Generation of square or hexagonal 16-QAM signals using a dual-drive IQ modulator driven by binary signals

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Abstract: We propose a simple square or hexagonal 16-QAM signal generation technique using a commercially available dual-drive IQ modulator driven by four binary electrical signals with properly designed amplitudes. We analytically derive the required driving signal amplitudes for square and hexagonal 16-QAM and characterize its implementation penalty. Polarization-multiplexed (PM)-16-QAM signals at 28 Gbuad are experimentally demonstrated and stable performance is achieved with simple bias control.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

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1. Introduction

Thanks to the advance of digital signal processing (DSP) techniques, high-order modulation format signals with coherent detection technologies enable more spectrally efficient optical transmission systems [1]. Dual polarization (DP) quadrature phase shift keying (QPSK) operating at 100 Gb/s with DSP are now commercially available [2]. 16-ary quadrature amplitude modulation (16-QAM), which doubles the spectral efficiency (SE) further to 4 bit/s/Hz [3], becomes the potential candidate for next generation optical transmission system beyond 100 Gb/s per channel. Several recent transmission experiments have verified the possibility of using polarization multiplexing (PM) 16-QAM for achieving 400Gbit/s transmission [4–6]. However, for practical system implementation, simple and low cost generation of 16-QAM signals proves to be a challenging task.

Extensive researches have been carried out for 16-QAM signal generation. 16-QAM signals can be generated with tandem-QPSK transmitter by cascading IQ modulator, Mach-Zehnder Modulators (MZM) and phase modulators (PM) [7], or cascading two IQ modulators [8]. Such transmitters were driven by binary electrical signals, simplifying the drive electronic circuits design. However, the need for cascading several discrete modulators in such transmitter leads to a large insertion loss. The long term stability is also a major issue. Another approach for 16-QAM generation was to integrate several modulators in a parallel structure, such as two IQ modulators, or several MZM modulators [9, 10]. One problem of these approaches is that the modulators with complex structure are hard to fabricate. Thus, no commercially available components are ready for practical engineering application. Another practical method to realize 16-QAM transmitter was to use four-level signals to drive a single drive IQ modulator [3, 11]. In this configuration, the IQ modulator operated on the linear region of its transfer function so that the electrical noise in driving signals would be linearly translated into the optical domain. Thus, the performance of the generated 16-QAM signals largely depends on the quality of the four-level signals generated. However, compared with typical binary driving signals, the generation and handling of the four-level electrical driving signals are relatively more difficult. A common method to generate four-level signals is to combine two binary signals with variable amplitudes. However, due to impedance mismatch, the reflections from IQ modulator, amplifiers, adapters and connectors will all degrade the quality of the generated four-level signals. Thus, extra attenuators are required to block the reflections to realize lossy matching. In order to compensate the loss, the driving signals should be amplified with expensive linear amplifiers. Thus, expensive digital-to-analog converters (DAC) are usually used for generating four-level electrical driving signal.

In addition to square 16-QAM, another attractive modulation format is hexagonal 16-QAM signals. It has a constellation that resembles a triangular lattice which is more compact and

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energy efficient than that for square 16-QAM. Doerr demonstrated the generation of hexagonal 16-QAM optically for the first time using a complex InP modulator [12]. However, it requires four optical modulators in parallel with a five-arm interferometer. Carefully designed power splitting ratios and phases of the star couplers are essentially and this lead to significant challenge to the fabrication process.

In this paper, we extend on our preliminary study in [13] and propose a simple technique for generating square or hexagonal 16-QAM signals using a commercially available dual-drive IQ modulator driven by binary electrical signals. Analytical derivations of the modulator transfer function shows that by appropriately adjusting the amplitudes of the binary driving signals, both square and hexagonal 16-QAM signal can be generated. 28 Gbaud polarization-multiplexed (PM) square 16-QAM signals are generated experimentally using our generation technique and back-to-back transmission performance of the generated square 16-QAM signals is characterized. For the hexagonal 16-QAM signal generation, some preliminary experiment results are presented with 25 Gbaud system. To the best of our knowledge, this is the first experimental demonstration of hexagonal 16-QAM signals with an IQ modulator.

