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DPSK Signal Restoration Using Four-Wave Mixing in a Dispersion-Flattened Highly Nonlinear Photonic Crystal Fiber

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Abstract

We demonstrate phase-noise reduction of a 10-Gb/s DPSK signal using pump-modulated four-wave mixing in a photonic crystal fiber. The extinction ratios at the decoder outputs are improved by 5 and 27 dB.

1 Introduction

Differential phase-shift keying (DPSK) data format has received much attention in its immunity to fiber nonlinearities [1]. However, phase noise of a DPSK signal will accumulate during transmission and processing of the signal, resulting in a degradation of the signal quality. In this work, we develop an all-optical approach to reduce the phase noise and to enhance the extinction ratio using pump-modulated four-wave mixing (FWM) [2]. The DPSK input acts as a pump source during the process. A dispersion-flattened, highly nonlinear photonic crystal fiber (PCF) is used as the FWM medium to provide a large optical bandwidth of operation [3]. The power penalty is improved by over 5 dB. Also, the extinction ratios are enhanced by 5 and 27 dB at the destructive and constructive ports of the decoder, respectively.

2 Principle and Experimental Setup

To optimize the extinction ratio for a DPSK signal, a π phase shift at bit "1" and a zero phase shift at bit "0" are required. The phase noise and the amplitude noise should also be minimized. Fig. 1(a) plots the calculated phase dependence of the decoded signal intensity for the case of destructive interference between the data bits. As shown by the dark curve, the output intensity is non-zero when the phase of bit "1" is smaller than π. By applying pump-modulated FWM and filtering out the converted signal at a frequency of (ω_s-ω_{cw}) from the input signal, the phase of bit 1 will be doubled. Here, ω_s and ω_{cw} are the frequencies of the DPSK signal and the cw pump, respectively. The intensity of the decoded output is pushed towards the zero level within the shaded region, resulting in an extinction ratio enhancement. When the phase of bit "1" varies between 0.3 π and 0.7 π, the normalized intensity output changes by 0.3 after FWM. The result compares favorably to an intensity change of 0.65 in the decoded output of the original signal. Hence, phase noise reduction can be obtained simultaneously with extinction ratio enhancement. The phase noise is converted into amplitude noise after the decoding process. Fig. 1(b) shows a reduction of the amplitude noise in the output when the phase of the bit "1' is set at 0.5 π. The light curve shows an improvement over the dark curve as a result of phase noise doubling in the FWM process.

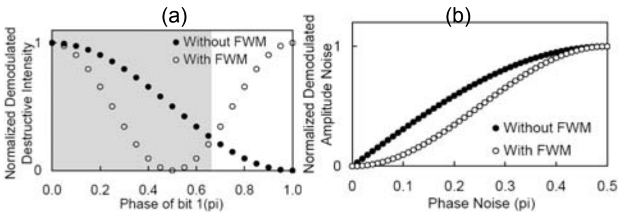

Fig. 1 Effect of four-wave mixing on (a) the normalized output intensity at destructive interference of the data bits. The extinction ratio is enhanced in the shaded region. (b) the normalized amplitude noise in the decoded output for an input with 0.5 π phase shift for bit "1".

Our experimental setup is shown in Fig. 2. A 10-Gb/s NRZ-DPSK signal at 1555 nm is generated at the phase modulator (PM). The driving amplitude is chosen to yield a 0.5 π phase shift for bit "1". Phase noise is also added to the signal by passing it through another sinusoidally driven PM. A tunable laser source is combined with the DPSK signal and the combined light is amplified and launched to a 64-m PCF to introduce FWM. The PCF has a dispersion coefficient of -1.3 ps/(km·nm) at 1550 nm. The dispersion slope is ~10^{-3} ps/(km·nm^2) and the nonlinear coefficient is 11.2 $(W·km)^{-1}$.

