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WDM Transmission over 320 km EDFA-Amplified SSMF Using 30 Gb/s Return-to-Zero Optical Differential 8-Level Phase-Shift Keying (OD8PSK)

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Abstract: Fiber transmission of optical differential 8-level phase-shift keying (OD8PSK) signals is demonstrated for the first time. Co-polarized 8 WDM channels of 10 Giga-symbol/s or 30 Gb/s return-to-zero (RZ) OD8PSK signals with a channel spacing of 50 GHz were transmitted over 320 km of standard single mode fiber (SSMF) with an EDFA spacing of 80 km. The BER of the worst WDM channel after transmission of 320 km was 2.3×10^{-5}.

OCIS codes: (060.0060) Fiber optics and optical communications, (060.2330) Fiber optics communications, (060.4080) Modulation, (060.5060) Phase modulation.

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1. Introduction

Multilevel modulation formats can lead to higher aggregate capacity for optical transmission, with several advantages over competing methods. Since multilevel modulation formats allow higher spectral efficiency, aggregate capacity can be increased without expanding the overall bandwidth of the system, which allows the use of existing optical amplifier technology rather than developing new amplifier technology for additional bandwidth. Other advantages of

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using multilevel modulation formats are increased tolerances to chromatic dispersion and polarization mode dispersion (PMD). Direct detection, on the other hand, allows simple receiver structures free of local oscillators and active polarization control. 4-ary differential quadrature phase-shift keying (DQPSK) using direct detection has been demonstrated [1-3]. 8-level amplitude- and phase-shift keying (8-APSK) with direct detection has been proposed by combining binary amplitude-shift keying and DQPSK [4]. However, as inter-channel cross-phase modulation (XPM) becomes major transmission impairment for multi-channel systems with narrower channel spacing, amplitude modulation is not desirable. In order to achieve better tolerance to XPM, we proposed a constant-amplitude optical differential 8-level phase-shift keying (OD8PSK) with direct detection for fiber-optic transmission [5]. In this work, we demonstrate, for the first time, 8-channel WDM transmission of RZ OD8PSK signals at 10 Giga-symbol/s (Gs/s) or 30 Gb/s with a channel spacing of 50 GHz.

2. Experimental setup

In OD8PSK, differential phase between successive bits can have a value of $0, \pi/4, \pi/2, 3\pi/4, \pi, 5\pi/4, 3\pi/2$, or $7\pi/4$. After transmission through optical fiber, the differentially encoded optical signal is demodulated interferometrically and the original data can be recovered using direct detection at the receivers with proper electrical and optical encoding at the transmitter.

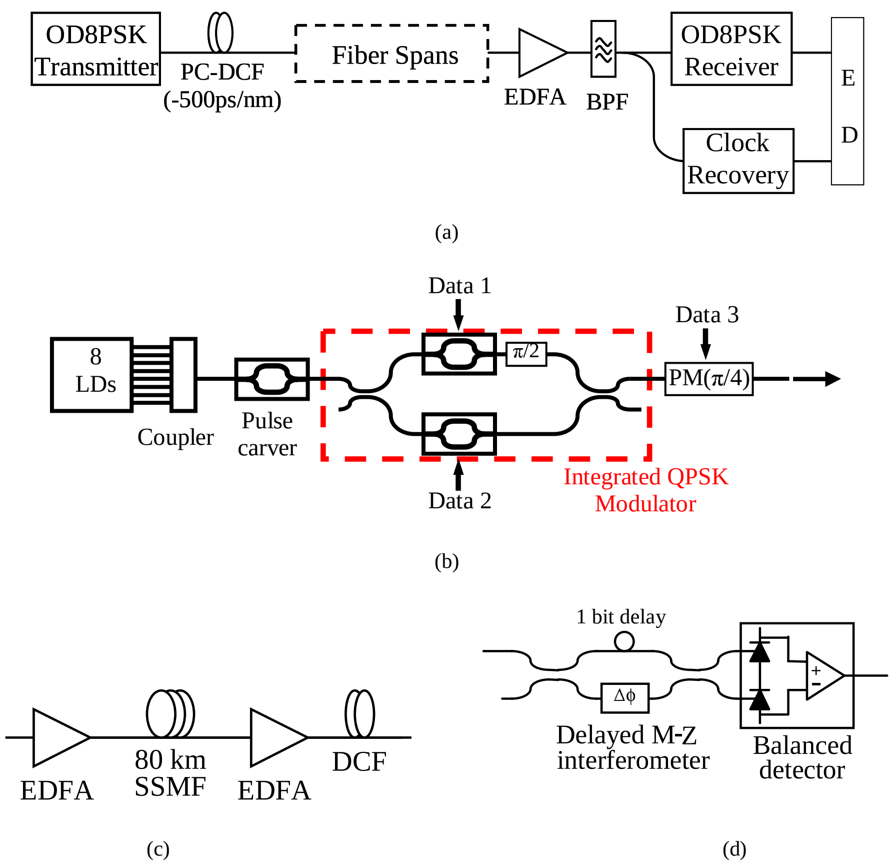

Fig. 1 Experimental setup: Detailed schematic diagrams of (a) OD8PSK transmission system (PC-DCF: Pre-dispersion compensation, BPF: optical bandpass filter, ED: error detector), (b) OD8PSK transmitter, (c) Fiber spans, and (d) OD8PSK receiver.

