a combination of 160-Gb/s DPSK and OOK signals into a 320-Gb/s DQPSK signal midway in a 200 km fiber link. This is the first demonstration of data combination to 320-Gb/s signal to date. This scheme has potential for operation at even higher bit rates.

Experimental setup

Figure 1 shows the experimental setup. In the all-optical data combiner, DPSK and OOK signals were launched into a HNLF. Data marks of the OOK signal induced an additional $\pi/2$-phase shift by XPM on the co-propagating DPSK signal for data combination. Before the combiner, a polarization-independent optical parametric limiter (OPA-limiter) was used to equalize the amplitude level of the DPSK signal. The OPA-limiter consisted of polarization diversity OPAs, OPA1 and OPA2, in a two-stage configuration. Each OPA basically consisted of a polarization beam splitter (PBS1, PBS2), a highly-nonlinear fiber (HNLF1, HNLF2) and a CW pump wave (E_{P1}, E_{P2}) in one pump loop configuration [5]. The polarization axes of PBS1 (x, y) and PBS2 (x', y') were set to be tilted by 45° with respect to each other and the pump power was equally divided to both directions of each loop. Since the gain saturation of OPA depends on the signal power, the higher the signal power the stronger the gain saturation in OPAs. In the configuration, if the gain saturation was strongest in OPA1 then that in OPA2 was weakest and vice versa. By passing OPA1 and OPA2, the magnitude of gain saturation was thus averaged for all the SOP of input signal, which provided a polarization-independent OPA-limiter.

In each OPA, we used a 500 m HNLF1 and a HNLF2 with the nonlinearity coefficient of γ~25 $W^{-1}km^{-1}$ and the zero-dispersion wavelength at λ_{01} = 1563 nm and λ_{02} = 1564 nm. The wavelengths of the two pump waves E_{P1} and E_{P2} for OPA1 and OPA2 were tuned to λ_{P1}~λ_{01} and λ_{P2}~λ_{02}, respectively. The input pump powers into the HNLF1 and HNLF2 were set to +21.2 and 21.9 dBm, respectively. To suppress the stimulated Brillouin scattering (SBS), E_{P1} and E_{P2} were phase-modulated with a single tone at 70 MHz. The input power of the 160-Gb/s DPSK signal into the OPA limiter was set to +14.5 dBm, resulting in an on-off gain of 6.5 dB at 3-dB gain saturation condition. The total loss of the OPA-limiter was ~9 dB.

Power transfer characteristics were measured when the state of polarization (SOP) of the DPSK signal was set to be linear and tilted by every 22.5° from 0°

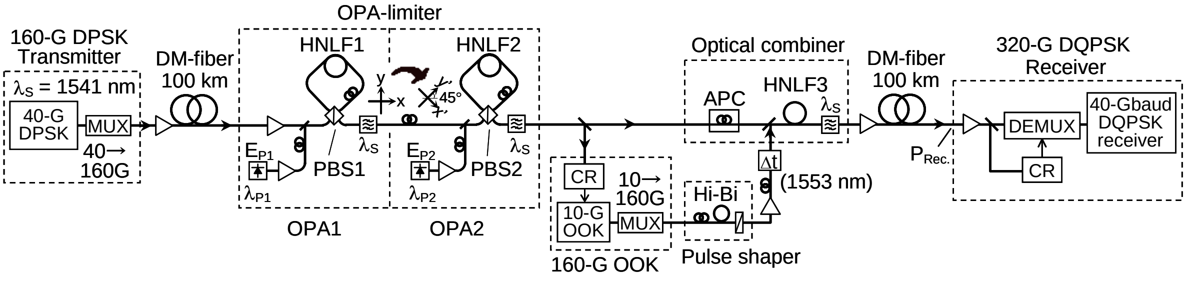

Fig. 1: Experimental setup

978-3-8007-3173-2

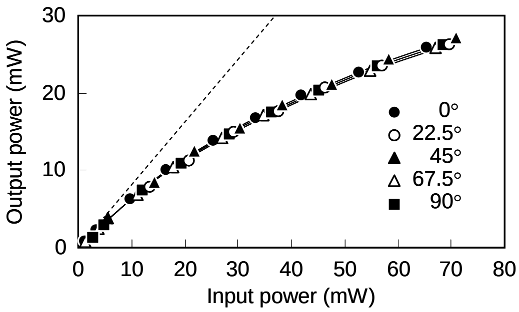

Fig. 2: Power transfer characteristics of the OPA-limiter for different SOPs of DPSK signal

to 90° with respect to the main axes of the PBS1. As shown in Fig.2, the measured curves for the five SOPs coincided well, demonstrating the polarization independent operation of the OPA-limiter [4].