2. Operating principle

The operating principle of the proposed 16-QAM transmitter is shown in Fig. 1. A commercially available dual-drive IQ modulator is used as the external modulator. Two Mach-Zehnder Modulators and a phase modulator are integrated together in the nested IQ modulator. Each MZM in the dual-drive IQ modulator is a dual-drive MZM (DD-MZM), driven by two binary signals with different amplitudes. The bias points of the MZMs can be adjusted independently for generating different signals. As we will show in subsequent analytical derivations, two independent four-level amplitude- and phase-shift keying (4-APSK) signals can be synthesized to modulate the I and Q components of the optical carrier. The 16-QAM signal is then generated by adding the components together, as shown in Fig. 1.

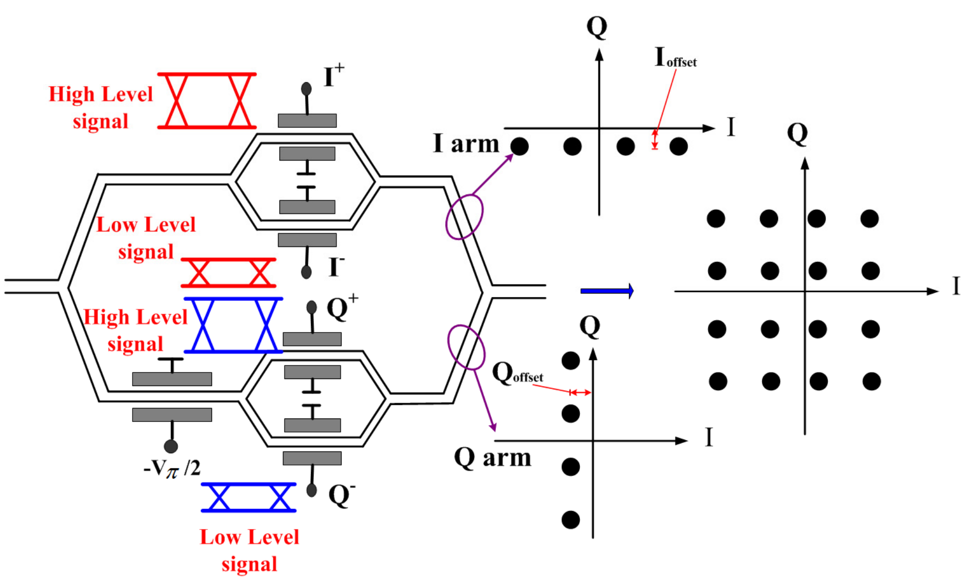

Fig. 1. Operating principle of the proposed 16-QAM transmitter using dual-drive IQ modulator driven by binary signals.

We will use the dual drive MZM in I arm of the IQ modulator to illustrate the principle for generating 4-APSK in more detail. The MZM is operated in push-pull mode and biased at the

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Null point. Neglecting insertion loss, the transmission function of the dual drive MZM is given by

$$\frac{E_{out}(t)}{E_{in}(t)}=\frac{1}{2}\left(e^{j\left(\frac{v_1}{V_\pi}\pi+\frac{v_b}{2}\right)}+e^{-j\left(\frac{v_2}{V_\pi}\pi+\frac{v_b}{2}\right)}\right), \tag{1}$$

where v_1, v_2 represent the amplitude of the driving signals, v_b is the bias point of the MZM (for Null point, $v_b=\pi$), and V_π is the half-wave voltage of the MZM.

In the setup, the drive signals are two AC coupled binary signals with amplitude V_H and V_L ($V_H > V_L$), for the upper arm and low arm of the MZM respectively. The two driving signals will introduce phases ϕ_H and ϕ_L given by

$$\phi_H=\frac{V_H}{2V_\pi}\pi \text{ and } \phi_L=\frac{V_L}{2V_\pi}\pi. \tag{2}$$

2.1 Square 16-QAM generation

For square 16-QAM generation, four equidistant and collinear signal points should be generated in parallel with the axis both in the I and Q arm, as shown in Fig. 1. The MZMs are biased at the Null point so that

$$\begin{aligned}\frac{E_{out}(t)}{E_{in}(t)}&=\frac{1}{2}\left(e^{j\left(\frac{\pm V_H\pi}{2V_\pi}+\frac{\pi}{2}\right)}+e^{-j\left(\frac{\pm V_L\pi}{2V_\pi}+\frac{\pi}{2}\right)}\right)=\frac{j}{2}\left(e^{j\frac{\pm V_H\pi}{2V_\pi}}-e^{-j\frac{\pm V_L\pi}{2V_\pi}}\right)\\&=-\sin\frac{\pm V_H\pm V_L}{4V_\pi/\pi}\cos\frac{\pm V_H\mp V_L}{4V_\pi/\pi}-j\sin\frac{V_H+V_L}{4V_\pi/\pi}\sin\frac{V_H-V_L}{4V_\pi/\pi}\\&=-\sin\frac{\pm\phi_H\pm\phi_L}{2}\cos\frac{\pm\phi_H\mp\phi_L}{2}-j\sin\frac{\phi_H+\phi_L}{2}\sin\frac{\phi_H-\phi_L}{2}.\end{aligned} \tag{3}$$

The output signal points of the dual-drive MZM can also be graphically represented in Fig. 2.

