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A flexible multi-16QAM transmitter based on cascaded dual-parallel Mach-Zehnder modulator and phase modulator

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In this paper, we propose a novel and flexible 16-quadrature amplitude modulation (16QAM) transmitter based on cascaded dual-parallel Mach-Zehnder modulator (DPMZM) and phase modulator (PM). The proposed transmitter is able to generate three types of 16QAM signals: square 16QAM, star 16QAM and four-amplitude-four-phase-16-QAM (FAFP-16QAM). The feasibility of the transmitter is verified through experiment, 20-Gb/s eye diagrams of the 16QAM signals are obtained. In order to evaluate the performances of the 16QAM signals, simulations are also conducted using VPI Transmission Maker, clear constellations of 40-Gb/s 16QAM signals are achieved by coherent detection.

16QAM, optical communication, Mach-Zehnder modulator (MZM), phase modulator (PM), multi-level format

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1 Introduction

The emerging internet applications, such as high-definition (HD) video, interactive game and communication between data centers, have required high data-rate transport (beyond 100 Gb s^{-1}) for optical networks. However, a binary signal beyond 40 Gb s^{-1} is limited by the operating speed of electronic components, and also by the rapidly reducing chromatic dispersion (CD) and the polarization mode dispersion (PMD) tolerances [1]. On the other hand, multi-level modulation formats and coherent detection have become promising technologies to increase the capacity of optical fiber transmission and also to extend transmission distance [1–4]. Among multi-level modulation formats, 16-quadrature amplitude modulation (16QAM), which carries four bits per symbol with high spectral efficiency, is an attractive candidate for high-speed transmission systems. With respect to the constellation distributions, 16QAM can be categorized to three groups: square-16QAM, star-16QAM and four-amplitude-four-phase-16QAM (FAFP-16QAM). In refs. [5–7], square-16QAM, star-16QAM and FAFP-16QAM have been realized, respectively. However, the transmitter only generated one type of 16QAM, which was lack of flexibility and not suitable for dynamic transmission systems. The three kinds of 16QAM have their own advantages: square-16QAM requires the simplest receiver and constellation mapping, star-16QAM has the highest tolerance to nonlinear effects of fiber transmission, while FAFP-16QAM has the lowest requirement for laser linewidth. As a result, it is of interest to design a 16QAM transmitter, which can flexibly produce the three types of 16QAM to accommodate different transmission systems.

In this work, we propose a novel 16-QAM transmitter using a dual-parallel Mach-Zehnder modulator (DPMZM) followed by a phase modulator (PM). The proposed transmitter is versatile and able to generate three types of

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16QAM: square-16QAM, star-16QAM and FAFP-16QAM, to satisfy different transmission systems. When the transmitter shifts one 16QAM format to another one, only the amplitudes of the electrical signals and the biases of the DPMZM need to be adjusted, while the structure of the transmitter keeps unchanged. In addition, the discrete devices of the transmitter have the potential to be integrated into one chip [8]. An experiment is implemented to verify the feasibility of the transmitter and the three types of 16QAM signals with a bit rate of 20 Gb s^{-1} are achieved. Simulations are also conducted to investigate the transmission performance and coherent detections are used to recover the 16QAM constellations. After 80-km standard-single-mode-fiber (SSMF) and 16-km dispersion chromatic fiber (DCF) transmissions, we achieve good performances for the 40-Gb/s 16QAM signals with open eye diagrams and clean constellations.

2 Principles

The schematic diagram of the proposed transmitter is depicted in Figure 1, which consists of a DPMZM followed by a PM. The DPMZM comprises a pair of X-cut $LiNbO_3$ MZMs (MZM-a, MZM-b) embedded in the two arms of a main MZM structure. The two sub-MZMs have the same structure and performance, and the main MZM superimposes the outputs of the two sub-MZMs. The architecture of the transmitter can be divided into two stages. In the first stage, both the sub-MZMs of the DPMZM are biased at the quadrature points of the transmission curves and driven by data-1 and data-2 to generate two 2-amplitude shift keying (2ASK) signals with the same amplitude. By adjusting the bias of the main MZM, the two ASK signals achieve a 90° phase difference (Figures 1(a) and 1(b)), which are combined to obtain an offset-quadrature phase shift keying (offset-QPSK) signal with its origin biased at the first quadrant, as depicted in Figure 1(c). In the second stage, the offset-QPSK signal is QPSK-modulated (Figure 1(d)) by the PM, which is driven by a 4-level electrical signal, to realize a square-16QAM signal (Figure 1(e)).

