A Novel Optical Orthogonal Modulation Format Based on Differential Phase-Shift Keying and Code-Shift Keying

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***Abstract*—We propose a novel orthogonal modulation format with differential phase-shift keying (DPSK) and code-shift keying (CSK) to improve transmission capacity of the optical code-based communication system. A 2-bit/symbol 10-Gb/s system with DBPSK/binary-CSK modulation is demonstrated.**

***Index Terms*—Modulation techniques, optical code-division multiple-access (OCDMA).**

I. Introduction

RECENTLY, coherent optical code division multiple access (OCDMA) using ultra short pulse is receiving increasing attention because of its outstanding performances, such as low multiple access interference (MAI) and large code cardinality [1], [2]. In the coherent OCDMA system, the coherent optical codes are based on the phase and amplitude of the optical field. Therefore, the optical codes are compatible with the phase modulation, based on which differential phase-shift keying (DPSK) OCDMA system was proposed. Differential binary phase-shift keying (DBPSK) OCDMA system with the balanced detection has the advantages of the improved receiver sensitivity and the better tolerance to beat noise and MAI [3]. Furthermore, multilevel modulation format can be adopted to improve the transmission capacity. Differential quaternary phase-shift keying (DQPSK) OCDMA system has been experimentally demonstrated in the synchronous condition [4]. Meanwhile, optical coding provides another domain for the modulation. Binary code-shift keying (CSK) OCDMA system with balanced detection can significantly improve the multiuser capability [5]. The multilevel CSK modulation format, M-ary CSK-OCDMA system, can enhance security [6], [7].

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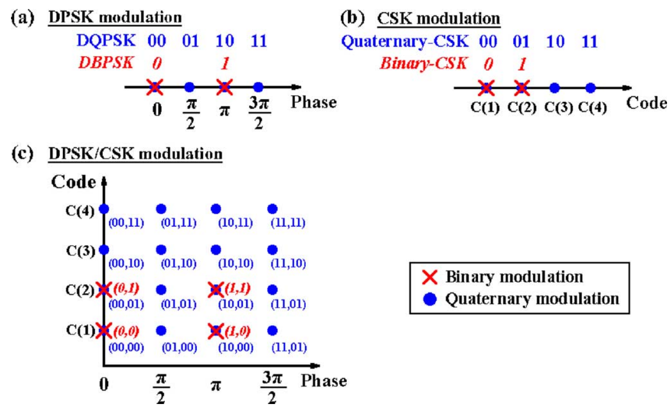

Fig. 1. Signal distribution diagram for (a) DPSK, (b) CSK, and (c) DPSK/CSK modulation scheme and associated symbols $(b_P, b_{C(n)})$. (a) DPSK modulation. (b) CSK modulation. (c) DPSK/CSK modulation.

In an optical communication system, the orthogonal modulation scheme can increase the total capacity. Several orthogonal modulation schemes have been proposed, such as amplitude-shift keying/phase-shift keying (ASK/PSK) [8], ASK/frequency-shift keying (ASK/FSK) [9] and ASK/polarization-shift keying (ASK/PolSK) [10]. They can not only increase the transmission capacity but also achieve a multibit per symbol optical communication. The coherent quadrature amplitude modulation (QAM) using ASK/PSK modulation format has been employed in the coherent transmission system, which is one of the most effective formats for increasing transmission capacity.

II. Principle of the Proposed Modulation Scheme

Fig. 1 illustrates the signal distribution diagram, which shows the principle of the DPSK modulation, the CSK modulation and proposed DPSK/CSK modulation.

In the DPSK modulation, different phases are used to represent different symbols as shown in Fig. 1(a). The two crosses on the phase-axis with possible phases of 0 and π, representing the symbols (b_P) '0' and '1', are for the DBPSK modulation, while the four dots (0, $\pi/2$, π and $3\pi/2$) are for the four symbols in the DQPSK modulation.

The CSK modulation processes the data transmission by means of the codes. Fig. 1(b) depicts the signal distribution diagram of the CSK modulation. The position of the code on the code-axis is not related to the magnitude, but only to the order of the code in the code set. Two codes ($C(1)$ and $C(2)$), marked with two crosses, are used for the symbols $(b_{C(n)})$

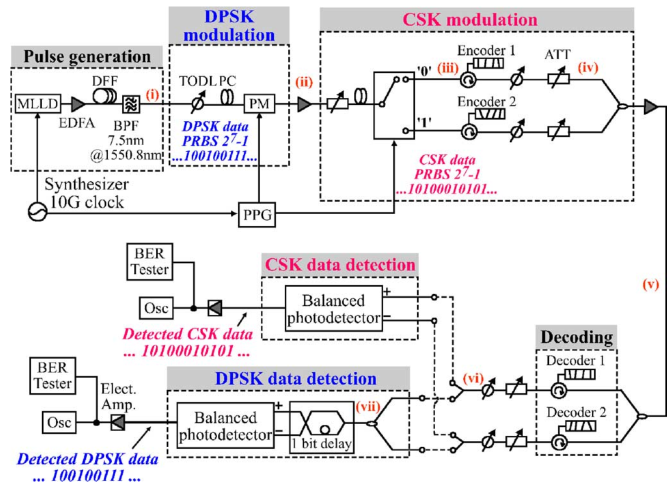

Fig. 2. Experimental setup of the proposed system.

