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Direct-detection optical differential 8-level phase-shift keying (OD8PSK) for spectrally efficient transmission

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Abstract: An implementation of optical differential 8-level phase-shift keying (OD8PSK) is proposed for spectrally efficient high capacity long-haul optical fiber transmission systems. Interferometric demodulation and direct detection at the receiver yield three output binary sequences identical to the three input binary sequences. This is accomplished by proper design of electrical encoding and optical encoding at the transmitter. Three optical encoding schemes are proposed with corresponding differential electrical encoding schemes. Numerical simulations are performed for a single channel transmission to evaluate the transmission performances of OD8PSK systems.

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1. Introduction

Multilevel modulation formats such as optical differential quaternary phase-shift keying (DQPSK) with direct detection have attracted much attention recently due to increased

spectral efficiency. High spectral efficiency not only leads to larger aggregate capacity but also provides better tolerance to chromatic dispersion and polarization-mode dispersion (PMD). Direct detection, on the other hand, allows simple receiver structures free of local oscillators and polarization control. Optical DQPSK with direct detection has been proposed [1] to reduce the spectral width by one half. Significant increase in chromatic dispersion tolerance and robustness against fiber nonlinearities in optical DQPSK transmission have been demonstrated while allowing simple direct detection [2, 3]. For further improvements in spectral efficiency, an 8-level amplitude- and phase-shift keying (8-APSK) with direct detection has been proposed by combining binary amplitude-shift keying and DQPSK. This approach is a straightforward combination of two well-known modulation formats, directly yielding three binary output data sequences identical to the three input data sequences. As a result, no new electrical/optical encoding and optical demodulation are required. Large dispersion tolerance has been demonstrated for return-to-zero (RZ) 8-APSK modulation [4]. In single-channel 8-APSK systems, the system performance is mainly limited by different amounts of self-phase modulation (SPM) accumulated for bits with two different amplitudes. This limitation due to SPM can be mitigated through post-transmission nonlinear phase compensation for single channel systems [5]. However, the effectiveness of post-transmission nonlinear phase compensation is limited for multi-channel systems as inter-channel cross-phase modulation (XPM) becomes major transmission impairment. Since inter-channel XPM increases with the increase of spectral efficiency (decrease of channel spacing) [6], novel 8-level modulation formats robust to XPM are desirable.

In order to make it more tolerant to both SPM and XPM, constant-amplitude 8-level modulation format must be devised. In this letter, we present a practical implementation of constant-amplitude optical differential 8-level phase-shift keying (OD8PSK) with direct detection for high-capacity spectrally-efficient fiber-optic transmission. Electrical encoding and optical encoding/modulation schemes have been designed to preserve the same simplicity of receiver architectures based on interferometric demodulation and direct detection, directly yielding three binary output data sequences identical to the three input data sequences. Three different optical encoding/modulation schemes and the corresponding electrical encoders are presented. The transmission performances of the proposed OD8PSK encoded signals have been investigated by numerical simulation.

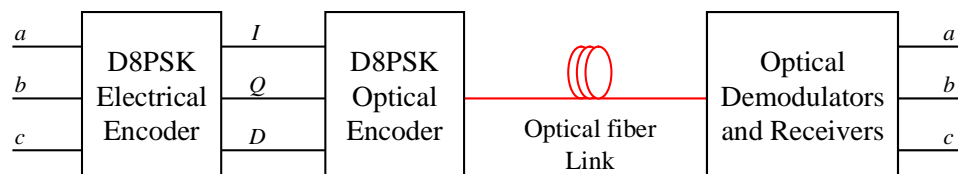## 2. OD8PSK Transmission System

Fig. 1. Schematic of OD8PSK transmission system

In OD8PSK modulation format, each 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 $7\pi/4$. Each encoded symbol carries three bits of information and the symbol rate is one third of the total bit rate. A schematic diagram for OD8PSK transmission systems is shown in Fig. 1. It consists of an electrical encoder and an optical encoder at the transmitter, and optical demodulators and balanced detectors at the receiver. The electrical encoder maps three independent data channels, $a, b,$ and $c,$ into three differentially-encoded data sequences, $I, Q,$ and $D.$ Gray code is implemented in the electrical encoding schemes so that when a symbol error occurs, it is more likely that only one bit error occurs in one of three output channels [7]. In the optical encoder, the encoded data sequences drive optical modulators to generate differentially-encoded optical signal at a