To obtain star-16QAM generation, one only needs to adjust the amplitudes of the electrical signals and the biases of the DPMZM, while the structure of the transmitter keeps unchanged. The schematic diagram for the star-16QAM generation is shown in Figure 2. In the first stage, a continual wave (CW) light is 4-amplitude phase shift keying (4APSK) modulated by the DPMZM. In detail, the two sub-MZMs of the DPMZM are biased at the null points of the transmission curves and driven by data-1 and data-2, respectively, to produce two binary-phase-shift-keying (BPSK) signals with unequal amplitudes, as shown in Figures 2(a) and 2(b). The two BPSK signals are then constructively added to generate a 4APSK signal (Figure 2(c)) by adjusting bias-3. In the second stage, the 4APSK signal is phase-modulated by a 4-level electrical signal, which is obtained by combining data-3 and data-4, to realize a 4-phase shift keying (4PSK) modulation (0, π/4, π/2, 3π/4). In that case, a star-16QAM signal is achieved.

By adjusting the amplitudes of electrical signals and the biases of the modulators, FAFP-16QAM modulation is achieved. In detail, the MZM-a of the DPMZM is biased at

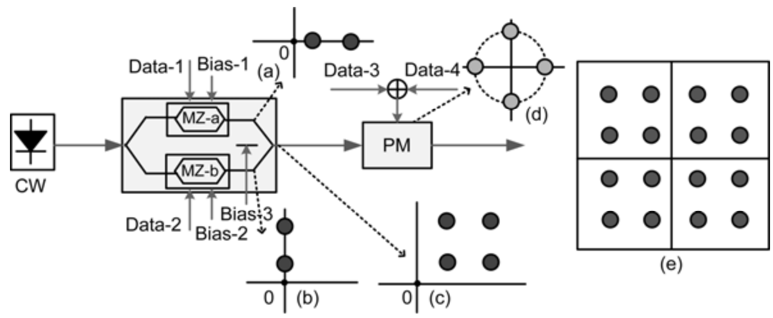

Figure 1 Schematic diagram of the proposed transmitter for square-16QAM generation.

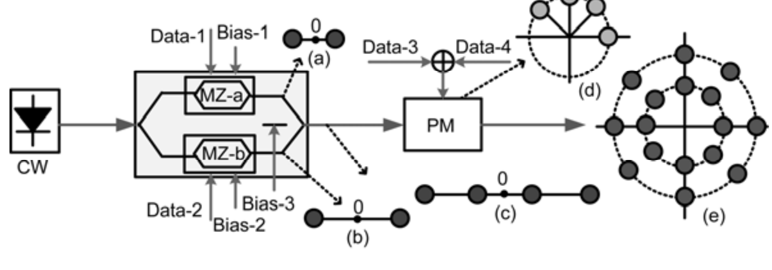

Figure 2 Schematic diagram of the proposed transmitter for star-16QAM generation.

the quadrature point and driven by data-1 to produce a 2ASK with finite extinction ratio (ER), as shown in Figure 3(a). The MZM-b of the DPMZM is biased at quadrature point and driven by data-2 to generate a 2ASK with infinite ER, which is illustrated in Figure 3(b). The two 2ASK signals are then constructively combined to produce a 4ASK signal with finite ER (Figure 3(c)). The following PM, driven by a 4-level electrical signal, is used to QPSK-modulate the 4ASK signal. A FAFP-16QAM is obtained, as depicted in Figure 3(e).