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The schematic diagram of the experimental setup of the 8-channel WDM OD8PSK transmission system is shown in Fig. 1(a). The transmitter is shown in detail in Fig. 1(b). Eight DFB lasers from 1548.9 nm to 1551.7 nm with a spacing of 50 GHz and linewidth of 2 MHz were combined with polarization maintaining optical couplers. These co-polarized optical carriers were coupled into the optical modulators. An integrated lithium niobate (LN) QPSK modulator [4], which generates four phase levels with a phase separation of $\pi/2$, and an LN phase modulator with a phase modulation depth of $\pi/4$ were used to encode 8 different phase levels on optical carriers. An LN intensity modulator was used as a pulse carver to generate return-to-zero (RZ) pulse trains with a 50% duty cycle. The QPSK modulator and the phase modulator encoded 3 streams of PRBS data on the RZ pulse trains to generate 10 Gs/s or 30 Gb/s OD8PSK encoded signals with the same data pattern for all 8 channels. The 3 data streams were derived from a 10 Gb/s 2^{15}-1 PRBS data signal generated by a pulse pattern generator (PPG). A delay of 49 bits between two data streams (Data 1 and Data 2 in Fig. 1(b)) to drive the QPSK modulator was applied electrically to partially decorrelate the two data streams. The delay between the third data (Data 3 in Fig. 1(b)) and other two data streams was provided by the fiber connecting the QPSK modulator and the phase modulator so that the delays between the third data and other two data were 200 bits and 249 bits, respectively. The electrical differential encoding was not applied. Before launching into the transmission system, pre-dispersion compensation of -480 ps/nm was applied using a dispersion-compensating fiber (DCF), which also partially decorrelates each WDM channels with the same data pattern. Standard single mode fiber (SSMF) of 80 km, DCF of a desired length and two Erbium-doped fiber amplifiers (EDFA) constitute each transmission span, as shown in Fig. 1(c), and the RZ OD8PSK signal was transmitted over up to 4 fiber transmission spans. The total loss of a span was 23.5 dB, which resulted from 16.5 dB of SSMF and 7 dB of DCF. The first EDFA is used to obtain a desired optical launch power and the second EDFA is used to partially compensate transmission losses in each span while keeping the launch power to DCF low enough to avoid nonlinearities. The EDFAs have a noise figure of 5.5 dB. Total residual dispersion was designed to be close to zero by controlling the dispersion of DCF in the last transmission span. The optical powers launched into SSMF and DCF were 9 dBm (0 dBm per channel) and 2 dBm (-7 dBm per channel), respectively. After transmission over the desired number of fiber spans, the optical signal was pre-amplified by an EDFA and filtered by a combination of a 50 GHz flat-top optical interleaver and a narrow band optical filter. The 1 dB bandwidth and 20 dB bandwidth of the optical filter pair were 35 GHz and 58 GHz, respectively. Since four binary decisions are needed to decode OD8PSK signals [5,6], one set of a delayed Mach-Zehnder interferometer (MZI) demodulator (ITF Optical Technologies) and a balanced detector, as shown in Fig. 1(d), was used to perform 4 successive binary decisions with 4 different phase shifts ($\Delta\phi$) of $\pi/8, -\pi/8, 3\pi/8, \pi, -3\pi/8$ in the delayed MZI demodulator. Demodulations with phase shifts of $3\pi/8$ and $-\pi/8$ recover Data 1 and Data 2 in Fig. 1(b), respectively, and demodulations with phase shifts of $-3\pi/8$ and $\pi/8$ and XOR gating of two demodulated signals recover Data 3. The sensitivity of this receiver setting has been shown to outperform that of the receiver setting using multi-level detection by 3 dB [7]. Before coupled into the OD8PSK receiver, a part of the optical signal was used to recover the clock using a photodectector and a narrow band electrical filter, as shown in Fig. 1(a). The output from the balanced detector and the recovered clock were sent to an error detector (ED) to measure the bit error ratio (BER). Since differential encoding was not applied, the expected data patterns at the receiver were calculated and input to the error detector as expected word patterns to measure BER correctly. BER performances of the system were obtained by first measuring 4 BERs with four binary decisions and then dividing the sum of four BERs by 3, assuming that in decoding of Data 3, errors do not occur at the same bit for demodulations with phase shift of $-3\pi/8$ and $\pi/8$ [5].

