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RESEARCH ARTICLE

A simple experimental scheme for M-QAM optical signals generation

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Abstract A simple scheme to generate optical quadrature amplitude modulation (QAM) signals is proposed based on different types of delay interferometers (DIs). The simulated results show that 16QAM, 64QAM and 256 QAM optical signals can be generated by 2×2, 3×3 and 4×4 DI, respectively, and the outputs of the proposed scheme are similar to those of the conventional schemes. The operation principle is discussed and the transmission properties of the square 16QAM as well as 64QAM signals are analyzed and compared with common approach.

Keywords advanced modulation formats, multi-level modulation formats, quadrature amplitude modulation, delay interferometers (DIs)

1 Introduction

To meet the increasing demand of expanding the transmission capacity within a fixed optical amplification bandwidth, multi-level modulation formats have attracted a lot of attention [1–3]. Among these formats, quadrature amplitude modulation (QAM) is an outstanding candidate for its ability of enhancement of spectral efficiency. With respect to the constellation distribution, M-ary QAM (M-QAM) can be categorized as three groups, such as star M-QAM, square M-QAM and M-amplitude phase shift key (M-APSK) [4]. However, square M-QAM is more widely used for its transmission robustness and demodulation simplicity. Recently, numerous schemes have been proposed and demonstrated for 16QAM [5–7], 64QAM [8,9] and 256QAM [10].

In principle, any square M-QAM could be realized by utilizing enough Mach-Zehnder Modulators (MZMs) and Phase Modulators (PMs) regardless of system cost. In this paper, we firstly propose a novel scheme to generate 16QAM, 64QAM and 256QAM optical signals. Square 16QAM and star 16QAM optical signals are successfully generated by two MZMs and a 2×2 delay interferometer (DI). When the 3×3 DI substitutes the 2×2 DI, a 64QAM signal is achieved. Similarly, we can get a 256QAM signal when use a 4×4 DI. The transmission simulation results show that the signals generated from the simple approach have the similar transmission properties compared with those of the conventional method. Thus, the simple scheme is a better choice to investigate the transmission properties of the high-order modulation formats.

2 Principles

2.1 Square 16QAM and star 16QAM generations

The schematic diagram of the proposed square 16QAM signal transmitter is shown in Fig. 1(a). Firstly, a differential quadrature phase shift keying (DQPSK) signal is generated by a conventional In-phase Quadrature (IQ) modulator. The DQPSK signal can be written as

$$E_{\mathrm{DQPSK}} = \frac{\mathrm{j}E_{\mathrm{in}}}{\sqrt{2}}\left[\exp\left(\mathrm{j}\pi I_k\right) + \exp\left(\mathrm{j}\pi Q_k + \mathrm{j}\frac{\pi}{2}\right)\right], \quad (1)$$

where E_{in} is the electrical field of the continuous wave (CW) light, I_k and Q_k are the precoded electrical signals. Then the DQPSK signal is launched into a 2×2 DI, which consists of two 2×2 couplers, a phase shifter and a delay line. To achieve the square 16QAM signal, the power splitting ratio of the former and latter couplers of 2×2 DI are adjusted to 1:4 (amplitude ratio of the optical signals in upper and lower arm is 1:2) and 1:1, respectively. The optical signal in the upper arm is introduced a $\pi/2$ phase shift, while the optical signal in the lower arm is delayed for 5 bits. At the output of the second coupler, a square

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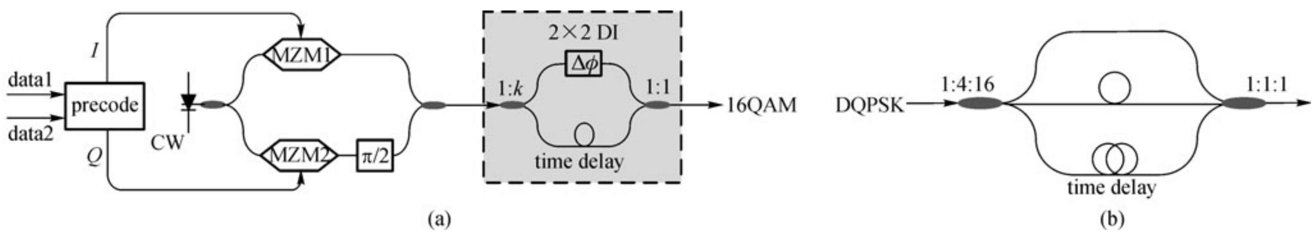