3 Experimental setup and results

A back-to-back (BTB) experiment was performed to verify the feasibility of the proposed 16-QAM transmitter with a setup shown in Figure 4. A continual wave (CW) light was used as the light source with a wavelength of 1551.44 nm and an optical power of 3 dBm. Four 5-Gb/s pseudo-random binary sequence (PRBS) streams with a word length of 2^{31}-1 were generated by a pulse pattern generator (PPG) ((ANRITSU MP1763c)), whose eye diagram is shown in Figure 5(a). Two of them were amplified by power amplifiers (PAs) (JDSU H301) and used to drive the two data ports of the DPMZM (COVEGA Mach-10060), while the other two were combined to form a 4-level electrical signal, with the eye diagram illustrated in Figure 5(b). The generated 4-level electrical signal was boosted by a PA (JDSU H301) and employed to drive the PM (CONQUER PMS 1552-EX). After the PM, an erbium-doped fiber amplifier (EDFA) (JIASYS HPEDFA-001) was used to compensate the insertion losses of the modulators and a following tunable optical filter (TOF) (Alnair TF-100) with a bandwidth of 1.6 nm was utilized to suppress the amplified spontaneous emission (ASE) noise. Square-16QAM, star-16QAM and FAFP-16QAM signals with a data rate of 20 Gb s^{-1} were realized by adjusting the amplitudes of the electrical data and the biases of the DPMZM. The optical spectrum of the square-16QAM is illustrated in Figure 5(c) and the optical spectra of the star-16QAM and FAFP-16QAM had the same shape as that in Figure 5(c). The optical eye diagrams of the 16QAM signals are shown in Figures 5(d)–5(f), whose fluctuations on the levels can be attributed to the non-ideal driving signals and inaccurate bias voltages for the DPMZM. In the experiment, due to the lack of phase measurement instrument, we did not provide the corresponding phase allocations. It is noted that several electrical delay lines (EDL: SHF 2000DEL, 160 ps) were used to de-correlate the electrical data and an optical delay line (ODL: General Photonics VDL 001, 500 ps) was employed to ensure bit-aliasing of the cascaded DPMZM and PM.

4 Simulations and results

To investigate the transmission performance of the proposed transmitter, we performed simulations with a setup depicted in Figure 6, using VPI Transmission Maker. At the transmitting terminal, the proposed transmitter was used to produce a 40-Gbit/s square-16QAM signal. The output of the transmitter was amplified by an EDFA to reach a power of 3 dBm and filtered by a TOF with a bandwidth of 1.6 nm. At the receiving terminal, coherent detection was performed. In detail, a CW light with the same frequency and phase as the laser of transmitter was used as local oscillator (LO), which was mixed with the received square-16QAM

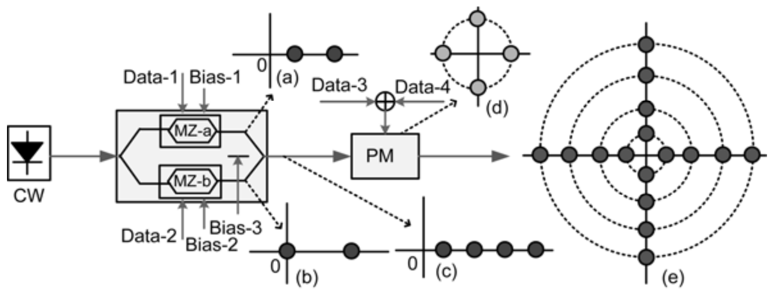

Figure 3 Schematic diagram of the proposed transmitter for FAFP-16QAM generation.

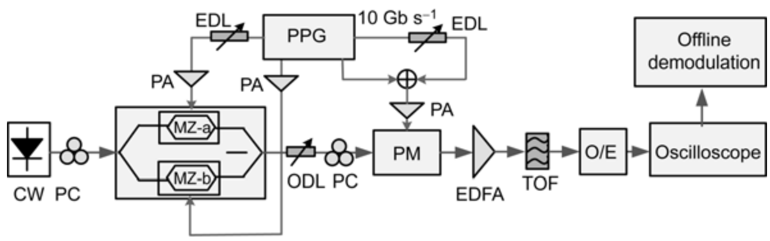

Figure 4 Experimental setup of the proposed flexible 16QAM transmitter.

