Generation of DQPSK format and its performance against polarization mode dispersion

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Received February 18, 2008

We propose a novel transmitter and receiver for differential quadrature phase-shift keying (DQPSK) format. The impact of the first-order polarization mode dispersion (PMD) on systems using DQPSK with 100-Gb/s non-return-to-zero (NRZ) or return-to-zero (RZ) format is investigated. Through computing the eye openings of DQPSK formats under different PMD conditions, it is found that NRZ DQPSK, as compared with RZ DQPSK, incurs smaller eye opening due to PMD. Carrier-suppressed return-to-zero (CSRZ) DQPSK format has better tolerance than RZ DQPSK format to PMD for a given bit rate.

OCIS codes: 060.4510, 060.4080, 060.2420.

doi: 10.3788/COL20090701.0015.

With the rapid growth of data-centric services, the bit rate of the next-generation Ethernet will be 100-Gb/s class[1]. The 100-Gb/s Ethernet architectures based on wavelength multiplexing for metro networks have been proposed, and an electrical time-division-multiplexing (ETDM) transmitter has been demonstrated recently[2]. However, the transmission of 100-Gb/s signals per channel over wide-area network will result in strong penalties from residual chromatic dispersion (CD) and polarization mode dispersion (PMD), even after practical optical impairment compensation. Optical time-division-multiplexing (OTDM) transmission of 100-Gb/s signals has been reported[3,4], but OTDM technology requires bulky components, and it is not suited for economical systems. In order to realize future 100-Gb/s Ethernet transport, system demonstrations of 100-Gb/s transmission without 100-GHz-class electronics and OTDM are favorable. Therefore it is necessary to study the advanced optical modulation format and its PMD tolerance on transmission, which can be suitable for future 100-Gb/s Ethernet.

Recently, there has been increasing interest in multi-level phase modulation as differential quadrature phase-shift keying (DQPSK) format because of its high spectral efficiency, relaxed dispersion management, and better PMD tolerance[5,6]. Two parallel Mach-Zehnder modulators (MZMs) have been used in the common DQPSK transmitter, which need to adjust π phase shift exactly, so the method is complex and expensive. The most common solution for the DQPSK receiver consists of a pair of Mach-Zehnder delay interferometers (MZDIs) with differential time delay between the two arms equal to the inverse of the bit rate. From the interference between two adjacent bits, the phase modulation will be converted into directly-detectable amplitude modulation. However, it shows more sensitive to the imperfection of two MZDIs. Two or multiple wavelengths with fixed wavelength spacing have been generated by optical carrier suppression[7]. After optical filtering, two sets of 50-Gb/s DQPSK signals can be carried by the two separated lightwaves with stable wavelength and fixed wavelength spacing. So the bandwidth for electrical amplifiers and external modulators is only 25 GHz for the 100-Gb/s signal generation. Although an optical filter or interleaver can be used to reduce the linear crosstalk between the up and down sub-channels, it can result in an increasing cost of system.

In this letter, we propose a novel DQPSK transmitter using two cascaded phase modulators (PMs) and a novel DQPSK receiver based on time delay and phase shift, which can easily generate non-return-zero (NRZ), return-to-zero (RZ), and carrier-suppressed return-to-zero (CSRZ) DQPSK formats. At the same time, it can overcome the sensitivity to the imperfection of two MZDIs from the common receiver. We also compare the first-order PMD tolerances of different 100-Gb/s DQPSK formats.

The proposed 100-Gb/s DQPSK transmitter and receiver are shown in Fig. 1. The transmitter consists of a continuously oscillating laser followed by a differential Mach-Zehnder modulator (DMZM) and two cascaded PMs. The continuous-wave (CW) laser has a wavelength of 1558 nm. The DMZM is used to generate different duty cycle RZ or CSRZ pulse trains respectively

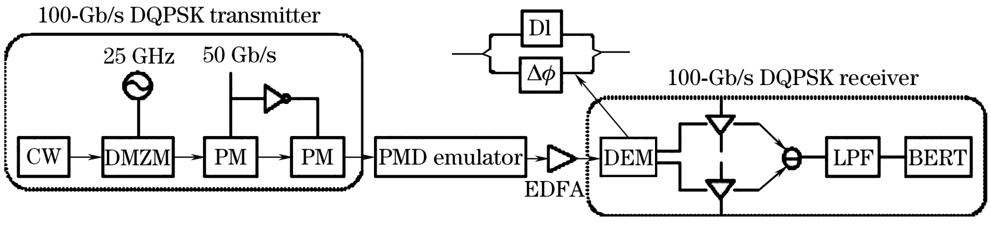

Fig. 1. DQPSK system model. EDFA: erbium-doped fiber amplifier; DEM: demodulator; BERT: bit error rate tester.