symbol rate equal to the bit rate of each input data channel. After transmission through optical fiber, the differentially encoded optical signal is demodulated optically and the original data, $a, b,$ and, $c,$ are recovered by the receivers with direct detection.

2.1 Optical demodulator and receivers

Due to eight possible differential phases, four optical inteferometric demodulators and four receivers are needed to decode OD8PSK encoded signals. The structure of optical demodulators and receivers is illustrated in Fig. 2. Each optical demodulator is a one-bit delayed Mach-Zehnder (MZ) interferometer with a phase shift of $\pi/8, 3\pi/8, -\pi/8,$ or $-3\pi/8$ between two arms of the interferometer. A balanced detector is used after each optical demodulator to detect the demodulated signal. The demodulators are arranged so that the original input data are recovered directly from the output signals of the receivers. Two input data channels, a and b, are recovered directly while the third input data channel, c, is recovered from two balanced detectors, c_1 and c_2, through an XOR gate, as shown in Fig. 2.
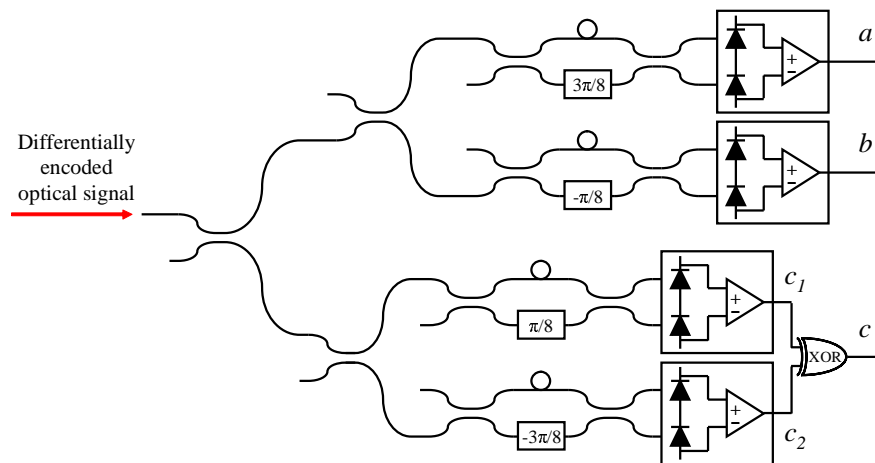

Fig. 2. Schematic diagram of optical D8PSK demodulator and receiver

2.2 OD8PSK electrical and optical encoders

To encode OD8PSK on an optical carrier, generation of eight different phases whose differences are integer multiples of $\pi/4$ is required. In this section, we present three different optical encoding schemes and the corresponding electrical encoders to generate OD8PSK encoded optical signals. An obvious method to encode eight different phases is to use three cascaded optical modulators as shown in Fig. 3(a). The modulator after the source laser is for RZ pulse carving for RZ OD8PSK. Without this modulator, non-return-to-zero (NRZ) OD8PSK can be encoded. The first modulator is a Mach-Zehnder (MZ) modulator biased at transmission null and driven by one (I) of the three encoded outputs of the electrical encoder with a peak-to-peak voltage of $2V_\pi$ so that the encoded phase difference is 0 or π. The second and third modulators are optical phase modulators with the encoded phase differences of 0 or $\pi/2$ and 0 or $\pi/4$, respectively. To exactly recover the three original binary input data sequences with the optical encoding and demodulation schemes defined above, the relationships between the input and output of the electrical encoder are found to be