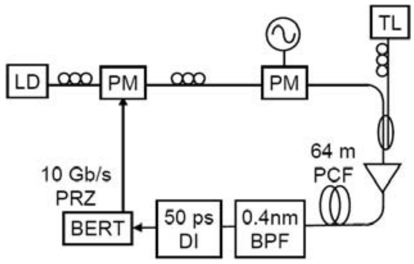

Fig. 2 Experimental setup. LD: laser diode; PM: phase modulator; TL: tunable laser; PCF: photonic crystal fiber; BPF: optical bandpass filter; DI: delay interferometer; BERT: bit-error rate test set.

3 Results and Discussion

The eye diagram of the 1555-nm DPSK signal with added phase noise is measured by decoding the signal with a 50-ps delay interferometer (DI). The results are shown in Fig. 3. The insufficient phase shift for bit "1" and the addition of phase noise result in a poor signal quality. Fig. 3(a) depicts the eye diagram at the destructive port showing a semi-closed eye with an extinction ratio of 24 dB. The eye is completely closed at the constructive port as shown in Fig. 3(b).

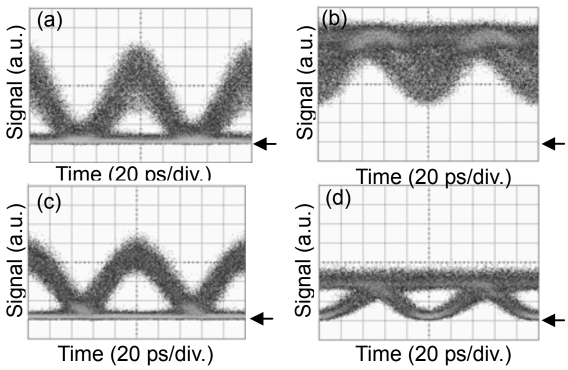

Fig. 3 Eye diagrams. (a) input signal with added phase noise at the destructive port. (b) input signal with added phase noise at the constructive port. (c) regenerated signal at the destructive port. (d) regenerated signal at the constructive port.

By filtering out the converted wavelength at 1553 nm from the FWM output, phase noise reduction and extinction ratio enhancement are obtained and the results are shown in Fig. 3(c) and (d). The eyes are clearly open and extinction ratio improvements of 5 and 27 dB are obtained at the destructive and constructive ports, respectively. By tuning the cw light from 1545 to 1565 nm, the converted wavelength has been changed from 1565 to 1545 nm. Over the tuning range, the output extinction ratio varies by 1.5 dB and improvements in both the extinction ratio and the eye opening are obtained.

The bit-error rate measurement results are shown in Fig. 4. At the destructive port, it is clearly observed that the regenerated signal shows a significant improvement in the BER performance and the error floor is removed. At the constructive port, the BER of the degraded input signal is very large and cannot be determined. Instead, the BER of the DPSK input without added phase noise is plotted. The regenerated signal, even with the addition of phase noise, shows a significant improvement.

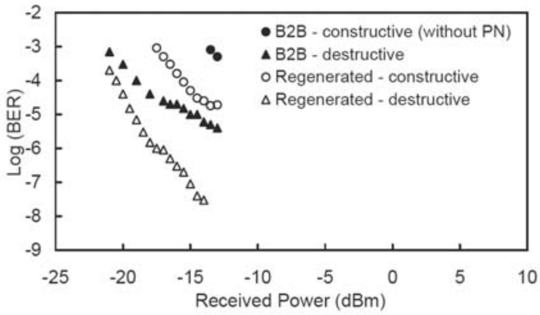

Fig. 4 BER performance of the input and the regenerated signals at the destructive and constructive output ports of the delay interferometer.

4 Conclusion

Phase noise reduction and extinction ratio enhancement have been demonstrated for a 10-Gb/s NRZ-DPSK signal using four-wave mixing in a dispersion-flattened and highly nonlinear PCF. The scheme has been experimentally demonstrated over a converted wavelength range of 20 nm. The eye opening is enhanced along with a significant improvement of the power penalty in the BER measurement.

Acknowledgment

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