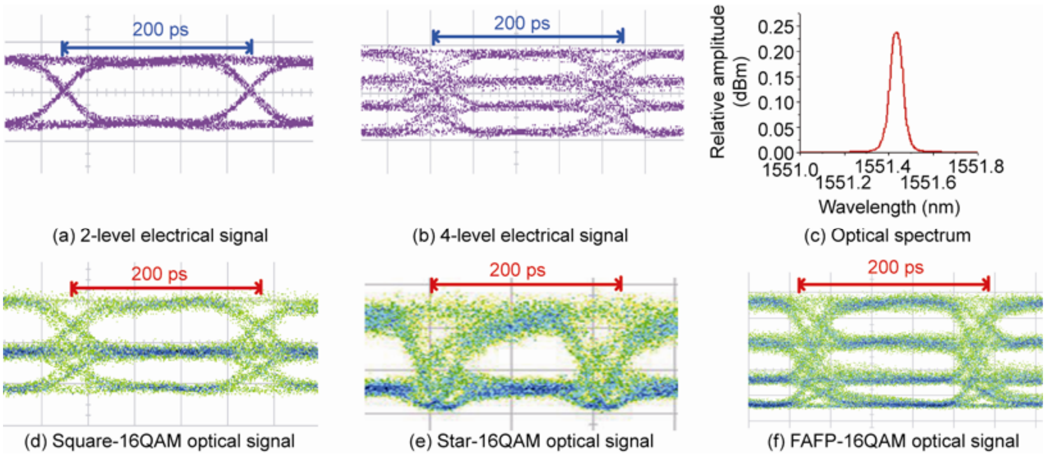

Figure 5 Experimental results. (a) Electrical eye diagram of 2-level data; (b) electrical eye diagram of 4-level data; (c) optical spectrum of square-16QAM; (d) optical eye diagram of square-16QAM; (e) optical eye diagram of star-16QAM; (f) optical eye diagram of FPFA-16QAM.

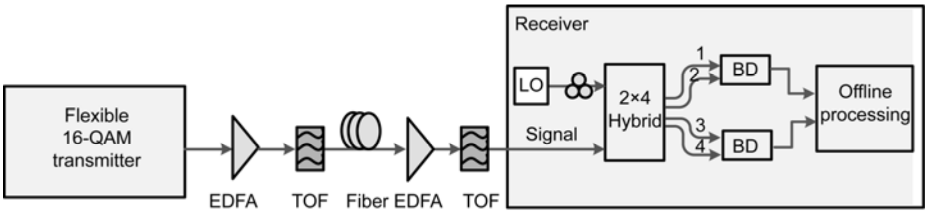

Figure 6 Simulation setup for the proposed 16QAM transmitter with coherent detection.

signal in an optical 90º 2×4 hybrid. The outputs of hybrid were detected by two balanced detectors (BD) with the same performance. The real and imaginary parts of the square-16QAM signal were obtained by simultaneously sampling the outputs of the BDs and 16384 bits were sampled for offline process by MATLAB program, including re-sampling, carrier phase estimation and constellation recovery. The BTB eye diagram and constellation of the square-16QAM are shown in Figures 7(a) and 7(b), respectively. After transmission through 80-km standard single-mode fiber (SSMF), the signal was boosted by a second EDFA to 6 dBm and 16-km dispersion compensating fiber (DCF) was used to compensate the chromatic dispersion (CD) accumulated through the transmission link. The SSMF has a dispersion coefficient D = 16ps (nm km)$^{-1}$, a dispersion slope S = 0.06 ps (nm^2 km)$^{-1}$, a nonlinear index γ= 1.31 W^{-1} km^{-1}, and a loss coefficient α =0.2 dB km^{-1}. The DCF parameters are D =–80 ps (nm km)$^{-1}$, S =–0.18 ps (nm^2 km)$^{-1}$, γ= 2.64 W^{-1} km^{-1}, and α= 0.6 dB km^{-1}, respectively. It was observed that after 80-km transmission, the eye diagram and constellation map of the square-16QAM were still clear enough to be error-free, as depicted in Figures 7(a) and 7(b), respectively. By adjusting the amplitudes of electrical signals and biases of the DPMZM in the transmitter, star-16QAM and FAFP-16QAM signals were realized, which were transmitted through the same fiber link as the square-16QAM. After coherent detection and off-line process, clear eye diagrams and constellations were achieved in the conditions of BTB and after 80-km transmission, as shown in Figures 8 and 9, respectively.