Fig. 1 (a) Schematic diagram of square 16QAM optical signal generation; (b) structure of the 3×3 DI. MZM: Mach-Zehnder modulator; CW: continuous wave

16QAM signal is received. This signal can be represented as

$$E_{\mathrm{QAM}} = \frac{\mathrm{j}E_{\mathrm{in}}}{\sqrt{2}}\Big\{\Big[\exp(\mathrm{j}\pi I_k) + \exp\Big(\mathrm{j}\pi Q_k + \mathrm{j}\frac{\pi}{2}\Big)\Big] + 2\Big[\exp\Big(\mathrm{j}\pi I_{k-5} + \mathrm{j}\frac{\pi}{2}\Big) + \exp(\mathrm{j}\pi Q_{k-5} + \mathrm{j}\pi)\Big]\Big\}, \tag{2}$$

where I_{k-5} and Q_{k-5} are the input I_k and Q_k signals after 5 bits time delay. When I_{k-5}, Q_{k-5}, I_k and Q_k change from 0000 to 1111, 16 optical fields can be obtained, resulting in the desired square 16QAM signal. To show the feasibility of the proposed transmitter, adjust the splitting ratio of the two couplers, shifted phase and delay time to 1:1, 1:1, $\pi/4$ and 5 bits. Then, a star 16QAM signal can be generated.

2.2 Square 64QAM generation

To obtain a square 64QAM optical signal, we substitute a 3×3 DI for the 2×2 DI. The structure of the 3×3 DI is shown in Fig. 1(b). The splitting ratio of the 3×3 DI is adjusted to 1:4:16, thus, the amplitude ratio of optical signals is 1:2:4. Signals in three arms are delayed for 0, 3 and 5 bits, respectively. The output of the 3×3 DI can be expressed by

$$E_{\mathrm{QAM}} = \frac{\mathrm{j}E_{\mathrm{in}}}{\sqrt{2}}\Big\{\Big[\exp(\mathrm{j}\pi I_k) + \exp\Big(\mathrm{j}\pi Q_k + \mathrm{j}\frac{\pi}{2}\Big)\Big] + 2\Big[\exp(\mathrm{j}\pi I_{k-3}) + \exp\Big(\mathrm{j}\pi Q_{k-3} + \mathrm{j}\frac{\pi}{2}\Big)\Big] + 4\Big[\exp(\mathrm{j}\pi I_{k-5}) + \exp\Big(\mathrm{j}\pi Q_{k-5} + \mathrm{j}\frac{\pi}{2}\Big)\Big]\Big\}, \tag{3}$$

when I_{k-5}, Q_{k-5}, I_{k-3}, Q_{k-3},I_k and Q_k change from 000000 to 111111, 64 optical fields are achieved, which is the 64QAM signal.

2.3 Square 256QAM generation

When use a 4×4 DI, a 256QAM signal is generated. The construction of the 4×4 DI is displayed in Fig. 2. Power splitting ratio of the former coupler is 1:4:16:64 (amplitude ratio is 1:2:4:8) and the latter is 1:1:1:1. Signals in four arms are delayed for 0, 3, 5 and 7 bits, respectively. The output of the second coupler is

