40-Gb/s star 16-QAM transmitter based on single dual-drive Mach-Zehnder modulator

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We propose a 40-Gb/s star 16-ary quadrature amplitude modulation (16-QAM) transmitter using a single dual-drive Mach-Zehnder modulator (DDMZM). This transmitter is demonstrated through experiment and simulation and shows the advantage of simplicity for implementation. Simulation results indicate that error free performance could be achieved for the generated signal after 80-km standard single-mode fiber (SSMF) transmission with coherent detection scheme.

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Advanced modulation formats have become a key technology to meet the increasing demand for bandwidth in optical transmission systems. High-order optical modulation formats, such as differential quadrature phase-shift keying (DQPSK)[1,2] and differential 8-ary phase-shift keying (D8PSK)[3], have already been demonstrated. 16-ary quadrature amplitude modulation (16-QAM), which carries four bits per symbol, is regarded as a promising candidate for future high capacity and high spectral efficiency optical transmission systems. With respect to the constellation distributions, 16-QAM can be categorized to two groups, square 16-QAM and star 16-QAM, both requiring more complex transmitter structures compared with lower-order modulation formats. By using two Mach-Zehnder modulators (MZMs) in an interferometer structure and two four-level driving signals, a transmitter was introduced to implement square 16-QAM[4]. A transmitter with four integrated parallel MZMs was also proposed and implemented[5]. In Ref. [6], a dual-drive MZM (DDMZM) was used to generate (D)QPSK signals. The authors also mentioned that based on this modulator, square 16-QAM signal could be obtained with 16-level driving signals which required a complicated electronic circuit. A star 16-QAM transmitter was designed with three phase modulators in series to generate 8PSK followed by a MZM as an intensity modulator to achieve star 16-QAM[7]. It was verified that, compared with square 16-QAM, star 16-QAM showed a better tolerance towards laser linewidth when employing feed-forward digital carrier-phase estimation in coherent detection schemes[8].

In this letter, we propose a novel star 16-QAM transmitter based on a single DDMZM with two four-level driving signals. Experiment and simulation are carried out to demonstrate its feasibility. Compared with the previous schemes, this method exhibits the features of simplicity and easy implementation.

A DDMZM consists of two independent phase modulators in a Mach-Zehnder interferometer. Suppose that the drive signal voltages and the bias voltages of the two phase modulators are V_1, V_2, V_{bias1}, and V_{bias2}, respectively. V_π is the half-wave voltage of the DDMZM. Given an input electric field E_i, the corresponding output electric field E_o is expressed as

$$\begin{aligned} E_\text{o} &= \frac{E_\text{i}}{2}\left[\exp\left(\text{j}\pi\frac{V_1+V_{\text{bias1}}}{V_\pi}\right)+\exp\left(\text{j}\pi\frac{V_2+V_{\text{bias2}}}{V_\pi}\right)\right] \\ &= \frac{E_\text{i}}{2}\exp\left(\text{j}\pi\frac{V_{\text{bias1}}}{V_\pi}\right)\underbrace{\exp\left(\text{j}\pi\frac{V_1}{V_\pi}\right)}_{\text{QPSK1}} \\ &+\frac{E_\text{i}}{2}\exp\left(\text{j}\pi\frac{V_{\text{bias1}}}{V_\pi}\right)\underbrace{\exp\left(\text{j}\pi\frac{V_{\text{bias2}}-V_{\text{bias1}}}{V_\pi}\right)\exp\left(\text{j}\pi\frac{V_2}{V_\pi}\right)}_{\text{QPSK2}}. \end{aligned} \quad (1)$$

Suppose that the four possible voltages of driving signals are −3/4, −1/4, 1/4, and 3/4, all normalized to V_π. Under this condition, the two phase modulators will generate two independent signals, QPSK1 and QPSK2. By adjusting the two bias voltages and setting $(V_{\text{bias1}}-V_{\text{bias2}})$ to be 1/4 normalized to V_π, there will be a $\pi/4$ phase shift between the two generated QPSK signals, as depicted in Figs. 1(a) and (b). The DDMZM combines the two QPSK signals, resulting in a star 16-QAM signal, as shown in Fig. 1(c). The generated 16-QAM signal has two possible amplitudes, with an amplitude ratio of 2.4 between the bigger one and the smaller one. The 16 constellation points occupy eight different phase states in a symmetrical distribution of a circle.

