

Direct detection differential polarization-phase-shift keying based on Jones vector

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Abstract: In this paper, differential polarization-phase-shift keying (DPolPSK) is proposed for digital lightwave communication, in which information is encoded in both polarization and phase. The DPolPSK symbols are demodulated by optical delayed interference and electrical multilevel detection, without using any polarization control or polarization selection at the receiver. Simulation results show that single-channel error-free transmission at 20 Gb/s (10 Gsymbol/s) through 25 spans of 100 km standard single-mode fiber is possible. Unlike for DPSK, the Gaussian BER estimation method is found to be reasonably accurate for this new modulation format. The constellation diagram of DPolPSK can be represented by a set of Jones vectors. Hence DPolPSK can also be called differential Jones-vector shift keying (DJSK).

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1. Introduction

Conventional digital communication encodes information in both the amplitude and phase of electrical signals. At the optical frequency, an additional degree of freedom, namely the polarization, can be used to carry information. Polarization-Shift Keying (PolSK) is one of such techniques to encode information in the State Of Polarization (SOP) of lightwaves [1,2]. Another technique that takes advantage of polarization is to transmit two independent channels simultaneously in orthogonal SOPs at the same wavelength, known as Polarization-Division Multiplexing (PDM) [3,4]. Unfortunately, the SOP of lightwave can not be preserved during transmission through optical fibers. Dynamic polarization control is usually required at the receiver to track the SOP of the incoming signal. Since polarization rotation in fiber is wavelength sensitive, channel-by-channel polarization control is necessary in wavelength-division-multiplexing (WDM) systems. The cost of polarization control prevents widespread applications of these techniques in practical optical communication systems. In this paper, we propose a novel method to utilize polarization yet without using any polarization control or polarization selection at the receiver. Altering both polarization and phase of lightwave, the simplest form of this modulation format can transmit 2 bits per symbol and hence double the spectral efficiency. As a constant power modulation format, DPolPSK is expected to be tolerant to fiber nonlinearity. We name this format differential polarization-phase-shift keying or differential Jones-vector shift keying.

2. DPolPSK transceiver

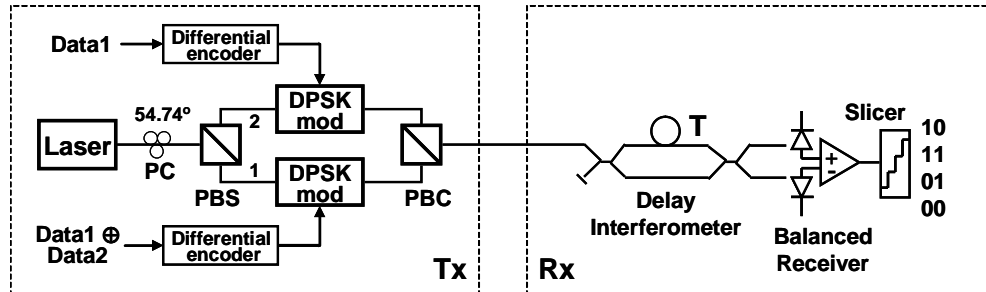


Fig. 1. Block diagram of quaternary DPolPSK transmitter and receiver.

The transmitter and receiver for quaternary DPolPSK are shown in Fig. 1. At the transmitter, a polarization beam splitter (PBS) is used to divide the parallel and orthogonal polarization components of the laser source. The polarization of the linearly-polarized laser is adjusted to 54.74 degrees (relative to the parallel state) by a polarization controller to achieve a 1:2 power ratio between the parallel and orthogonal polarization states. Each polarization state is then independently modulated by a Differential Phase-Shift Keying (DPSK) modulator, e.g., a Mach-Zehnder (MZ) modulator biased at the null with a $2V_{\pi}$ voltage swing. The data source is differentially encoded. The two DPSK signals residing in the orthogonal polarization states are combined by a polarization beam combiner (PBC) before transmission. The receiver for DPolPSK is the same as the standard DPSK receiver; no polarization control or polarization selection with polarizers is required. Since orthogonally-polarized lightwaves do not interfere with each other, the two DPSK signals are independently interferometrically demodulated without any crosstalk. If the parallel polarization state generates voltage levels of $+V$ and $-V$, the orthogonal state will generate $+2V$ or $-2V$ since its power is twice as much. Adding the voltages from the parallel and orthogonal polarization state together, four voltage levels, $+3V$, $+V$, $-V$ and $-3V$ are possible at the output of balanced receiver. After multi-level detection, four symbols can be recovered.