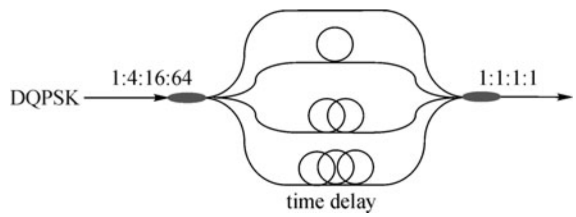

Fig. 2 Structure of 4×4 DI

$$E_{\mathrm{QAM}} = \frac{\mathrm{j}E_{\mathrm{in}}}{\sqrt{2}}\Big\{\Big[\exp(\mathrm{j}\pi I_k) + \exp\Big(\mathrm{j}\pi Q_k + \mathrm{j}\frac{\pi}{2}\Big)\Big] + 2\Big[\exp(\mathrm{j}\pi I_{k-3}) + \exp\Big(\mathrm{j}\pi Q_{k-3} + \mathrm{j}\frac{\pi}{2}\Big)\Big] + 4\Big[\exp(\mathrm{j}\pi I_{k-5}) + \exp\Big(\mathrm{j}\pi Q_{k-5} + \mathrm{j}\frac{\pi}{2}\Big)\Big] + 8\Big[\exp(\mathrm{j}\pi I_{k-7}) + \exp\Big(\mathrm{j}\pi Q_{k-7} + \mathrm{j}\frac{\pi}{2}\Big)\Big]\Big\}. \tag{4}$$

As I_{k-7}, Q_{k-7}, I_{k-5}, Q_{k-5}, I_{k-3}, Q_{k-3}, I_k and Q_k change from full “0”s to full “1”s, we can achieve 256 optical fields, and the 256QAM signal is obtained.

3 Simulation and results

3.1 Signals generation

The simulation setup for 16QAM signals is shown in Fig. 3. The commercial software VPI Transmission Maker is employed to carry out the simulation. The CW at 193.1 THz is produced via a distributed-feedback laser with the line width of 300 Hz. Both MZMs are driven at 10 Gbit/s and biased at the null point. At the output of the transmitter, a 40 Git/s 16QAM signal is achieved. When using 3×3 DI, which is realized with the help of matlab program. a 64QAM signal with the bit rate of 60 Git/s can be performed. For the 256QAM, the bit rate reaches to 80 Git/s.

The simulated constellations and corresponding eye

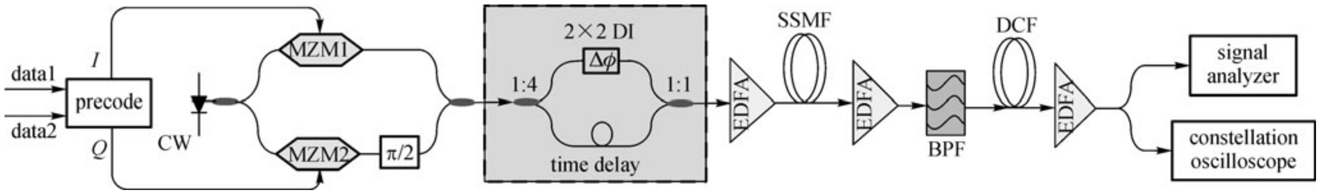

Fig. 3 Simulation setup for the generations of square and star 16QAM. SSMF: Standard single mode fiber; BPF: band pass filter; EDFA: erbium-doped fiber amplifier; DCF: dispersion compensation fiber