when the DMZM is biased at the zero or peak in its transmission curve and driven by a 25-GHz sinusoidal wave[8]. Then the two cascaded PMs are utilized for generating DQPSK format. The first PM is used to generate a phase shift of $\pi/2$ followed by another PM with a phase shift of π. The 50-Gb/s data sets, data 1 and data 2 for driving the two PMs, are from 50-Gb/s NRZ electrical pseudo random bit sequence (PRBS) of length $2^{20}-1$. There is some bits delay between data 1 and data 2, which ensures that the two PRBS signals should be uncorrelated. In this way, the 100-Gb/s DQPSK signal can be generated.

In the receiver, the received bit streams are not a pseudorandom pattern as that of the transmitter due to the nature of the DQPSK modulation. The proposed DQPSK receiver consists of a power splitter, a delay interferometer (DI) with an optical delay τ equal to the symbol period $2/B$ (B is the bit rate), an optical phase shifter, a balanced receiver with two avalanche photodiodes (APDs), and an electrical Bessel low-pass filter (LPF), as shown in Fig. 1. In the optical DQPSK format, information is usually encoded in the differential optical phase between successive bits $\Delta\phi$, where $\Delta\phi$ may take one of the four values $\{0, \pi/2, \pi, 3\pi/2\}$. To detect data 1 and data 2 of DQPSK signal, two adjacent bits should interfere with each other in the output ports. Therefore the generated signal can be divided into two equal-intensity parts by a power splitter, one part passes through a DI which can adjust different path length to realize differential delay, the other part goes into an optical phase shifter with differential optical phase $\pi/4$. Due to the absence of an optical phase reference at such a receiver, the phase reference has to be provided by the signal itself. Thus the preceding symbol in a DQPSK encoded bit stream acts as the phase reference for demodulating the current symbol.

In high-speed transmission, PMD may be costly to avoid[9,10]. It is random and may vary frequently over time due to fiber stress and temperature change. PMD becomes one of the leading causes of signal degradation in data transmission. To study the effect of 100-Gb/s DQPSK signal with NRZ or RZ formats against PMD, we adopt a PMD emulator as shown in Fig. 2. The PMD emulator model consists of the PMD channel transfer function considering the first- and second-order PMD effects. A linear dispersive fiber can be represented by a 2 × 2 transfer matrix of the form[11]

$$T(l,w) = \exp[-(\alpha + j\bar{\beta}(\omega))z]M(l,\omega), \qquad (1)$$

$$M(l,w) = R^{-1}(\omega)D(l,\omega)R(\omega)$$

$$= \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}^{-1} \begin{bmatrix} \exp(-j\phi/2) & 0 \\ 0 & \exp(j\phi/2) \end{bmatrix}$$

$$\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \qquad (2)$$

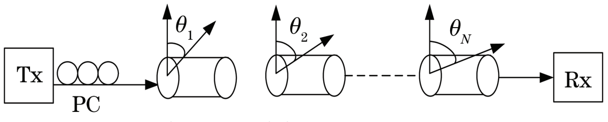

Fig. 2. PMD emulator model. Tx: transmitter; Rx: receiver; PC: polarization controller.

where α is the fiber attenuation, β is the mean propagation constant, $M(l,\omega)$ is the unitary matrix, $R(\omega)$ takes into account the rotation of the principal states of polarization (PSP), and $D(l,\omega)$ takes into account the different propagation speeds on the two PSPs. In the second-order approximation, the time difference between the two polarizations is given by

$$\Delta\tau = \Delta\tau_0 + \Delta\tau' \cdot \omega, \qquad (3)$$

where $\Delta\tau_0$ is the frequency-independent differential group delay (DGD), and the DGD frequency dependency is represented by the depolarization rate $\Delta\tau'$. We can set certain optical fiber length based on the PMD emulator model. However, when only considering the first-order PMD effects, the PMD value of fiber should be different to the change of DGD in the PMD emulator model.