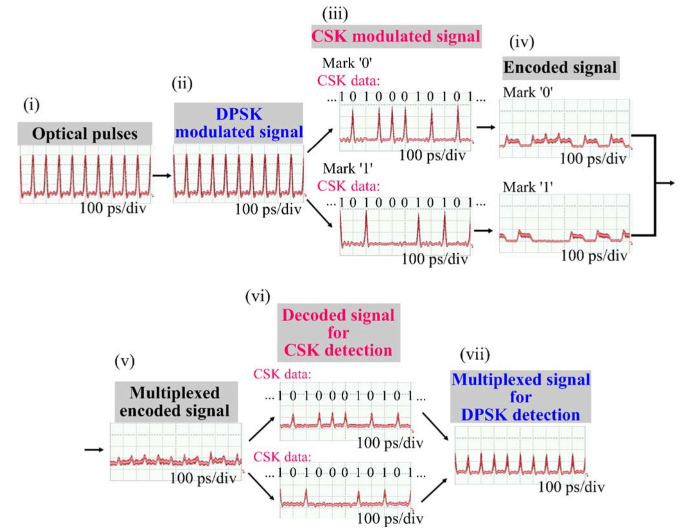

Fig. 3. Waveforms at different positions of the system.

’0’ and ’1’ respectively in the binary-CSK modulation. In the quaternary-CSK modulation, four codes are used (four dots) to represent four different symbols.

Due to the fact that coding is coherent, the coding and the phase modulation can be realized simultaneously in a coherent code based system. Thus, the CSK modulation can provide another dimension of the orthogonal modulation with DPSK modulation. The proposed DPSK/CSK modulation scheme is to realize the coexistence of two orthogonal modulation formats in the same system.

Fig. 1(c) shows the signal distribution for the proposed DPSK/CSK modulation scheme. Considering the DBPSK/binary-CSK modulation, two possible phases (0 and π) and two codes ($C(1)$ and $C(2)$) are used to represent the different symbols. Compared to the single DBPSK or binary-CSK modulation, the DBPSK/binary-CSK modulation scheme has one more dimension of the modulation to support the twofold transmission capacity (2-bits/symbol).

Generally, the proposed scheme can be extended to the multilevel modulation formats. Fig. 1(c) shows the signal distribution of the DQPSK/Quaternary-CSK modulation scheme. In this case, four possible phases and four codes are used, marked with sixteen dots, which results in 4-bits/symbol transmission. If the higher-level DPSK and CSK modulation formats are adopted, the transmission capacity can be significantly improved.

III. Experimental Demonstration

A. Experiment Setup

Fig. 2 shows the experimental setup and operation principle of the proposed modulation format. The architecture can be divided into several sections. In the pulse generation section, a 10 GHz Gaussian shaped pulse train is generated by the mode locked laser diode (MLLD). A 2000 m dispersion-flattened fiber (DFF) and a 7.5 nm band-pass filter centered at 1550.8 nm are used to compress the pulse to 1 ps (FWHM). The pulse train is modulated by a phase modulator driven by the 10 Gb/s 2^7-1 pseudorandom bit sequence (PRBS) DBPSK data. Then, the DPSK modulated pulse train is switched into two branches by an optical switch, which is driven by another 2^7-1 PRBS data at a data rate of 10 Gb/s. The optical switch with 30 dB extinction ratio is used for the suppression of the untargeted signals. For the binary-CSK modulation, the upper and lower branches represent for the bits ’0’ and ’1’ of the binary-CSK data respectively. In the experiment, the encoders and decoders are 63-chip 640 Gchip/s superstructured fiber Bragg gratings (SSFBG). The DBPSK data and the binary-CSK data are simultaneously encoded in this stage. The encoded signals present as noise-like waveforms and are combined into one path, after the precise adjustment of the delay and the power. In the decoding section, the multiplexed encoded signals are split into two branches. The SSFBG decoders for bits ’0’ and ’1’ are placed on each branch and recover the corresponding encoded signals into autocorrelation high peaks. The autocorrelation signal has the pulse duration of about 3 ps and will be detected by both binary-CSK and DBPSK detection modules, while the incorrectly decoded cross-correlation signals become the interference to the target signals. Due to polarization independence of the coding devices, the signals in the two decoded branches have the same polarization and polarization controls are not necessary before DBPSK demodulation. The encoding and decoding blocks are placed in the temperature-stabilized environment to improve the phase-stabilization of the DBPSK transmission. Considering the further improvement of long-term phase-stabilization, either integrated components or active stabilization techniques could be used in the future work. The waveforms for the binary-CSK modulation with the data pattern after switching, encoding, multiplexing and decoding are depicted in Fig. 3.