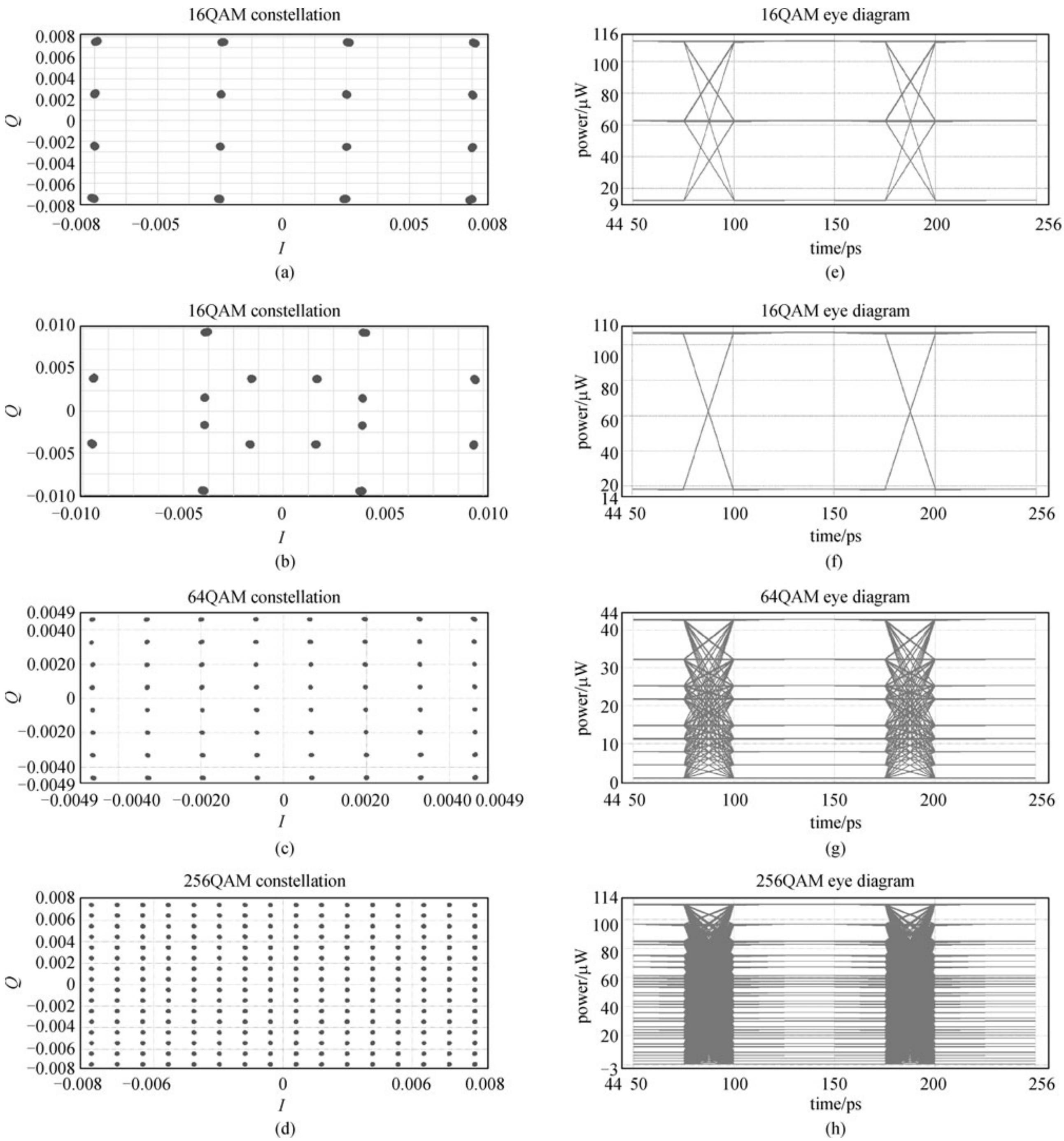

Fig. 4 Constellations and eye diagrams of 16QAM, 64QAM and 256QAM signals. (a),(e) Square 16QAM; (b),(f) star 16QAM; (c),(g) 64QAM; (d),(h) 256QAM