To verify this scheme, a simulation has been carried out using the proposed configuration. DQPSK transmitter and receiver can be regarded as the multiplexing and demultiplexing processes, respectively. In this scheme, information is encoded in the differential optical phase between successive bits $\Delta\phi$, where $\Delta\phi$ may take one of the four values $\{0, \pi/2, \pi, 3\pi/2\}$. Since each symbol transmits two bits of information, the symbol rate is equal to half of the total bit rate. Therefore, only half bandwidth electrical component and modulator is required to generate 100-Gb/s DQPSK format, which not only promotes the transmission performance effectively, but also reduces the cost of system by using low-speed electrical component. The simulated optical spectrum of the generated NRZ DQPSK signal is shown in Fig. 3(a). The

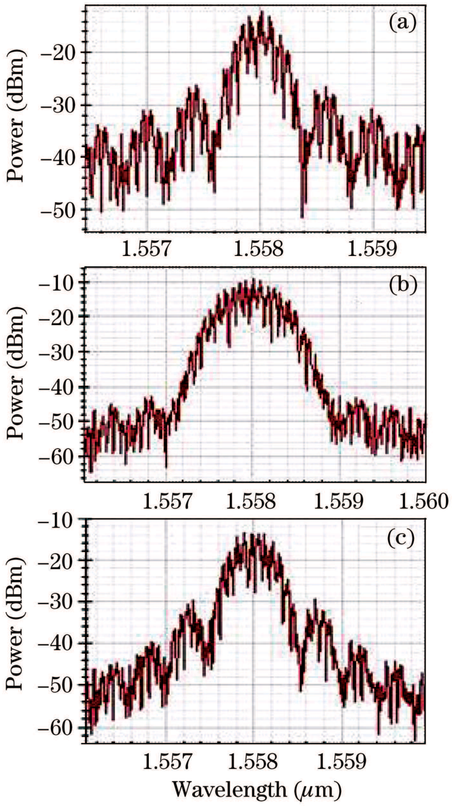

Fig. 3. Spectra of (a) NRZ, (b) RZ, and (c) CSRZ DQPSK signals.

optical spectrum of RZ DQPSK signal with 33% duty cycle is shown in Fig. 3(b). And the optical spectrum of CSRZ DQPSK signal with 66% duty cycle is shown as Fig. 3(c). From Fig. 3, it can be seen that NRZ DQPSK signal has a compact spectrum. The carrier of CSRZ DQPSK signal is suppressed and the spectrum space of band can be decreased. Meanwhile, the spectrum of RZ DQPSK signal is wider than that of NRZ DQPSK and CSRZ DQPSK signals. Moreover, the shape of the DQPSK optical spectrum is identical to that of differential phase-shift keying (DPSK), but the DQPSK spectrum is compressed in frequency by a factor of two due to the halved symbol rate for transmission at a fixed bit rate. The compressed spectrum will be beneficial for achieving high spectral efficiency in wavelength-division-multiplexing (WDM) systems, as well as for increasing the tolerance to CD.

Based on the DQPSK system model shown in Fig. 1, we investigate the impact of first-order PMD on the systems using 100-Gb/s NRZ, RZ, and CSRZ DQPSK signals and the PMD tolerance of these signals by comparing eye diagram and eye opening. Considering the tolerance of first-order PMD alone, the CD tolerance of the 100-Gb/s DQPSK signal is neglected. In the numerical simulation, the generated DQPSK signal goes into the PMD emulator above-mentioned and will be transmitted over a 300-km standard single mode fiber (SMF). The output optical power of the 100-Gb/s DQPSK transmitter is set to 0 dBm. Note that PMD value of SMF will be changed as the DGD value of PMD emulator is different, but the fiber length can be constant. In this way, the first-order PMD tolerance of DQPSK signal can be evaluated.

In the receiver, the 100-Gb/s signals are pre-amplified by using an EDFA with a 1480-nm pump light. Optical noise may be caused by incoherent amplified spontaneous emission in EDFA and can be modeled as complex additive white Gaussian noise in the classical limit[12]. When the DGD value of first-order PMD is set to 5 ps, the eye diagrams of NRZ, RZ, and CSRZ DQPSK signals after demodulation using differential delay and phase shift method are shown in Fig. 4. Since the optical spectrum of DQPSK is narrow compared with binary modulation formats, there is an improvement in tolerance to CD. Meanwhile, the longer symbol duration of DQPSK format makes it more robust to PMD tolerance. For RZ DQPSK format, optical power of each bit means optical pulse. The pulse energy will concentrate in a narrow region of symbol so that the energy overflow needs larger DGD value than that of NRZ DQPSK format. For CSRZ DQPSK format generation, a PM is driven by half sinusoidal signal. The pulse will be phase alternation between its transmission maximum values, which can make the change of phase between adjacent bits. So the optical phase of CSRZ DQPSK format takes half data rate as a cycle. But it takes entire data rate as a cycle in the NRZ DQPSK format. From Fig. 4, it can be seen that the eye diagrams of NRZ, RZ, and CSRZ DQPSK formats are open clearly by considering first-order PMD effects. It means that different DQPSK formats have better tolerance to PMD. Since the spectrum of CSRZ DQPSK format with 66% duty cycle is narrower than that of RZ DQPSK format, CSRZ DQPSK format have higher spectrum efficiency and better PMD tolerance compared with RZ DQPSK format.

