High-speed polarization-shift keying: experimental and numerical investigation

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Polarization-shift keying (PolSK), which is performed based on two orthogonal polarization states, is investigated in detail by experimental and numerical simulation for data rates of 10 and 40 Gb/s. Using a general Mach-Zehnder intensity modulator, a new type of PolSK transmitter is presented and demonstrated by polarization coupling technology. And then the PolSK transmission is experimentally demonstrated in a 50-km single mode fiber system, whose eye diagrams show that the PolSK transmitter works well at 10 Gb/s and the power fluctuation is ∼8%. Further simulation reveals that the PolSK has great potential in long distance transmission with data rate of 40 Gb/s, while its error-free distance goes beyond 2 100 km.

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As data rate of optical fiber communication increases to 40 Gb/s and above, traditional modulation formats are facing a serial tough challenges[1], which pushes more researchers to pursue new modulation formats. At present, polarization modulation or polarization-shift keying (PolSK) is becoming a promising approach since it has more advantages such as power equalization, better polarization characteristics, less power penalty, and so on, thus greatly reduce the nonlinear effects, suppress the polarization mode dispersion (PMD), and improve the spectrum efficiency[1,2]. Recently the virtues of the polarization modulation technology have been gradually revealed by experiment, for example, simply increasing the polarization alternation of encoded signals can efficiently prevent the nonlinear degradation in on-off-keying (OOK) systems[3]. And recently, its validity has also been demonstrated for ultra-long distance transmission[4].

The first PolSK transmission experiment was reported in 1987 with data rate of 560 Mb/s[5], which illustrated that the PolSK format improves the effective receiver sensitivity compared with OOK or amplitude shift keying (ASK). Five years later the theoretical foundation of PolSK modulation has been investigated detailedly in Ref. [2]. Subsequently some new PolSK schemes have been proposed, for example, the differential Jones-vector shift keying[6], multilevel differential PolSK[7], duobinary PolSK[8], but most researchers still focus on theoretical or numerical analysis. Recently we have proposed a PolSK experimental scheme based on cross polarization modulation in a semiconductor optical amplifier (SOA)[9], and realized the PolSK transmission at 2.5 Gb/s. And soon a dual-channel PolSK transmission has been demonstrated by using SOA-based polarization modulation[10].

In PolSK format the digital information is encoded in the state of polarization (SOP) of the launched light. For a binary PolSK system, logical “1” and “0” are generally associated with two given orthogonal SOPs. Although the SOP evolves along the fiber, the initial orthogonality can be better preserved in single mode fiber (SMF) systems[11]. Thus we can employ two orthogonal SOPs to carry out the high-speed fiber-based digital communications. Theoretically, the phase modulator (PM) is a proper choice for polarization modulation[6], however the practical PMs have residual amplitude modulation (RAM) effect[12] which destroys the power equalization of PolSK signals and then increases the nonlinear effects. To enhance the practicability of PolSK scheme for easily merging into present communication systems, in this letter, a general Mach-Zehnder modulator (MZM) is directly employed to build a power-equalized PolSK transmitter based on polarization coupling technology, which also combines with a feedback device to compensate the phase shift in the MZ interferometer configuration. And then the PolSK transmission is successfully demonstrated by experiment at 10 Gb/s and by numerical simulation at 40 Gb/s.

The PolSK transmitter and its principle are schematically shown in Fig. 1.

A tunable semiconductor laser (TSL) produces continuous wave (CW) whose SOP is firstly polarized to −45° linear polarization by a compact in-line fiber polarization controller (PC1), and then divided by a fiber coupler (FC1) into two power-equalized parts (B and C). Subsequently part C is attenuated by a variable optical attenuator (ATT) and converted to vertical polarization (or S-state) by PC2, while part B is modulated by a MZM driven by a signal quality analyzer (SQA, Anritsu MP1800A). After polarization coupling of pulsed signal B′ and CW signal D in a 3×3 fiber coupler (FC2), we will get power-equalized PolSK signals S_{P} and S_{S} with orthogonal SOPs as illustrated in Fig. 1. To stabilize the output signal, a feedback device is employed by balance detect of two output ends of FC2 after polarization filter (PF1, PF2), and then adjust the phase shifter (PS) in real time.