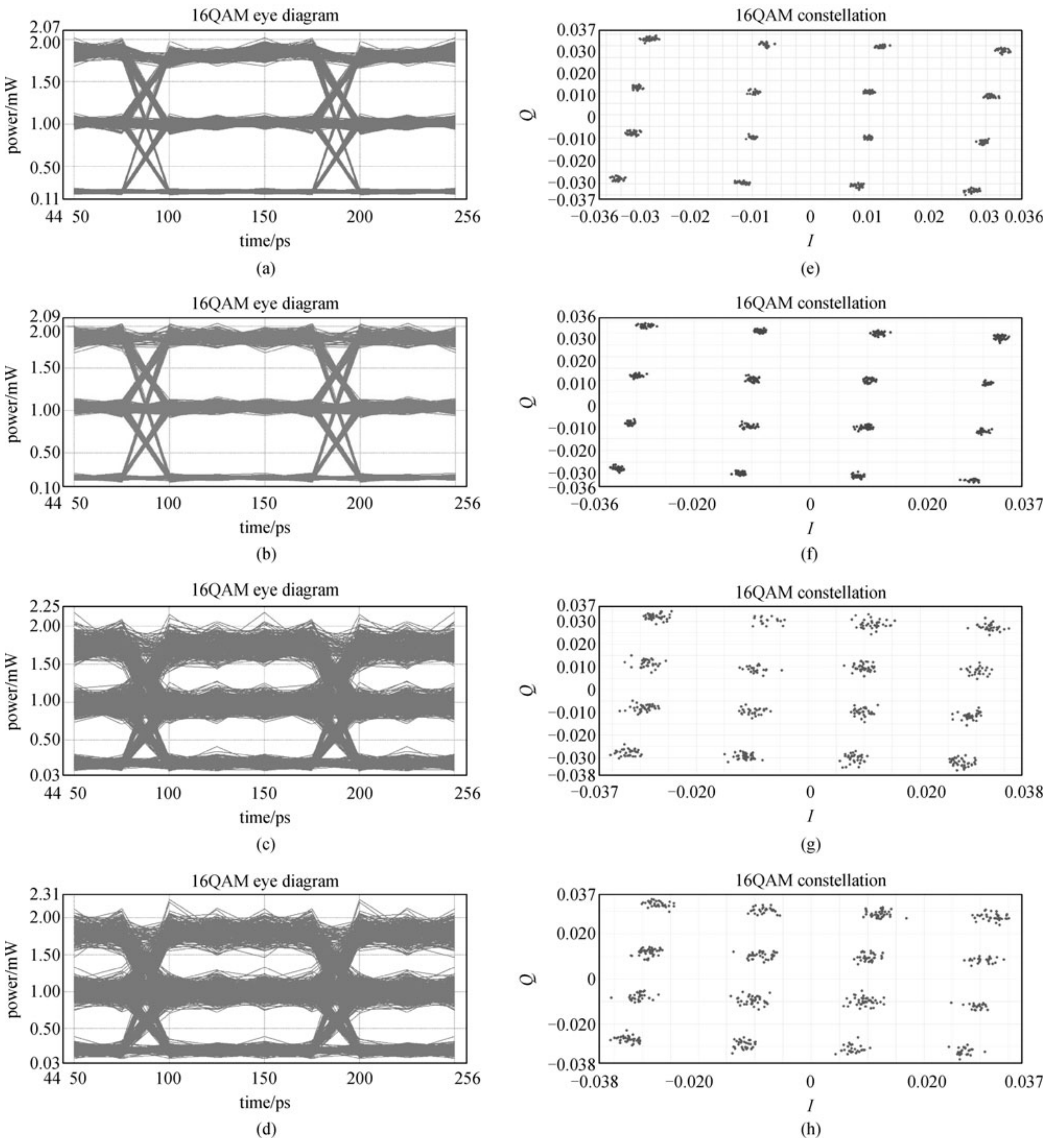

Fig. 5 Eye and constellation diagrams of 16QAM signals after transmission. (a),(e) Scheme A, 80 km SSMF; (b),(f) scheme B, 80 km SSMF; (c),(g) scheme A, 140 km SSMF; (d),(h) scheme B, 140 km SSMF