From the figure, four signal points will be generated if we drive the dual- drive MZM with different driving amplitudes. We see that the four signal points will fall on a line with a distance I_{offset} parallel with the *I*-axis. Normalizing the input optical carrier power $|E_{in}(t)|^2=1$, the offset from the *I*-axis I_{offset} is

$$I_{offset}=\left|\cos\phi_L-\cos\phi_H\right|=\sin\frac{V_H+V_L}{4V_\pi/\pi}\sin\frac{V_H-V_L}{4V_\pi/\pi}. \tag{4}$$

The offset value depends on the amplitudes of the driving signals and V_π.

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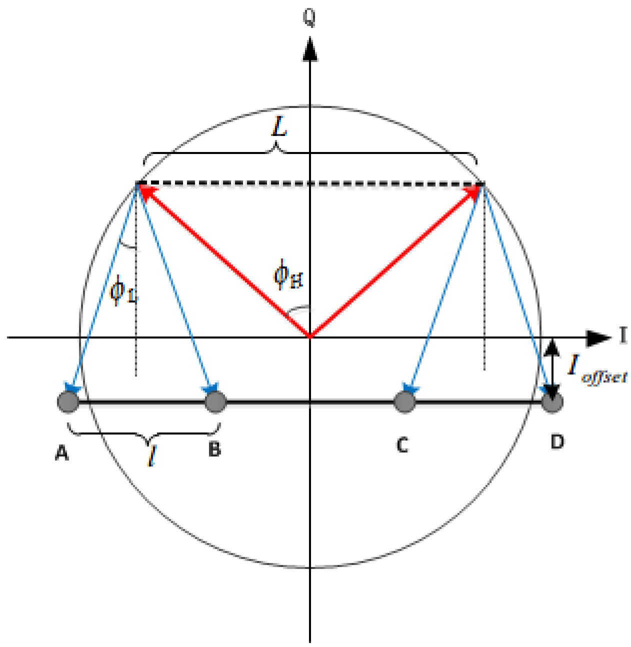

Fig. 2. Constellation points generated by a dual-drive MZM with different driving amplitudes. By appropriately designing the driving amplitudes V_H and V_L, one can generated 4 signal points A,B,C and D that falls on the same line and equi-distant from each other i.e. essentially a 4-APSK signal.

Another requirement for the generation of square 16-QAM signals is that the four constellation points should be equally spaced from each other along the line. As shown in Fig. 2, the requirement can be expressed as $|AB|=|BC|=|CD|$, i.e. $L=2l$. As $l=2\sin(\phi_L)=2\sin\left(\frac{V_L}{2V_\pi}\pi\right)$ and $L=2\sin(\phi_H)=2\sin\left(\frac{V_H}{2V_\pi}\pi\right)$, the condition $L=2l$ becomes $\sin\phi_H=2\sin\phi_L$, i.e.

$$2\sin\left(\frac{V_L}{2V_\pi}\pi\right)=\sin\left(\frac{V_H}{2V_\pi}\pi\right). \tag{5}$$

In this case, four equidistant and collinear signal points can be obtained by using two binary electrical signals with amplitudes V_H and V_L satisfying Eq. (5). Four equidistant and collinear signal points in the *Q*-arm of the IQ modulator can be generated in a similar fashion and the overall square 16-QAM can be generated by adding the two 4-APSK signals from the output of the *I* and *Q* arms.