$$I = \bar{d}(i\,\bar{a}+\bar{i}\,a)\,\bar{q}+(\bar{d}\,q+d\,\bar{c})(i\,\bar{b}+\bar{i}\,b)+d\left[(i\,\bar{q}+\bar{i}\,q)\,\bar{a}+(i\,q+\bar{i}\,\bar{q})a\right]c$$

$$Q = \left[q\,\bar{c} + (q\,\bar{d} + \bar{q}\,d)\,c \right](a\,b + \bar{a}\,\bar{b}) + \left[\bar{q}\,c + (q\,d + \bar{q}\,\bar{d})\,\bar{c} \right](a\,\bar{b} + \bar{a}\,b)$$

$$D = (d\,\bar{c} + \bar{d}\,c)(a\,b + \bar{a}\,\bar{b}) + (d\,c + \bar{d}\,\bar{c})(a\,\bar{b} + \bar{a}\,b)$$

where the bar above the symbol indicates a logical inversion, $I, Q,$ and, D are the output bits of the electrical encoder for a given set of input bits, a, b, and c, and i, q, and d are the output bits of the electrical encoder in the previous time slot (i.e., $i_k = I_{k-1}$, $q_k = Q_{k-1}$, and $d_k = D_{k-1}$). These logical relationships have been verified by numerical simulations.
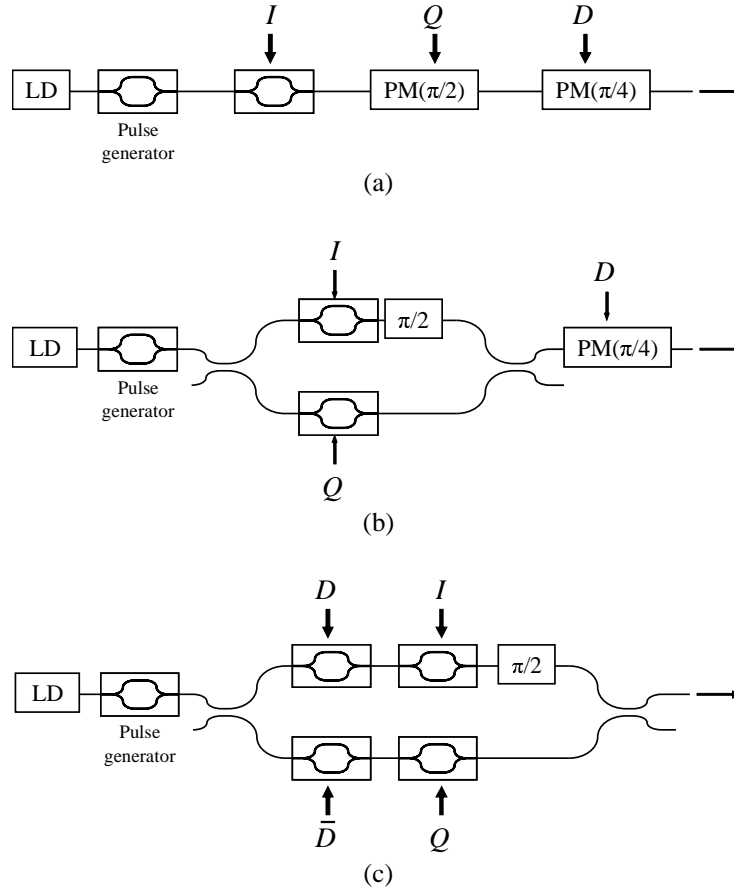