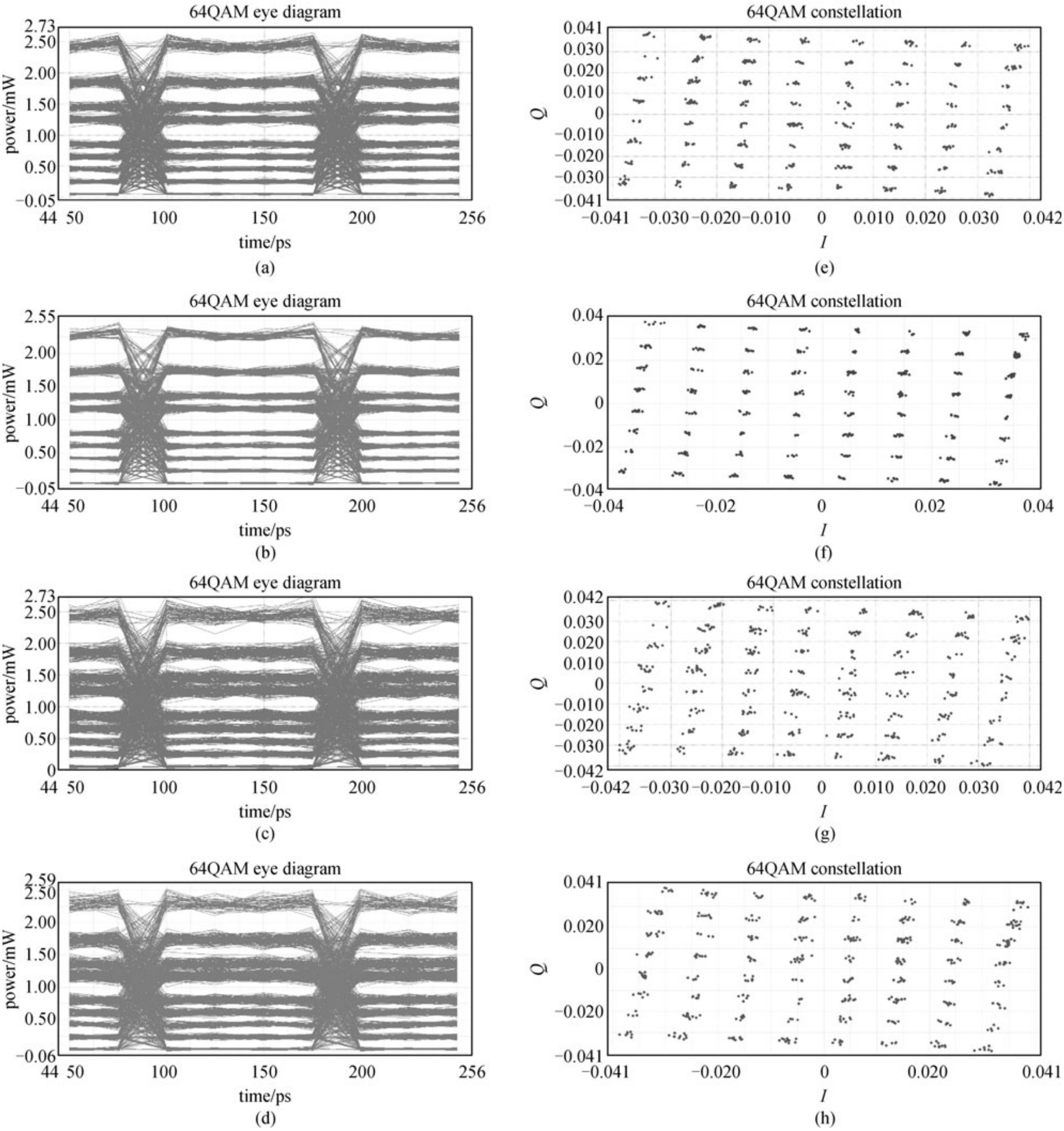

Fig. 6 Eye and constellation diagrams of 64QAM signals after transmission. (a),(e) Scheme A, 80 km SSMF; (b),(f) scheme B, 80 km SSMF; (c),(g) scheme A, 100 km SSMF; (d),(h) scheme B, 100 km SSMF