A 160-Gb/s OOK signal at 1553 nm was locally generated by optical time division multiplexing (OTDM) a 2-ps, 10-Gb/s (PRBS : 2^7-1) OOK signal which was driven by a 10-GHz RF clock, recovered from the DPSK signals after the first transmission fiber by a clock recovery circuit (CR). Then a pulse shaper [6] was employed for the OOK signal to generate flat-top pulses for a constant phase shift over the entire pulse envelope of the DPSK signal in the all-optical combiner. In the pulse shaper, the OOK signal was coupled into a high birefringent (HiBi) fiber with a polarization controller providing the same amount of power along the two main axes of the HiBi-fiber. The differential group delay was adjusted to ~1.0 ps. The pulse shape changed to be flat-top (FWHM~2.4 ps) after passing through the polarizer.

The amplitude equalized 160-Gb/s DPSK signal by the OPA-limiter and the locally generated 160-Gb/s OOK signal were launched into the all-optical combiner. It consisted of a 250 m HNLF3 (λ_{03}~1547 nm) and an automatic polarization controller (APC), which was used to stabilize the SOP of the transmitted DPSK signal at the combiner input. In the HNLF3, the data marks in the OOK signal induced an additional $\pi/2$-phase shift by XPM on the co-propagating 160-Gb/s DPSK signal when the OOK signal power was adjusted to 15.7 dBm. This resulted in quaternary differential phase shifts and thus a 320-Gb/s DQPSK signal was generated. The SOPs of DPSK and OOK signals were adjusted to optimize the XPM generation. Polarization-independent operation is also required for the combiner, which is subject of future work. Please note that the data combination of two independent data will require an additional effort for synchronization.

Results

The all-optical data combiner was tested in the transmission experiment. A 160-Gb/s DPSK signal at 1541 nm was prepared by OTDM-multiplexing of 2-ps, 40-Gb/s (PRBS: 2^7-1) DPSK signal. After the 100-km first dispersion managed (DM) fiber transmission, the all-optical data combiner was applied. Then after

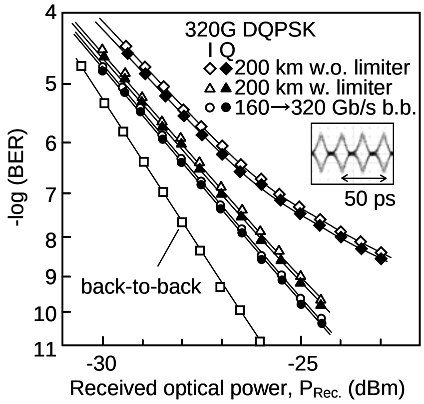

Fig. 3: Bit-error rate characteristics

transmission through the second 100-km DM fiber span, bit error rates (BERs) were measured. In the receiver, the 320-Gb/s DQPSK signal was demultiplexed to 80-Gb/s DQPSK by an EA-modulator and then led into a balanced photo-detector after a 1-bit delayed interferometer. The BER characteristics are shown in Fig.3. Almost similar performance was obtained for all OTDM channels. Open and filled symbols represent BERs for in-phase and quadrature components, respectively. The circle symbols show the performance of the all-optical data combiner in a back-to-back configuration. About 2-dB shift of the receiver sensitivity was observed (@BER=10^{-9}). We attribute this mainly to the cross-talk due to the walk-off and incomplete phase shift on DPSK data from dispersion slope of the HNLF3. After the transmission, the BER curves had a hard floor when no limiter was employed as shown by diamonds. By using the OPA-limiter in the middle of the 200-km transmission line, the error-free performance (BER < 10^{-9}) was achieved. As compared to the back-to-back reference data (circles), the penalty was reduced to less than 0.5 dB by the level equalizing effect of the OPA-limiter. Figure 3 inset shows the eye-diagrams of 40-Gb/s signal demultiplexed and demodulated from the 320 Gb/s DQPSK signal. Clear eye-opening was confirmed.

Conclusions

We have reported on all-optical data combination of 160-Gb/s DPSK and OOK signals into a 320-Gb/s DQPSK signal by XPM in a HNLF. A polarization-insensitive OPA limiter was employed for amplitude level equalization of the transmitted DPSK signal. The data combination was applied midway of the 200-km fiber link and error-free performance after the transmission was successfully demonstrated.

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