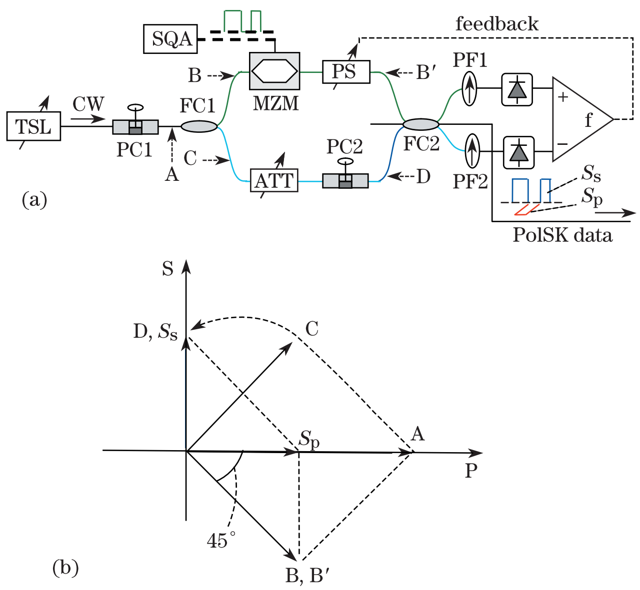

Fig. 1. (a) Principle diagram of the PolSK transmitter, (b) vectogram description of PolSK signal generation.

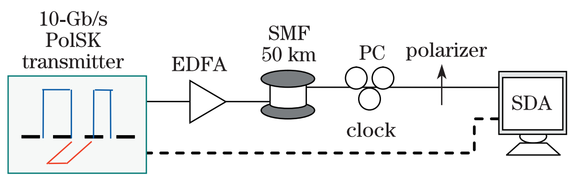

Fig. 2. Experimental setup for 10-Gb/s PolSK transmission.

The principle of PolSK signal generation is clearly shown in Fig. 1(b). When part B′ is in the status of logical "1", the output signal is converted to S_P with P-state after polarization coupling with part D, when part B′ is in the status of logical "0", the output SOP is still S-state (S_S) as part D. Based on this polarization coupling technology, the PolSK signals are obtained from a general MZM intensity modulator.

To evaluate the performance of the PolSK transmitter, an experimental 10-Gb/s transmission system is configured as shown in Fig. 2.

In Fig. 2, the SQA is set to generate $2^{15}-1$ pseudorandom-bit-sequence (PRBS) non-return-to-zero (NRZ) signals at 10 Gb/s with synchronous clock of 10 GHz, and the TSL emits CW at 1 556 nm with power of ∼8 dBm. Since the attenuation of the MZM is 4.5 dB, while the intensity of signal at point D is 3 dB less than signal at B′ which can be calculated from the vectogram in Fig. 1(b), to achieve power-equalized PolSK signals, the attenuation of the ATT is finely adjusted to 7.5 dB. After amplified by an erbium-doped fiber amplifier (EDFA), the PolSK signal is launched into a disk of single mode fiber (SMF) with total length of 50 km. At receiving end, the output signal is detected by a serial data analyzer (SDA, Lecroy SDA100G) after decoding by a polarizer with a polarization controller.

Firstly the waveforms and eye diagrams of the PolSK signal directly from the transmitter are measured by a SDA. Figure 3(a) shows the waveforms for the fixed input signals "10110001110111100", where the upper one is the total output waveform, and the middle and lower are P-state and S-state waveforms. From Fig. 3(a) one can find that two orthogonal polarization signals are definitely complementary, while the power fluctuation is ∼8% which indicates that the PolSK signal is power equalized, thus it will greatly decrease the nonlinear effects induced in the fiber system. Furthermore, the eye diagrams in Fig. 3(b) show that PolSK signals have good quality which confirms the validity of the PolSK transmitter scheme in Fig. 1.

After transmission through the 50-km SMF, the signal-to-noise ratio (SNR) of the PolSK signal decreases due to fiber loss and dispersion, but two orthogonal signals are still keeping complementary well. Figure 4 partly shows the measured results.