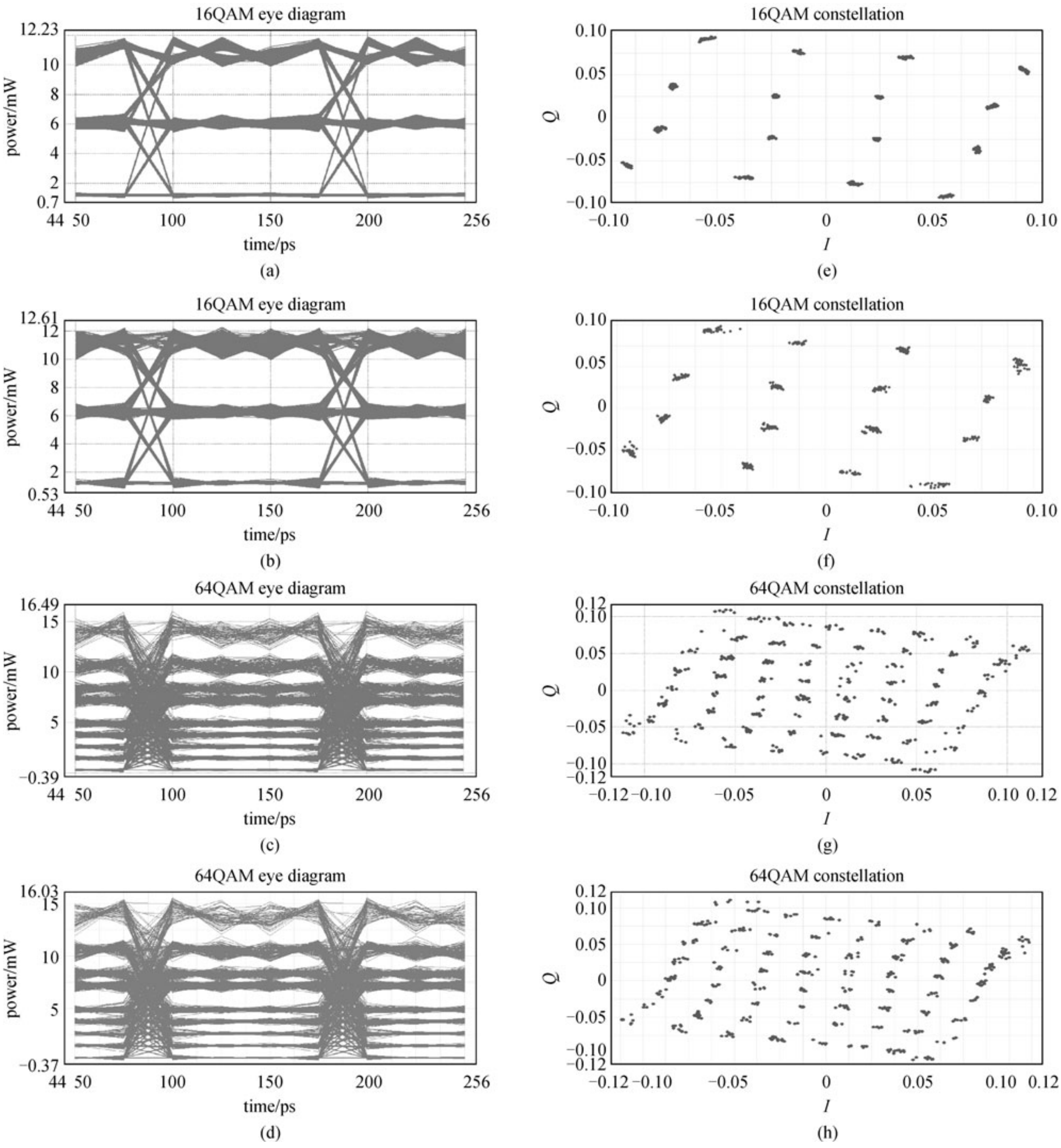

Fig. 7 Eye and constellation diagrams of 16QAM and 64QAM signals after transmission. (a),(e) Scheme A, 20 km SSMF; (b),(f) scheme B, 20 km SSMF; (c),(g) scheme A, 20 km SSMF; (d),(h) scheme B, 20 km SSMF