Fig. 3. Schematic diagrams of optical encoders for OD8PSK modulation

Another method to produce eight different phases whose differences are integer multiples of $\pi/4$ is to use a QPSK modulator consisting of two MZ modulators, and a phase modulator as shown in Fig. 3(b). The QPSK modulator driven by I and Q generates a differential phase between successive bits of $0, \pi/2, \pi,$ or $3\pi/2$ [1]. The phase modulator driven by D provides a phase change of 0 or $\pi/4$. The logical equations of the electrical encoder for this optical encoding method are given by

$$I = \bar{d}\left[i(\bar{q}\,a + q\,\bar{b}) + i(q\,a + \bar{q}\,b) \right] + d\left[(i\,\bar{b} + \bar{i}\,b)\,\bar{c} + (q\,a + \bar{q}\,\bar{a})\,c \right]$$

$$Q = \bar{d}\left[i(q\,\bar{a} + \bar{q}\,b) + \bar{i}(\bar{q}\,a + q\,\bar{b}) \right] + d\left[(i\,\bar{a} + \bar{i}\,a)\,c + (q\,\bar{b} + \bar{q}\,b)\,\bar{c} \right]$$

$$D = (d\,\bar{c} + \bar{d}\,c)(a\,b + \bar{a}\,\bar{b}) + (d\,c + \bar{d}\,\bar{c})(a\,\bar{b} + \bar{a}\,b)$$

The third method for optical OD8PSK encoding is to use four modulators in a MZ interferometer as shown in Fig. 3(c). The MZ interferometer has also differential phase of $\pi/2$ between two arms. The first MZ modulators in the upper and lower arms are biased at $V_\pi/2$ and driven by D and $\bar{D}$, respectively, with a peak-to-peak voltage of $V_\pi/2$ so that the peak power ratio between the outputs from the two modulators is $\sin(\pi/8)/\cos(\pi/8)$ or $\cos(\pi/8)/\sin(\pi/8)$. The second MZ modulators in the upper and lower arms are biased at transmission null and driven by I and Q, respectively, of three encoded outputs of the electrical encoder with a peak-to-peak voltage of $2V_\pi$. The logical equations of the electrical encoder for this optical encoding method are given by

$$I = \left[(\bar{q}\,a\,b + q\,a\,\bar{b}) + (i\,d + q\,\bar{d})\,a\,b + (\bar{i}\,d + \bar{q}\,d)\,a\,\bar{b} \right] c$$

$$+ \left[(i\,a\,\bar{b} + \bar{i}\,a\,b) + (i\,d + q\,\bar{d})\,\bar{a}\,b + (\bar{i}\,d + \bar{q}\,d)\,a\,b \right] \bar{c}$$

$$Q = \left[(i\,a\,\bar{b} + \bar{i}\,\bar{a}\,b) + (\bar{i}\,d + \bar{q}\,\bar{d})\,a\,b + (i\,d + q\,d)\,a\,\bar{b} \right] c$$

$$+ \left[(\bar{q}\,a\,b + q\,a\,\bar{b}) + (\bar{i}\,d + q\,\bar{d})\,a\,\bar{b} + (i\,d + \bar{q}\,d)\,a\,b \right] \bar{c}$$

$$D = \left[(i\,\bar{q} + \bar{i}\,q)(\bar{a}\,\bar{b} + a\,b) + (q\,d + \bar{q}\,\bar{d})(a\,\bar{b} + \bar{a}\,b) \right] c + \left[(i\,q + \bar{i}\,\bar{q})(a\,b + \bar{a}\,\bar{b}) + (i\,d + \bar{i}\,d)(a\,\bar{b} + \bar{a}\,b) \right] \bar{c}$$