Based on the above configuration with experimental results, we further numerically investigate the transmission performance of the PolSK at high-speed rate of 40 Gb/s assisted with the professional optical communication

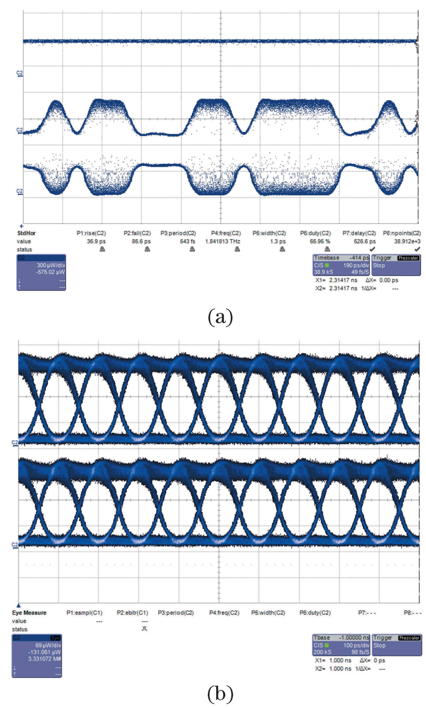

Fig. 3. (a) Waveforms for fixed input signals "10110001110-111100", upper: total output waveform, middle and lower: P-state and S-state waveforms; (b) eye diagrams of P-state (upper) and S-state (lower) signals.

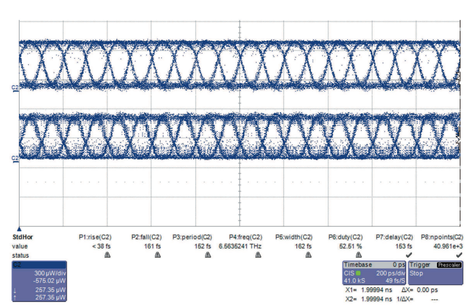

Fig. 4. PolSK signals (PRBS, $2^{15}-1$) after 50-km transmission, upper: P-state signal, lower: S-state signal.

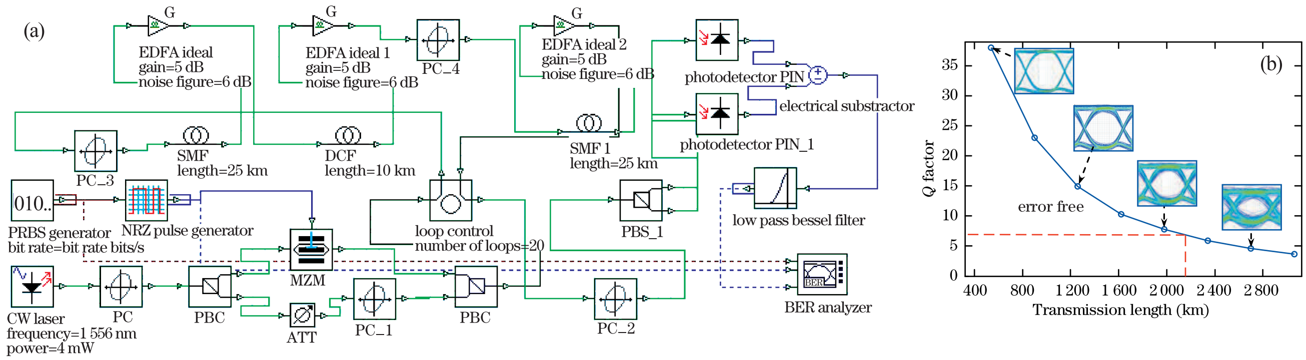

Fig. 5. (a) 40-Gb/s PolSK transmission system; (b) BER (Q factor) with related eye diagrams versus transmission distance.

software (OptiSystem). The long-distance fiber system is configured by loop control, while the wavelength of the CW laser is 1 556 nm. Each transmission span includes three EDFAs (gain: 5 dB, noise figure: 6 dB), two 50-km standard SMFs, and a 10-km dispersion compensating fiber (DCF) as shown in Fig. 5(a). The dispersion of SMF is 16 ps/nm and the loss is 0.2 dB/km, while the DCF dispersion and loss are −80 ps/nm and 0.5 dB/km, respectively. To further improve the transmission performance, two PCs have been added in the loop for finely adjustment of the polarization state in the fiber system.

The bit error rate (BER: Q factor) has been measured for different transmission distances over 2 000 km, and also the related eye diagrams obtained. The results presented in Fig. 5(b) demonstrate that the error-free transmission distance for 40-Gb/s PolSK is ∼2 170 km, which is much longer than OOK format reported in Ref. [13].

In conclusion, by using a general MZ intensity modulator, we present and demonstrate a new type of PolSK transmitter based on polarization coupling, which is further stabilized by a phase feedback device. And then the PolSK transmission performs well at 10 Gb/s with the power fluctuation of about 8% after 50-km SMF. Further simulation results show that the PolSK has great potential for 40-Gb/s long distance transmission, and its error-free distance achieves 2 170 km. The results demonstrate that the PolSK is an efficient modulation format for high-speed optical fiber communication.

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