Gray code can be used to label the four voltage levels to avoid two bit errors generated by a symbol error. To accomplish this, an XOR logic operation in addition to differential

encoders is required at the transmitter as shown in Fig. 1. This corresponds the gray code +3V (10), +V (11), -V (01) and -3V (00).

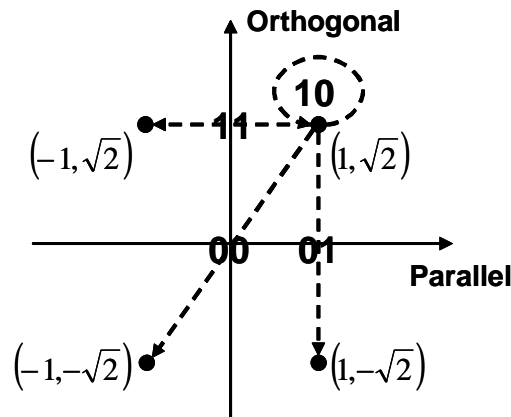


Fig. 2. Four Jones vectors corresponding to four symbols in quaternary DPolPSK.

A fundamental way to describe DPolPSK is to use Jones vectors. The Jones vectors corresponding to the four states in quaternary DPolPSK are $(1, \sqrt{2})$, $(-1, \sqrt{2})$, $(1, -\sqrt{2})$ and $(-1, -\sqrt{2})$, as visualized in Fig. 2. In the figure, the x-axis and y-axis denote the lightwave with parallel and orthogonal polarization states, respectively. Negative values denote a π -phase shift or a polarization state in the opposite direction. At a given symbol interval, the state of lightwave can be represented by one of the four vectors. The transitions between the four vectors correspond to four possible voltage levels in the receiver. Mathematically, the output voltage is proportional to the real part of the inner product of the Jones vectors. An example is given in Fig. 2. One of the extensions of quaternary DPolPSK is to use Differential Quaternary Phase-Shift Keying (DQPSK) modulator and demodulator [5] to replace the DPSK modulator and demodulator in Fig. 1. Hence, the 16-ary DPolPSK, or DPolQPSK, can be achieved. The Jones vectors for the 16-ary DPolPSK are $(\pm 1, \pm \sqrt{2})$, $(\pm j, \pm \sqrt{2})$, $(\pm 1, \pm j\sqrt{2})$ and $(\pm j, \pm j\sqrt{2})$ if the phase set $\{0, \pi/2, \pi, 3\pi/2\}$ is used. Again, the output voltage is proportional to the real part of the inner product of Jones vectors, one of which should be modified by a static $\pi/4$ or $-\pi/4$ phase offset in the delay interferometer. Therefore, DPolPSK is essentially Differential Jones-vector Shift Keying (DJSK). The name of DPolPSK highlights the fact that interferometric demodulator is phase sensitive. This is in sharp contrast to conventional PolSK [1,2] where only the polarization state is detected by measuring the Stokes vectors (S_1, S_2, S_3) , which is phase insensitive. The number of output voltage levels at balanced receiver(s) in the quaternary and 16-ary DPolPSK is four. Higher-order DPolPSK formats using more constellation points of Jones vectors can be designed, which can lead to more than four voltage levels at the output of balanced receiver.

It should be noted that DPolPSK is a constant power modulation format, even though the detection is multilevel. This results in good nonlinearity tolerance in transmission. In its simplest form of quaternary DPolPSK, the four-level detection scheme is similar to the power unbalanced polarization-division-multiplexing technique proposed in [6], which combines two independent OOK modulated signals. However, the nonconstant power feature in power unbalanced polarization-division-multiplexing is undesirable in high spectral efficiency transmission systems. Additionally, since the signal-ASE beat noise is signal dependent, the four levels in power unbalanced polarization-division-multiplexing are not equally noisy. This introduces ~ 5 dB additional power penalty [7]. In contrast, the four levels in DPolPSK are almost equally noisy, as be shown in the next section.

3. Transmission Performance

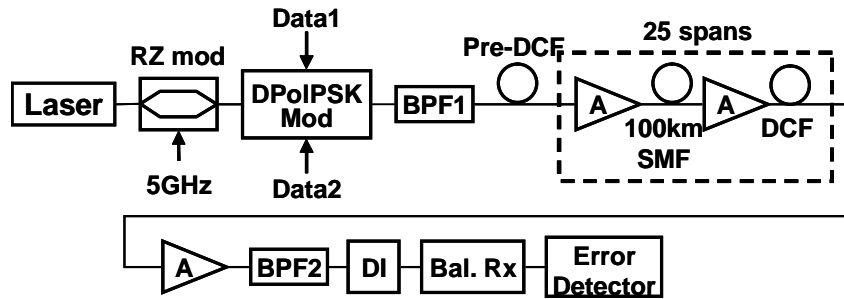


Fig. 3. 20Gb/s DPolPSK 2500 km SMF transmission setup.

