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Transmission of 32.1 Gbit/s RZ-D8PSK over 160 km using Dispersion Compensation by Optical Phase Conjugation

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Abstract: A 32.1 Gbit/s RZ-D8PSK modulated signal was transmitted through 160 km SSMF with optical phase conjugation after 80 km. The phase conjugation was performed by four wave mixing.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

1. Introduction

Due to a combination of high spectral efficiency and robustness towards chromatic dispersion, optical multilevel modulation has attracted considerable interest in recent years. The most thoroughly investigated multilevel modulation format is the two bits per symbol differential quadrature phase shift keying (DQPSK), demonstrated for optical communication systems in 2002 [1]. Adding additional phase modulation to DQPSK yields the 3 bits per symbol modulation format known as differential 8-ary phase shift keying (D8PSK) [2, 3, 4].

Dispersion compensation by optical phase conjugation (OPC) was suggested as early as 1979 [5], and demonstrated experimentally for on-off keying signals in 1993 [6]. More recently, the technique has been investigated for dispersion compensation in ultra long-haul DQPSK systems [7].

In this paper, we present for the first time experimental demonstration of dispersion compensation by OPC of a 32.1 Gbit/s return to zero (RZ) D8PSK signal. The total amount of dispersion compensated by the OPC was 2720 ps/nm.

OPC can be provided by the four wave mixing (FWM) process. In the case of degenerate FWM between a pump and a signal wave, the phase of the idler at the output of the nonlinear medium can be expressed as

$$\phi_+ = 2\phi_s - \phi_p \text{ and } \phi_- = 2\phi_p - \phi_s \text{ for } \omega_s > \omega_p \text{ and} \tag{1}$$

$$\phi_+ = 2\phi_p - \phi_s \text{ and } \phi_- = 2\phi_s - \phi_p \text{ for } \omega_s < \omega_p, \tag{2}$$

where ϕ_p and ϕ_s are the phases of pump and signal respectively, ϕ_+ and ϕ_- are the phases of the up and down converted idler respectively, and ω_p and ω_s are the angular frequencies of the pump and signal respectively. From these equations it can be seen that the FWM process can provide a conjugation of the signal phase.

2. Experimental Setup

The setup used in the experiment is illustrated in Figure 1. The RZ-D8PSK transmitter comprised an I/Q-modulator in series with a phase modulator for the data modulation, and a Mach-Zehnder modulator for the RZ-carving. Each arm of the I/Q modulator was driven by an electrical 10.7 Gbit/s $2^7 - 1$ bit long pseudo random bit sequence (PRBS) with an amplitude equal to 2V_π of the modulator, thereby generating differential binary phase shift keying (DBPSK) signals. The two DBPSK signals were phase offset $\pi/2$ from each other, resulting in a DQPSK signal upon recombination in the overall Mach-Zehnder structure. The phase modulator was driven by a third 10.7 Gbit/s $2^7 - 1$ bit long PRBS with an amplitude equal to $V_\pi/4$ of the modulator in order to apply a $\pi/4$ phase shift to the DQPSK signal, resulting in a 32.1 Gbit/s D8PSK signal. Decorrelation of the data signals was ensured by applying appropriate time delays between the three electrical drive signals. Differential encoding of the data signals was not applied and therefore the error detector in the receiver was programmed with the expected pattern. The short pattern length of $2^7 - 1$ was chosen because of limitations in programming the error detector with longer patterns.

In the receiver, noise from an open ended erbium doped fiber amplifier (EDFA) was added to the signal in order to vary the optical signal to noise ratio (OSNR), before optical bandpass filtering with a 3 dB bandwidth of 0.4 nm, demodulation by a 1-symbol delay interferometer (MZI) and detection by a pair of balanced photodiodes (BPD).

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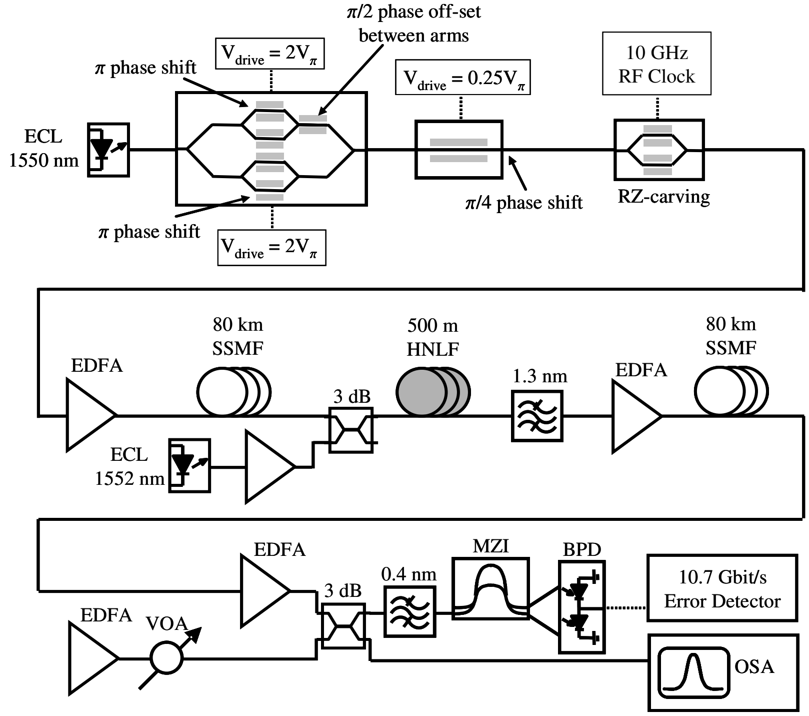

Fig. 1. Block diagram of the setup used in the OPC assisted RZ-D8PSK transmission experiment.