3. Numerical simulations of transmission of RZ OD8PSK encoded signals

Numerical simulations were carried out to evaluate transmission performances of RZ (50% duty cycle) OD8PSK encoded signals in a dispersion-managed transmission system at 10 Gs/s (giga symbols per second) or 30 Gb/s as shown in Fig. 4. The OD8PSK transmitter consists of an electrical encoder with three independent 10 Gb/s PRBS input signals and an optical encoder. An optical launch power of 2 dBm and a laser linewidth of 1 MHz were used for the simulation. Before launched into the transmission system, the OD8PSK encoded signals are filtered by a Gaussian optical bandpass filter (BPF) with a 3 dB bandwidth of 15 GHz. Pre-dispersion compensation using a dispersion-compensating fiber (DCF) is also applied. The optical fiber transmission system consists of 8 spans. Standard single mode fiber (SSMF) of 100 km, DCF of a desired length and two Erbium-doped fiber amplifiers (EDFA) constitute each transmission span. The DCF has a dispersion of 80 ps/nm km and a loss of 0.5 dB/km. The EDFAs have a noise figure of 5 dB. 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. Dispersion is compensated evenly in each span without post-dispersion compensation. After transmission through the optical fiber link, the optical signal is filtered by another Gaussian optical BPF with a 3 dB bandwidth of 15 GHz. To evaluate the transmission performance of the OD8PSK encoded signals, the differential phase Q factor method of estimating symbol error ratio (SER) is used [8]. For OD8PSK, the differential phase Q factor is calculated from

the differential phase eye diagram and the SER is obtained from the differential phase Q factor by assuming Gaussian noise in differential phase for each phase state. The system SER is then obtained by statistically averaging the SERs of all 8 differential phase states. Comparison of SERs calculated by the differential phase Q factor method and by direct error counting at high SERs ($> 10^{-4}$) showed that results using these two methods agree very well, corresponding to a difference of less than 0.1 dB in the Q factor. We shall use the differential phase Q factor method for the remainder of this paper. When symbol errors are caused by mistaking symbols for adjacent symbols, each symbol error causes a single bit error in one of the three channels due to Gray code implementation. Since the likelihood that symbols are mistaken for other than adjacent symbols is relatively remote, the bit error ratio (BER) of the system is about one-third of SER.
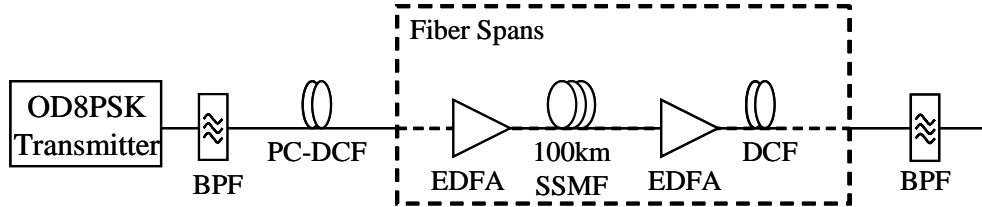

Fig. 4. Schematic diagram of OD8PSK transmission system for simulations (PC-DCF: Predispersion compensation)

Differential phases as functions of differential amplitude can provide information about the transmission performance of differential PSK signals. The differential phases of the OD8PSK signal as functions of differential amplitude after transmission of 8 spans are depicted in Fig. 5(a). The slope of differential phases in each differential phase state is a manifestation of nonlinear phase change due to amplified spontaneous emission (ASE) noise of the optical amplifiers, SPM and dispersion [9], which is the main cause of system degradation for single channel systems. The slope can be used as a measure of nonlinear phase noise and post-transmission nonlinear phase compensation can be designed easily by monitoring this slope. It should be noted that the slopes are the same for all 8 differential phase states. To investigate the dispersion tolerance of OD8PSK for transmission, we calculated the differential phase Q factor as a function of total residual dispersion of the