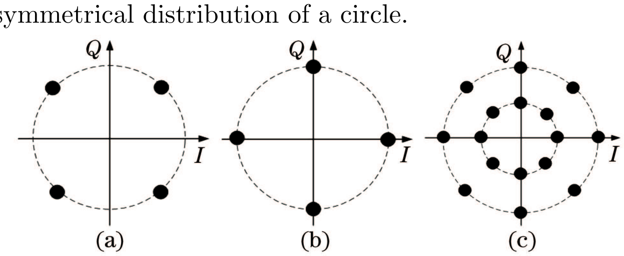

Fig. 1. Constellation maps of (a) QPSK1, (b) QPSK2, and (c) star 16-QAM.

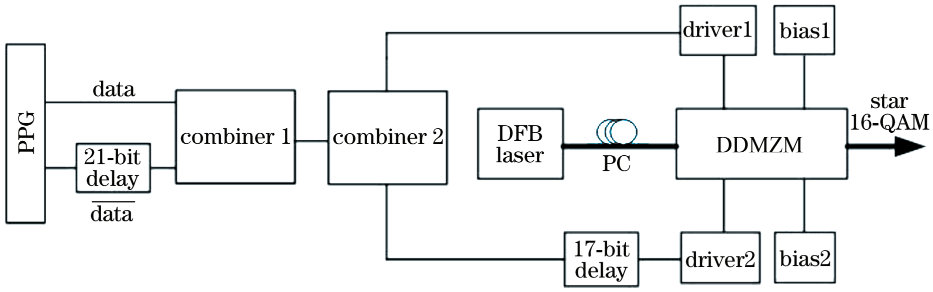

Fig. 2. Experimental setup of 40-Gb/s star 16-QAM transmitter.

An experiment is performed to generate 40-Gb/s star 16-QAM signal with the setup shown in Fig. 2. The transmitter consists of a distributed feedback (DFB) laser and a DDMZM (JDSU, 21051696-006). The DDMZM has a 3-dB bandwidth of ~ 12 GHz and a V_π of ~ 3.1 V at 10 GHz. Two 10-Gb/s pseudo-random binary sequence (PRBS) tributaries, data and $\overline{\text{data}}$ with a word length of $2^{11}-1$, are generated by a pulse pattern generator (PPG). An electrical delay line is used to achieve 21-bit delay between the two data streams before combined by an electric combiner 1. A four-level signal is then obtained, whose eye diagram is depicted in Fig. 3(a). The signal is divided into two paths by combiner 2 and a 17-bit delay between the two paths is added by another delay line. The two signals are amplified to achieve a peak-to-peak voltage of $1.5V_\pi$ before driving the DDMZM. The eye diagram after amplification is provided in Fig. 3(b). By adjusting a proper voltage difference between V_{bias1} and V_{bias2}, a 40-Gb/s star 16-QAM signal can be generated, with some bit patterns captured in Fig. 4. One can see that there are two evident intensity levels which are consistent with Fig. 1(c). The fluctuations on the two levels can be attributed to the non-ideal four-level driving signals. Due to the lack of phase measurement instrument, we do not provide the corresponding phase allocations in this experiment. The spectrum of the obtained signal is provided in Fig. 5, with a 3-dB bandwidth similar to 10-Gb/s phase-shift keying (PSK) signal.

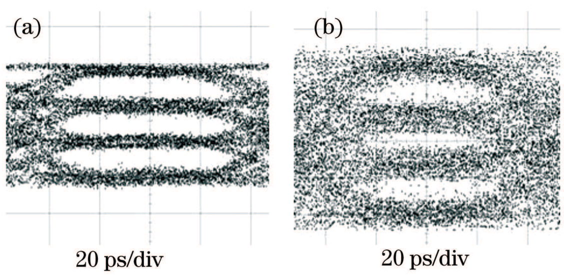

Fig. 3. Eye diagrams of electrical four-level signals. (a) After combiner 1, (b) after drivers.