The transmission performance of quaternary DPolPSK is investigated by numerical simulation. Figure 3 shows the 20 Gb/s DPolPSK single channel transmission system consisting of 2500 km of SMF. The laser frequency and linewidth is 193.1 THz and 10 MHz, respectively. A 33% return-to-zero (RZ) pulse carver is used before the DPolPSK modulator. The extinction ratio of all three MZ modulators is set to 20 dB. The two bandpass filters (BPF) are first-order Gaussian filters with a 3 dB bandwidth of 25 GHz. The electrical filter in the balanced receiver is a 3rd order Bessel filter with a 7.5 GHz bandwidth. Each transmission span includes two erbium-doped fiber amplifiers, a 100 km standard SMF and a dispersion compensating fiber (DCF). The noise figure of the fiber amplifiers is 5 dB. The dispersion of SMF is 16 ps/nm at 192.1 THz and the loss is 0.2 dB/km. The total optical power (sum of both polarizations) entering the SMF is optimized to be 6 dBm. The DCF dispersion and loss are -80 ps/nm and 0.5 dB/km. The core area is 31 μm^2 . The power at the input of DCF is 0 dBm. Optimal precompensation is found to be -850 ps/nm. Each span is undercompensated by 46 ps/nm and hence the total dispersion is 300 ps/nm.

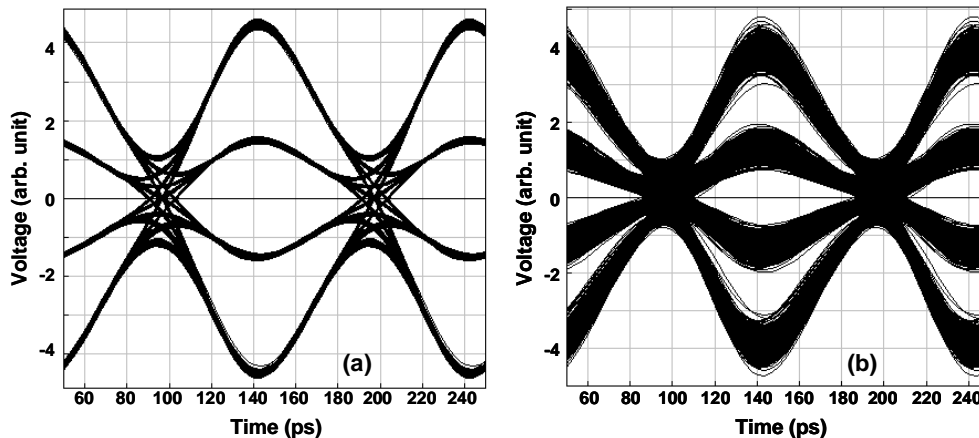


Fig. 4. Eye diagrams (a) before and (b) after 2500 km transmission.

The eye diagrams before and after 2500 km transmission are shown in Fig. 4. The length of PRBS used in simulations is $2^{12}-1$. The shift between data1 and data2 PRBS is 864 bits. After transmission, the upper and lower eye is slightly worse than the middle eye due to the nonlinear phase noise. The eye Q-factors for the upper, middle and lower eye are 6.42, 7.09 and 6.52, respectively. As shown below, unlike for DPSK, Gaussian BER estimation method is found to be reasonably accurate for DPolPSK. If Gray code is used, the estimated BER using Gaussian approximation is $[\text{erfc}(Q_1/\sqrt{2}) + \text{erfc}(Q_2/\sqrt{2}) + \text{erfc}(Q_3/\sqrt{2})]/8 = 2.62 \times 10^{-11}$.

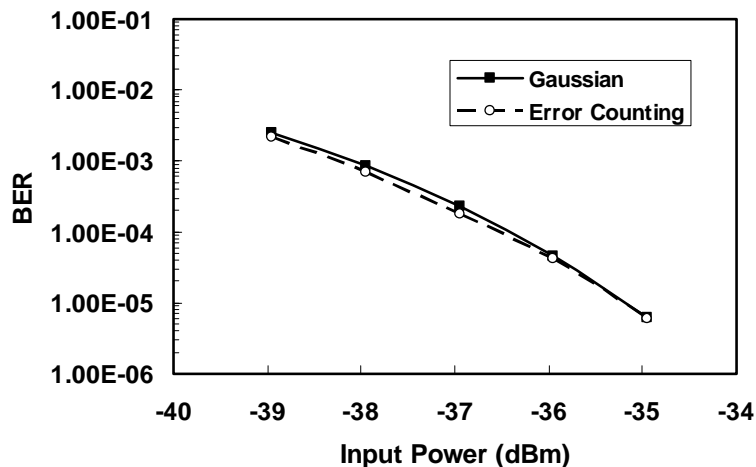


Fig. 5. Back-to-back BERs obtained by using Gaussian statistics and direct error counting.