The bit error ratio (BER) was measured by a 10.7 Gbit/s error detector programmed with the expected pattern. Four different data tributaries can be detected, and the total BER of the RZ-D8PSK signal can be calculated as one third of the sum of the BER of the individual tributaries [2]. Since only one receiver was available for the experiment, the 4 tributaries were measured one after the other.

The transmission span consisted of 2×80 km standard single mode fiber (SSMF), with a dispersion of 17 ps/(nm·km), corresponding to 2720 ps/nm dispersion for the complete transmission span.

OPC was performed by FWM in 500 m highly nonlinear fiber (HNLF) with a dispersion of –1.1 ps/(nm·km) and dispersion slope of 0.0055 ps/(nm^2·km) at a wavelength of 1550 nm. The nonlinear coefficient of the HNLF is $\gamma = 11$ W^{-1}·m^{-1}. The pump laser used for FWM was an external cavity laser (ECL) at a wavelength of 1552 nm. For the signal, an ECL with a wavelength of 1550 nm was used, resulting in a wavelength converted, phase conjugated signal at a wavelength of 1554 nm. External cavity lasers were used for the pump as well as the signal due to the low phase noise of this type of laser. Optical power at the input of the HNLF was 13.6 dBm for the pump and 8.9 dBm for the signal. At these power levels, no degradation from stimulated Brillouin scattering was observed. The optical power of the wavelength converted signal at 1554 nm at the output of the HNLF was –9.9 dBm, corresponding to a conversion efficiency of –18.8 dB. From equations 1 and 2, it can be seen that the phase conjugated idler contains a term with twice the pump phase, and hence twice the phase noise of the pump. Therefore, the phase noise requirements for the pump is twice as strict as for the signal. Polarization optimization between pump and signal in the HNLF was obtained with polarization controllers. After wavelength conversion, the pump, the signal and the unused idler at 1548 nm were suppressed by an optical bandpass filter with a 3 dB bandwidth of 1.3 nm.

3. Results

Figure 2 displays the measured BER curves from the OPC experiment. Results back to back, after phase conjugation without transmission, and after 160 km transmission with phase conjugation after 80 km are plotted. Down to a BER of 10^{-5}, the three curves are within the measurement uncertainties of each other. At lower BER, the phase conjugated signals display worse performance than the original. The signal after phase conjugation and transmission is slightly worse than the signal after phase conjugation without transmission. Despite these degradations, the signal could be received error-free in all three cases. OSNR requirements at a pre-forward error correction (FEC) BER of 10^{-5} as well

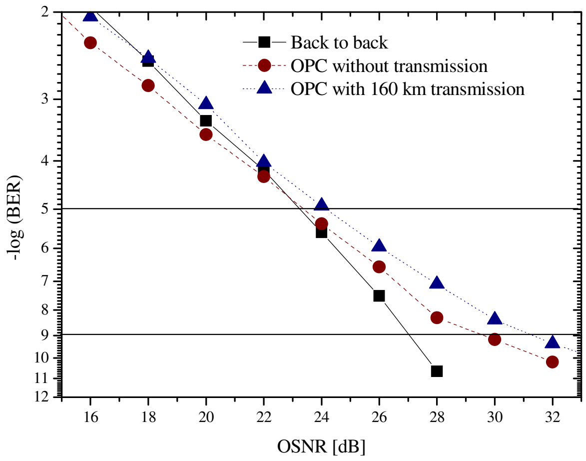

Fig. 2. BER of the 32.1 Gbit/s RZ-D8PSK OPC assisted transmission experiment.

as at a BER of 10^{-9} are listed in Table 1 together with the OSNR penalty with respect to the back to back case without OPC. Evaluating the system at a pre-FEC BER of 10^{-5} was decided because it leaves more than 3 dB margin before the FEC limit of BER = 2×10^{-3}. At this point, the degradation from the phase conjugation is negligible, and the penalty after 160 km transmission is less than 1 dB. At the low BER of 10^{-9}, the penalty from OPC and transmission adds up to 4.2 dB. Nevertheless, the signal could be received error free after 160 km transmission with 2720 ps/nm accumulated dispersion. This value has to be compared to the 600 ps/nm dispersion tolerance for 32.1 Gbit/s RZ-D8PSK reported in [3].

	B2B	B2B with OPC	160 km with OPC
OSNR requirement @ 10^{-5}	23.2 dB	23.4	24.1 dB
OSNR penalty @ 10^{-5}	N/A	0.2 dB	0.9 dB
OSNR requirement @ 10^{-9}	27.0 dB	29.6 dB	31.3 dB
OSNR penalty @ 10^{-9}	N/A	2.6 dB	4.2 dB

Table 1. OSNR requirements at a BER of 10^{-9} back to back, back to back with optical phase conjugation (OPC), and after 160 km transmission with OPC after 80 km.

4. Conclusion

The ability of optical phase conjugation to counteract dispersion has been demonstrated for a 32.1 Gbit/s RZ-D8PSK signal. The signal was received error-free after 160 km SSMF transmission, where the OPC was performed after the first 80 km. In this way, a total of 2720 ps/nm chromatic dispersion was compensated. The combined optical phase conjugation and 160 km transmission resulted in less than 1 dB OSNR penalty at a BER of 10^{-5}.

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