In the detection section, the DBPSK data and the binary-CSK data can be detected using two different setups. In the DBPSK data detection module, the decoded signals are firstly combined into one path and then detected by a DPSK demodulator, which is a 1-bit delay interferometer, and a balanced photodetector. As for the binary-CSK data detection module, it only contains a balanced photodetector. The binary-CSK data can be directly detected from the decoded signals by the balanced photodetector.

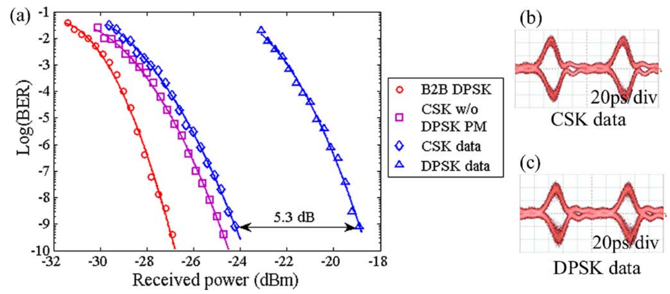

Fig. 4. (a) Measured BER performance and eye diagrams for both (b) binary-CSK data and (c) DBPSK data transmission.

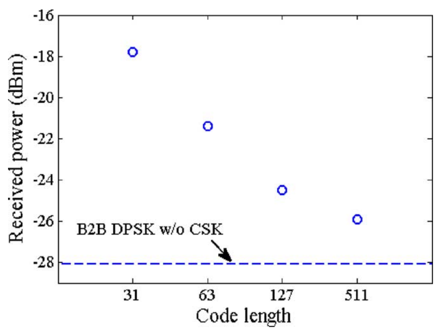

Fig. 5. Simulated received power of DBPSK data transmission with different code lengths at BER of 10^{-9}.

B. Result and Discussion

To verify the feasibility of the proposed system and investigate the orthogonality between the binary-CSK modulation and DBPSK modulation, we measure the eye diagram and bit-error ratio (BER) performance for both binary-CSK and DBPSK data. In the Fig. 4(a), we use the DBPSK back-to-back transmission and the binary-CSK transmission without DBPSK modulation as the references. The diamond and triangular marked curves are for the binary-CSK data and DBPSK data, respectively. Compared to the binary-CSK transmission without DBPSK modulation, the power penalty at the BER of 10^{-9} for the binary-CSK data transmission in the proposed system is less than 1 dB, which indicates that the existence of the DBPSK modulation has the subtle influence on the binary-CSK data transmission. The DBPSK data transmission suffers more power penalty, about 5.3 dB to the binary-CSK data transmission, which are resulted from the imperfect switching and the beat noise. Fig. 4(b) and (c) show the eye diagrams for both binary-CSK and DBPSK data transmission. The clear open eyes can be observed for the binary-CSK data transmission, while the eyes for the DBPSK data transmission have some degradation. The cross-correlation signals from another decoder cause the noise to the DBPSK data transmission. Therefore, in the proposed system, the coding with low cross-correlation is necessary to eliminate the noise and optimize the system. When longer codes are used, correlation performance and security can be improved. Fig. 5 illustrates the simulated result of the received power for DBPSK data transmission with different code lengths at the BER of 10^{-9}. The decrease of the received power indicates that less power penalty can be achieved if longer codes are used. Besides, if codes are well designed to minimize cross-correlation, the DBPSK data will suffer lower power penalty.

In the experimental demonstration, the error-free transmissions for both DBPSK data and binary-CSK data are achieved, which guarantees the orthogonality of the DBPSK and binary-CSK modulations. Compared to the conventional optical coding system, by modulating the signal with DPSK modulation, it can double the transmission capacity and achieve a 2-bit/symbol transmission. For a higher capacity system, we can use the codes with low cross-correlation to increase the data rate. Furthermore, the DPSK and CSK modulations can be upgraded to multilevel modulation formats. In this way, using the two-dimensional orthogonal modulation with the multilevel modulations, the transmission capacity can be significantly enhanced.

IV. Conclusion

We have proposed and experimentally demonstrated a novel 2-bit/symbol orthogonal modulation format in the 10 Gb/s coherent OCDMA system using DBPSK and binary-CSK modulations. The proposed modulation format can increase the transmission capacity in the optical code based communication system. It also implies a further enhancement with the replacement of the DBPSK and binary-CSK by the multilevel modulation formats in the phase and code domains.

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