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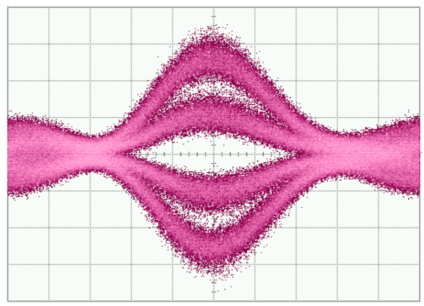
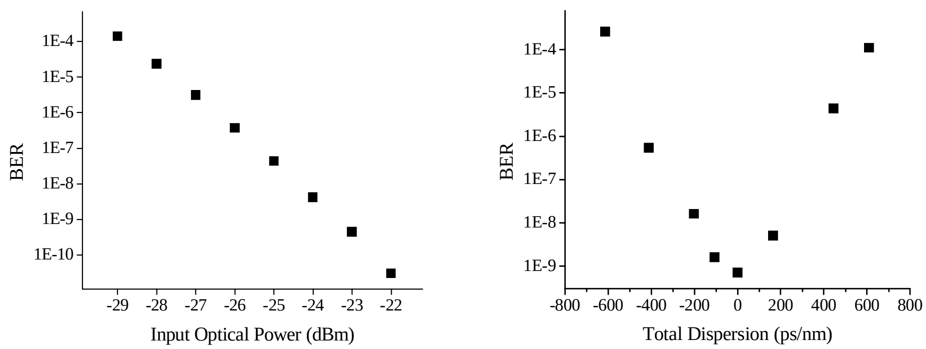
3. Experimental results and discussions

In the experiments, single channel back-to-back performance was first investigated. Only one DFB laser with a wavelength of 1550.1 nm was turned on. The single channel back-to-back demodulated eye diagram is shown in Fig. 2(a). Due to 8 levels of differential phase, the demodulated eye diagram of OD8PSK signals shows 4 amplitude levels, each amplitude levels resulting from two differential phases. The back-to-back sensitivity of the single channel at a BER of 10^{-9} was measured to be -23.5 dBm, as shown in Fig. 2(b). The back-to-back dispersion tolerance of OD8PSK signal was also measured and shown in Fig. 2(c). The dispersion tolerance corresponding to a 0.5 dB in Q factor penalty of this 30 Gb/s system is 370 ps/nm, comparable to the dispersion tolerance of 10 Gb/s RZ-DPSK system. This demonstrates increased dispersion tolerance of the OD8PSK modulation format.



(a)



(b) (c)

Fig. 2 (a) Back-to-back demodulated eye diagram (10 ps/div.), (b) Back-to-back BER as a function of optical power, and (c) Back-to-back BER as a function of total chromatic dispersion for single channel OD8PSK.

The measured back-to-back demodulated eye diagram of one (channel 4 with a wavelength of 1550.1 nm) of the 8 channels for a 50 GHz-spacing 8-channel WDM system is shown in Fig. 3(a). Due to optical filtering and linear crosstalk between adjacent WDM channels, the eye opening is slightly worse than that for the single channel system. The demodulated eye diagram of the same channel after transmission over 320 km of SSMF is shown in Fig. 3(b), in comparison with the back-to-back eye diagram of Fig. 3(a). In addition to ASE noises from EDFAs, self-phase modulation (SPM) and cross-phase modulation (XPM) are expected to be the main degradation mechanisms for this 50-GHz channel-spacing WDM system [8, 9]. The BER performance of the same channel as a function of transmission distance up to 320 km is shown in Fig. 4. The bit error ratio after 320 km of SSMF was

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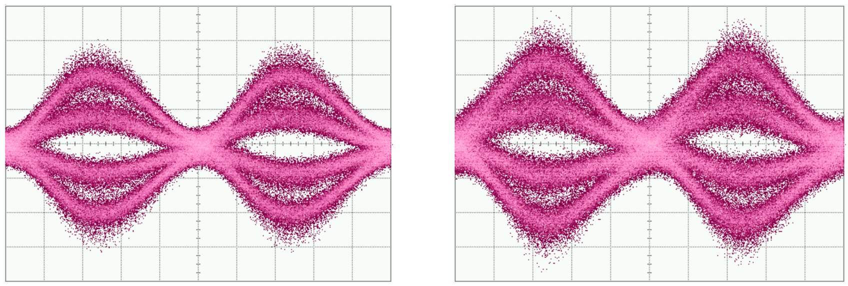
6.7×10^{-5}. The BER performance of each channel after transmission over 320 km of SSMF is also shown in Fig. 5(a). The difference between the best BER and the BERs of all other channels are less than one order of magnitude. The BER of the worst channel can still be improved to below 10^{-9} using forward error correction (FEC), at the expense of reduced effective bit rate. The optical spectrum of all 8 channels is shown in Fig. 5(b). Due to imperfect gain equalization of EDFA, channels with longer wavelength have higher output powers.