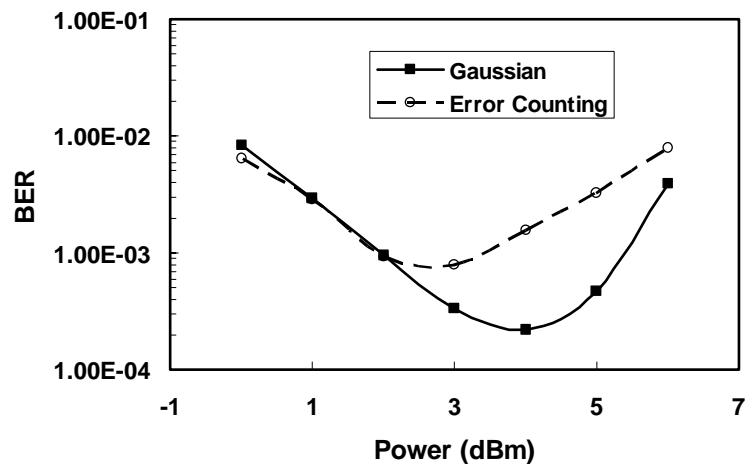


Fig. 6. BERs obtained by using Gaussian statistics and direct error counting after 45 spans transmission.

It has been known that Gaussian statistics can not be used to estimate the BER of DPSK signals [8]. To investigate the accuracy of Gaussian approximation for DPoIPSK with preamplified receivers, the back-to-back BERs obtained by using Gaussian statistics are compared with using direct error counting. The result is shown in Fig. 5. At least 240 errors have been recorded for each direct error counting. The agreement between the two approaches establishes the effectiveness of Gaussian statistics for back-to-back BERs. It is expected that Gaussian estimation should also work well in the linear transmission regime, where BERs are dominated by ASE. In the nonlinear transmission regime, nonlinear phase noise plays an important role. To investigate whether the BER still obeys Gaussian estimation, direct error counting is performed at 10^{-3} BER after 45 spans SMF transmission. The setup and simulation parameters are the same as those in 2500 km transmission. The seed numbers for the PRBS sequences are randomly chosen and the power difference between SMF and DCF fiber is maintained at 6 dB. The result is shown in Fig. 6, where at each amplifier power level more than 102 errors are recorded. The close agreement between these two error estimation methods in lower power levels reconfirms the back-to-back result in Fig. 5. When power level

increases, Gaussian method generally underestimates BER. The optimal power level obtained by Gaussian estimation is around 1 dB higher. Nevertheless, the general trend of BER with power increasing agrees with each other. Gaussian estimation method can be used for DPolPSK with the understanding that it may underestimate BER around the optimal power level.

As a modulation format utilizing the polarization, DPolPSK is expected to suffer penalties due to polarization-mode dispersion (PMD). In the presence of PMD, the four symbols in DPolPSK may experience different time delays. As a result, the eye may split or shift in DPolPSK. In addition, DPolPSK may suffer PMD-induced coherent crosstalk as other modulation formats [9]. A further PDM modeling and investigation are required for this new modulation format. In the case of WDM transmission, it has been known that nonlinear polarization rotation is another degradation mechanism for modulation formats utilizing polarization [10]. However, the constant power feature of DPolPSK is expected to reduce this effect as it has been investigated for a RZ-DPSK WDM transmission using alternate polarization between bits [11].

4. Conclusion

In summary, we have proposed a new constant-intensity modulation format, DPolPSK or DJSK that encodes information in both polarization and phase. Unlike the conventional PolSK or PDM, no polarization control or polarization selection is required at the receiver. The polarization-phase symbols are decoded by optical delayed interference and electrical multilevel detection. The transmission property of the proposed modulation format has been investigated by means of numerical simulation. Clear eye opening at 20 Gb/s is obtained after a single-channel transmission through 25 spans of 100 km SMF fiber. The estimated BER under the Gaussian assumption is 2.62×10^{-11} . By comparison with direct error counting, Gaussian BER estimation method is found to reasonably accurate for DPolPSK. This technique can be readily extended to 16-ary DPolPSK.

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