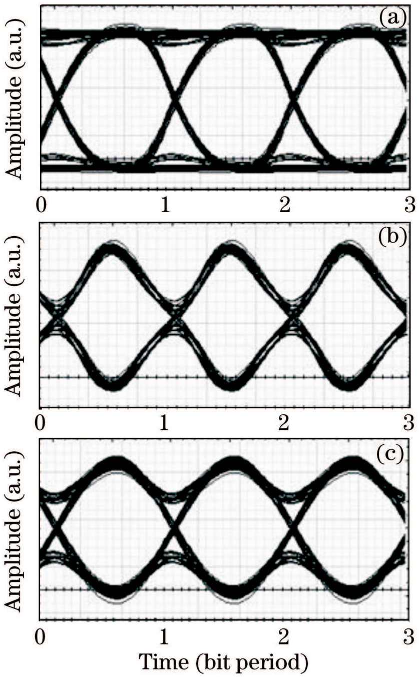

Fig. 4. Eye diagrams of (a) NRZ, (b) RZ, and (c) CSRZ DQPSK formats. DGD = 5 ps.

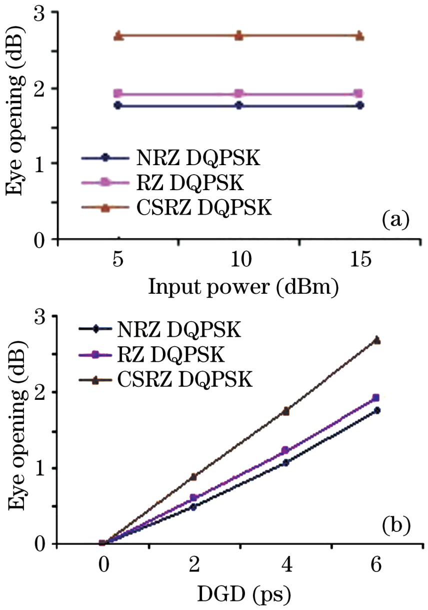

Fig. 5. Comparisons of eye opening at (a) different input powers and (b) different DGDs.

The comparison of eye opening of NRZ, RZ, and CSRZ DQPSK signals after changing the optical input power and DGD value of the PMD emulator is shown in Fig. 5. The eye opening can be defined as $-10\log M$, where M is the ratio of eye opening to eye range. In the numerical simulation, the optical power of source are set to 0, 9.5, and 6.8 dBm, respectively, so that the optical input powers into PMD emulator of NRZ, RZ, and CSRZ DQPSK signals are 0 dBm. As shown in Fig. 5, there is slight difference in the change of eye opening for NRZ, RZ, and CSRZ DQPSK signals. Because of the shorter pulse duration of RZ format, RZ DQPSK exhibits much greater PMD tolerance than NRZ DQPSK. It can also be seen that the eye opening of NRZ DQPSK is smaller than that of RZ DQPSK. From Fig. 5(a), the eye opening of CSRZ DQPSK is always higher than that of RZ DQPSK, no matter what the first-order PMD effect is, owing to the more compact spectrum of CSRZ DQPSK. Therefore the former modulation format should be of much more tolerance to PMD than the latter.

Comparing the eye openings of 100-Gb/s NRZ, RZ, and CSRZ DQPSK signals with different DGD value, the eye opening of CSRZ DQPSK signal is larger than that of RZ and NRZ DQPSK signals, which denotes that CSRZ DQPSK signal can tolerate to the first-order PMD better than RZ and NRZ DQPSK signals.

In conclusion, we propose a novel transmitter for 100-Gb/s DQPSK signal using a DMZM and two cascaded PMs, which can reduce the system cost by using lower speed electronics. Meanwhile, a novel receiver for 100-Gb/s DQPSK signal by the method of differential delay and phase shift is introduced. The impact of first-order PMD on the systems using 100-Gb/s NRZ, RZ, and CSRZ DQPSK formats based on DQPSK system model and PMD emulator model is investigated by numerical simulation. It is shown that CSRZ DQPSK exhibits higher eye opening performance than RZ and NRZ DQPSK in the presence of first-order PMD, which means that CSRZ DQPSK format has better tolerance than RZ and NRZ DQPSK formats to PMD for a given bit rate.

This work was supported by the National "863" Program of China (No. 2007AA01Z263), the Hunan Provincial Natural Science Foundation of China (No. 06JJ50108), the Open Fund of Key Laboratory of Optical Communication and Lightwave Technologies (Beijing University of Posts and Telecommunications, Ministry of Education, P. R. China), the Program for New Century Excellent Talents in University, and the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20040532005).

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