(a) (b)

Fig. 3 Measured demodulated eye diagrams (20 ps/div.) (a) Back-to-back and (b) after transmission of 320 km

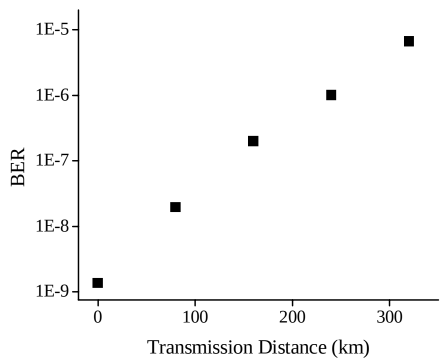
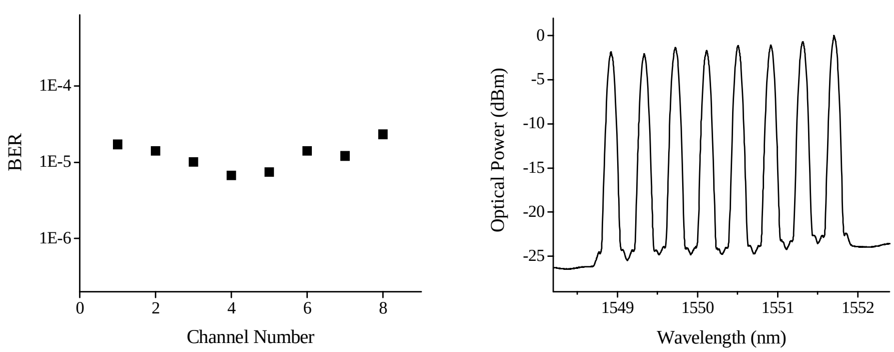


Fig. 4 Measured BER as a function of transmission distance



(a) (b)

Fig. 5 (a) Measured BERs and (b) optical spectrum (wavelength resolution: 0.01 nm) of all 8 WDM channels after transmission of 320 km

4. Conclusions

We demonstrated experimentally, for the first time, the transmission of OD8PSK signals, in particular 8-channel 10 Gs/s (30 Gb/s) OD8PSK signals over 320 km of SSMF with an EDFA spacing of 80 km. The channel spacing was 50 GHz, resulting in a spectral efficiency of 0.6 b/s/Hz. A BER of 2.3×10^{-5} for the worst WDM channel was achieved after transmission over 320 km of SSMF. When a 239/255 Reed-Solomon Forward Error Correction code is applied, this work effectively demonstrates error-free transmission of 8-channel 50 GHz-spaced 9.33 Gs/s (28 Gb/s) OD8PSK signals over 320 km of SSMF with an EDFA spacing of 80 km. High back-to-back chromatic dispersion tolerance was also demonstrated.

The noise apparent in the back-to-back demodulated eye diagram, shown in Fig. 1(a), limited the spectral efficiency and the transmission distance in the experiment. To generate 4 levels of phase states with low noise using a QPSK modulator, modulator drivers with a peak-to-peak voltage of $2V_\pi$ are required. In the current experiment, the modulator drives used for the experiments provided a peak-to-peak voltage of 8 V while the $2V_\pi$ of the QPSK modulator was about 10 V. In addition, the electrical driving signals for the QPSK modulator in the experiments, which were derived from the data output port in the PPG using a broadband electrical splitter, were degraded by electrical back-reflection from modulator drivers used to drive the QPSK modulator. The transmitter performance should be improved significantly by using low V_π modulators or modulator drivers with high peak-to-peak output voltage and by eliminating the degradation of electrical driving signals. In the current experiments, all 8 WDM channels were co-polarized. At a channel spacing of 50 GHz, degradations due to XPM can be reduced by using polarization interleaving [10]. Simulations indicate that, with a peak-to-peak voltage of $2V_\pi$ for the QPSK modulator and polarization interleaving, OD8PSK transmission can achieve a spectral efficiency of 1.2 b/s/Hz over 1000 km of SSMF by reducing channel spacing to 25 GHz, rather than the use of polarization multiplexing, which would eliminate active polarization control at the receiver.

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