5 Conclusions

A novel 16-QAM transmitter has been proposed with cascaded DPMZM and PM. The proposed transmitter has the

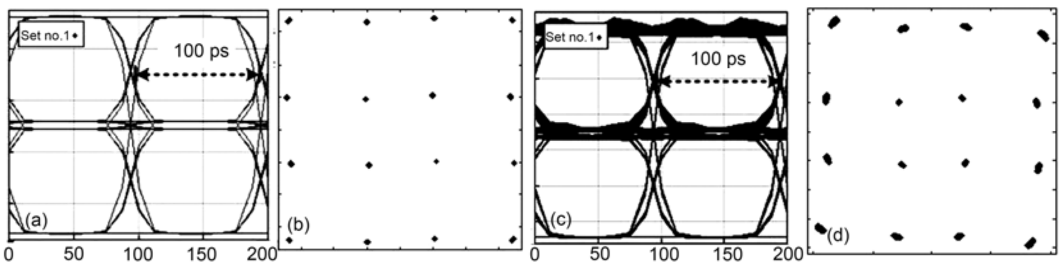

Figure 7 Simulation results for the square-16QAM. (a), (b) Eye diagram and constellation before transmission; (c), (d) eye diagram and constellation after 80-km SSMF transmission.

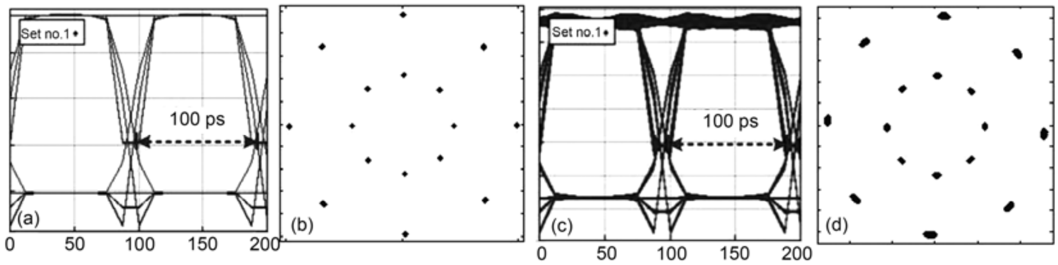

Figure 8 Simulation results for the star-16QAM. (a), (b) Eye diagram and constellation before transmission; (c), (d) eye diagram and constellation after 80-km SSMF transmission.

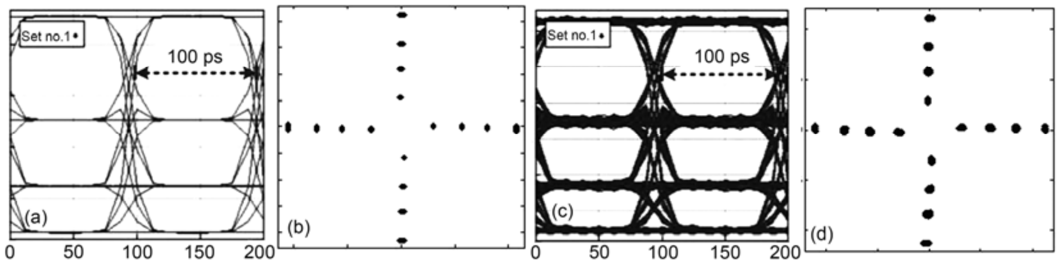

Figure 9 Simulation results for the FAFP-16QAM. (a), (b) Eye diagram and constellation before transmission; (c), (d) eye diagram and constellation after 80-km SSMF transmission.

ability to produce three types of 16QAM without changing its architecture. We conduct an experiment to verify the feasibility of the proposed transmitter, 20-Gb/s square-16QAM, star-16QAM, and 16APSK are realized. Simulations are carried out to illustrate the phase information and transmission performances of the 16QAM signals with a bit rate of 40 Gb s^{-1}. After 80-km SSMF transmission and CD compensation, coherent detections are used to recover the constellations, good performances are achieved. The experiment and simulation results show that our proposed transmitter is versatile and could be an attractive candidate for a dynamic transmission system.

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