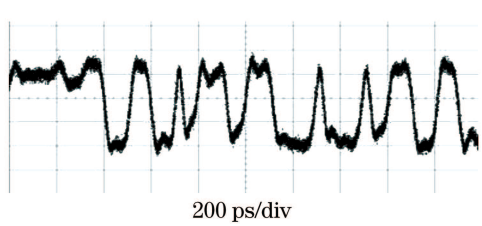

Fig. 4. Captured star 16-QAM bit patterns.

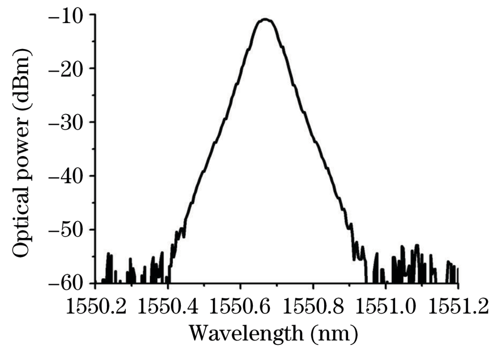

Fig. 5. Spectrum of 40-Gb/s star 16-QAM signal (0.07-nm resolution).

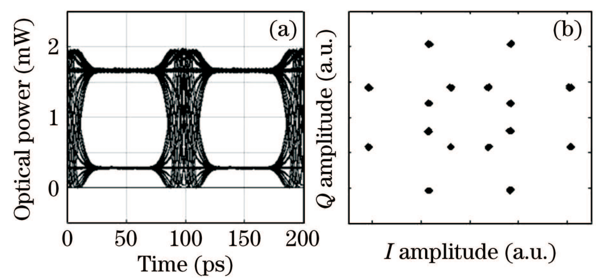

Fig. 6. (a) QAM eye diagram and (b) constellation map in back-to-back system.

In order to study the transmission performance of the proposed transmitter, a simulation is performed with VPI TransmissionMaker. Based on the transmitter in Fig. 2 and a 2 × 4 90°-hybrid coherent receiver implemented with four 3-dB couplers and a phase shifter[3], we set up a transmission system. A DFB laser with the linewidth of 1 MHz is used as continuous wave (CW) light source in the transmitter and also as a local oscillator (LO) at the receiver. 2048 bits are sampled in the system. The back-to-back eye diagram and constellation map are provided in Figs. 6(a) and (b), respectively. The transmission line consists of an erbium-doped fiber amplifier (EDFA), an 80-km standard single-mode fiber (SSMF), a second EDFA, and a 16-km dispersion compensating fiber (DCF). The SSMF has a dispersion $D = 16$ ps/(nm·km), a dispersion slope $S = 0.06$ ps/(nm^2·km), a nonlinear index $\gamma = 1.31$ W^{-1}/km, and a loss $\alpha = 0.2$ dB/km. The DCF parameters are $D = -80$ ps/(nm·km), $S = -0.18$ ps/(nm^2·km), $\gamma = 2.64$ W^{-1}/km, and $\alpha = 0.6$ dB/km, respectively. The launch powers into the SSMF and DCF are set to be 6 dBm and 2 dBm, respectively.

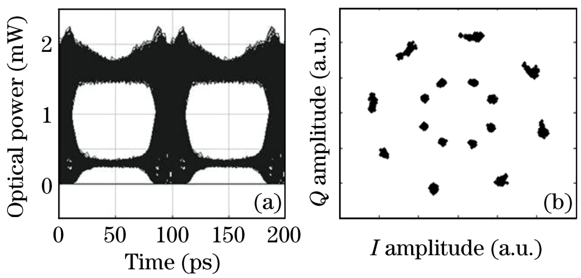

Fig. 7. (a) QAM eye diagram and (b) constellation map after transmission.

At the receiver side, the signal is amplified to be 0 dBm and then coherently detected. The eye diagram and constellation map are depicted in Figs. 7(a) and (b), respectively. One can see that after transmission, the recovered constellation map is still clearly allocated and error free performance can be expected.

In conclusion, we have proposed a star 16-QAM transmitter based on a single DDMZM. A 40-Gb/s signal is demonstrated through experiment and simulation to prove the feasibility of the scheme. The transmitter is studied in an 80-km SSMF transmission system by simulation, indicating error free performance.

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