diagrams are presented in Fig. 4. As shown in Figs. 4(a) and 4(e), square 16QAM signal has three different amplitudes and twelve different phase states. In addition, distances between the two adjacent symbols at in-phase or quadrature-phase direction are identical. For star 16QAM, the phases are arranged equally around concentric circles, and radiuses of the circles represent the multiple amplitudes of QAM signal. Therefore, star 16QAM has two different amplitudes and eight different phase states as illustrated in Figs. 4(b) and 4(f). The constellation distributions and characteristics of the square 64QAM and 256QAM signals are similar to those of the square 16QAM, which are shown in Figs. 4(c), 4(d), 4(g) and 4(h).

3.2 Transmission simulation

Due to square M-QAM is more widely used for its transmission robustness and demodulation simplicity, transmission properties of the square 16QAM and 64QAM are analyzed, moreover, we compare the transmission results between the proposed simple QAM transmitter and the conventional approach [11]. In the following presentation, the simple scheme we proposed is named scheme A, while the scheme quoted from Ref. [11] is named scheme B. As shown in Fig. 3, after being amplified to 0 dBm by the erbium- doped fiber amplifier (EDFA) with a noise figure of 4 dB, the generated 16QAM signal is launched into an 80 km standard single-mode fiber (SSMF) with dispersion of 16 ps/(nm·km), dispersion slope of 0.046 ps/(nm^2·km), a nonlinear index of 2.754×10^{-20} m^2/W, and a loss of 0.2 dB/km. Then the signal is filtered by a band-pass filter with the bandwidth of 0.4 nm. 16 km dispersion compensating fiber (DCF), whose corresponding parameters are -80 ps/(nm·km), -0.18 ps/(nm^2·km), 1.24×10^{-20} m^2/W and 0.6 dB/km, is used to compensate the chromatic dispersion. The 64QAM signal is passed through the identical transmission link.

The eye and constellation diagrams of both schemes after transmission are observed as shown in Figs. 5(a), 5(b), 5(e) and 5(f). The maximum transmission distances of scheme A and B reach to 140 km SSMF with 28 km DCF and the simulation results are depicted in Figs. 5(c), 5(d), 5(g) and 5(h). Obvious deterioration occurs because of the residual dispersion and nonlinearity. The signal degradation of scheme A is as similar as that of scheme B.

Simulations of the 64QAM are illustrated in Fig. 6. As shown in Figs. 6(a), 6(b), 6(e) and 6(f), clear eye and constellation diagrams are achieved after the transmission of 80 km SSMF with 16 km DCF. For the 64QAM, the maximum transmission distance is comparatively shorter than that of the 16QAM which only get to 100 km SSMF with 20 km DCF. Figures 6(c), 6(d), 6(g) and 6(h) show the transmission results of both schemes. The two amplitudes in the middle of the eye diagrams are difficult to distinguish in this case, however, the symbols in constellation diagrams are still clearly to recognize.

The influences of nonlinearity to the 16QAM and 64QAM signals are also investigated. The signals are amplified to 8 dBm before feeding into the fiber; meanwhile, dispersion and dispersion slope are all compensated during the 20 km SSMF transmission with 4 km DCF.

As shown in Fig. 7, the strong nonlinearity leads to a dramatic obliqueness to the constellation diagrams. The QAM signals are very sensitive to fiber nonlinearity since they have many different amplitudes and different phase states. The more constellation symbols the signal has, the shorter Euclidean distance will be between different symbols, and therefore, the signal is more sensitive to nonlinearity.

4 Conclusions

In this paper, a simple experimental scheme for the generations of different M-QAM signals are investigated based on MZMs and 2×2, 3×3 and 4×4 DI . Star 16QAM, square 16QAM, 64QAM and 256QAM signals are successfully realized with this scheme. With the help of VPI TransmissionMaker, the generation process is simulated. Transmission simulations show that the proposed simple scheme has the similar transmission characteristics to those of the conventional approaches. The most important point of the novel scheme is its simplicity which make it as a better choice to investigate the transmission properties of these high-order modulation formats.

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