(a)   (b)
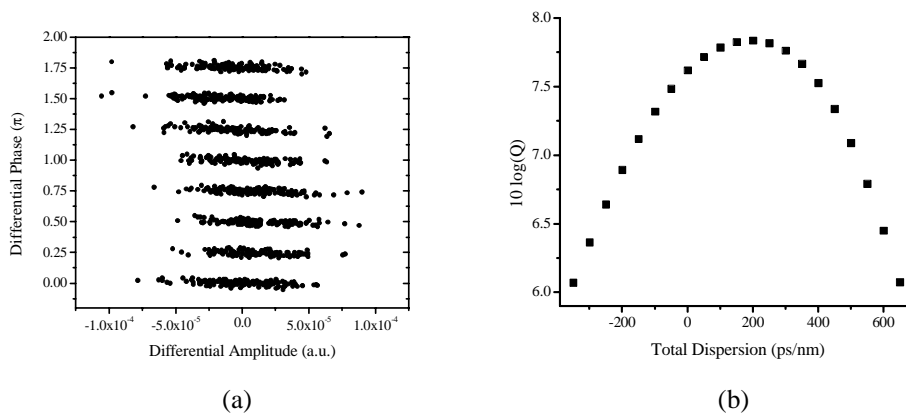
Fig. 5. Simulation results: (a) Differential phase as a function of differential amplitude (b) Differential phase Q factor as a function of total dispersion.

transmission systems. The differential phase Q factor after 8 spans of transmission is shown in Fig. 5(b). The dispersion tolerance with degradation of less than 0.5 dB is 550 ps/nm.

The SER of the system as a function of the number of fiber spans is shown in Fig. 6(a). The maximum distance that the OD8PSK signal can be transmitted with an SER better than 10^{-9} is approximately 800km. We also investigated the effect of laser linewidth in the transmitter on the system performance. Figure 6(b) plots the differential phase Q factor as a function of the laser linewidth after 8 spans of transmission. To limit the degradation of performance to 0.5 dB in differential phase Q factor due to finite laser linewidth, the laser linewidth has to be smaller then 2 MHz.
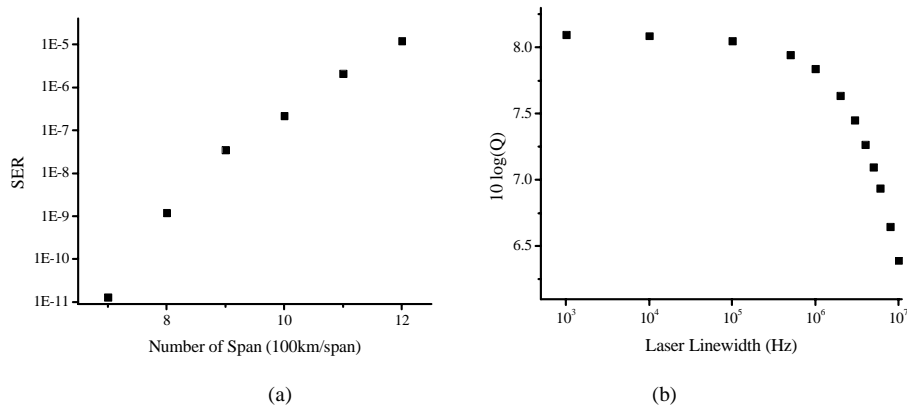

Fig. 6. Simulation results: (a) SER as a function of the number of span, (b) Differential phase Q factor as a function of laser linewidth

4. Conclusions

A practical implementation of optical differentially-coded 8-level PSK with direct detection has been proposed for spectrally efficient optical fiber transmission systems. Three different optical encoder structures and the corresponding differential electrical encoders have been presented. Numerical simulations show that the single channel OD8PSK modulation signal with a laser linewidth of 1 MHz can be transmitted up to approximately 800 km with a SER better than 10^{-9} without post-transmission nonlinear phase compensation.

Post-transmission nonlinear phase compensation can be used to improve the transmission performance of single-channel OD8PSK transmission [9, 10]. Our simulations show that post-transmission nonlinear phase compensation can improve the SER of OD8PSK transmission by two to three orders of magnitude. Due to reduced differential phase in OD8PSK, it is expected that tight control of phase errors in the one-bit delayed MZ interferometers is required. Our numerical simulation shows that a 5° phase error results in a 0.5 dB penalty in the differential phase Q factor.