The 16-QAM constellation diagram from our proposed technique shows an offset from the origin of the complex IQ plane and hence a residual carrier will be present in the generated 16-QAM signals. The power of such residual carrier is given by

$$P_c=I_{Offset}^2+Q_{Offset}^2=2\sin^2\left(\frac{V_H+V_L}{4V_\pi/\pi}\right)\sin^2\left(\frac{V_H-V_L}{4V_\pi/\pi}\right). \tag{6}$$

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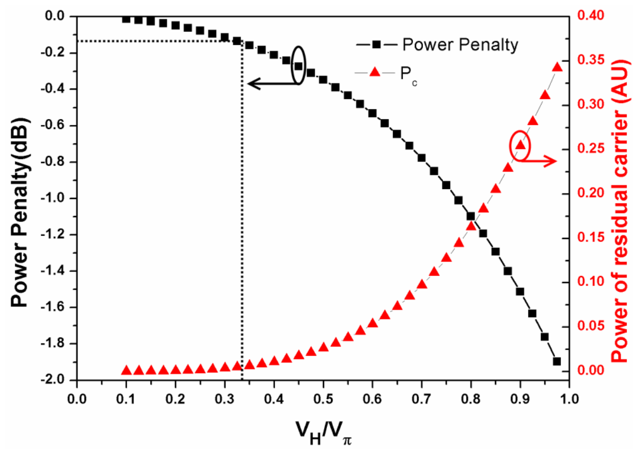

Fig. 3. Power of the residual carrier P_c and power penalty introduced by the residual carrier for various driving signal amplitudes V_H .

The power of the residual carrier P_c and the corresponding power penalty for various driving amplitudes V_H is depicted in Fig. 3. When V_H increases, the residual carrier P_c will increase and will lead to an OSNR penalty compared with standard 16-QAM generation techniques. The power penalty can be decreased when the driving signals are decreased. However, smaller driving signals introduce extra signal loss due to the low modulation index and therefore an apparent trade-off exist between minimizing power penalty and minimizing extra signal loss. Nonetheless, it should be noted that as long-haul systems are typically OSNR limited, the extra signal loss can be compensated with a post-amplifier and the transmitter SNR together with a post-amplifier will not really affect the overall transmission performance by much. Therefore, the trade-off between extra signal loss due to low modulation index and power penalty is not that practically relevant. The optimal value of V_H/V_π may depend on the actual design of the 16QAM transmitter and the link configuration and such details will be topics of future study. In our experiment described later in the paper, we use a V_H/V_π level of 0.34 which causes a 0.13 dB power penalty. Figure 4 shows the back-to-back transmission performance of 28 Gbaud PM-16-QAM signals with different driving voltages simulated by VPI TransmissionMaker 8.3. The corresponding optical spectra are also shown in the inset and are vertically displaced from each other for visual clarity. It is clear that the residual carrier is more pronounced when V_H/V_π increases and it will manifest itself as a DC offset in the received signal distributions. Fortunately, from a signal processing point of view, such DC offset can be easily eliminated at the receiver digital signal processing (DSP) unit and will not affect overall transmission performance.

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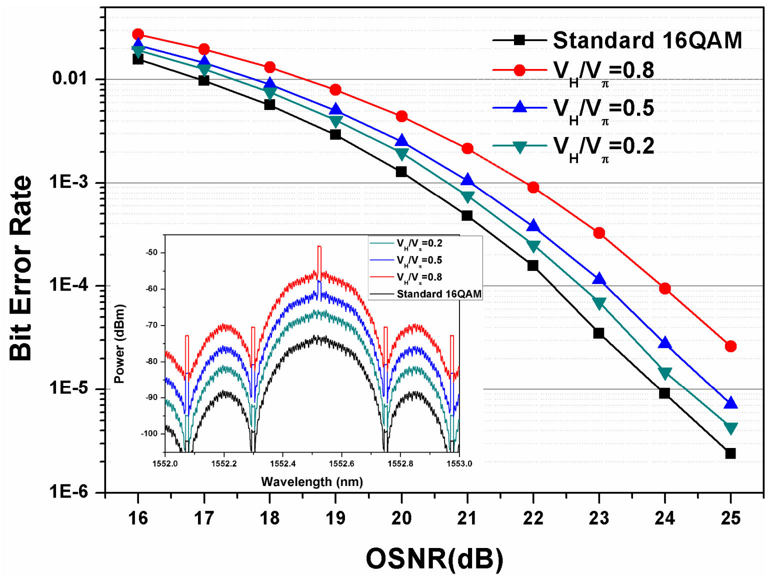

Fig. 4. Simulated back-to-back transmissions results for PM-16QAM signals with variable driving signal amplitudes. Inset: Corresponding optical spectra (vertically displaced for visual clarity).

2.2 Hexagonal 16-QAM generation

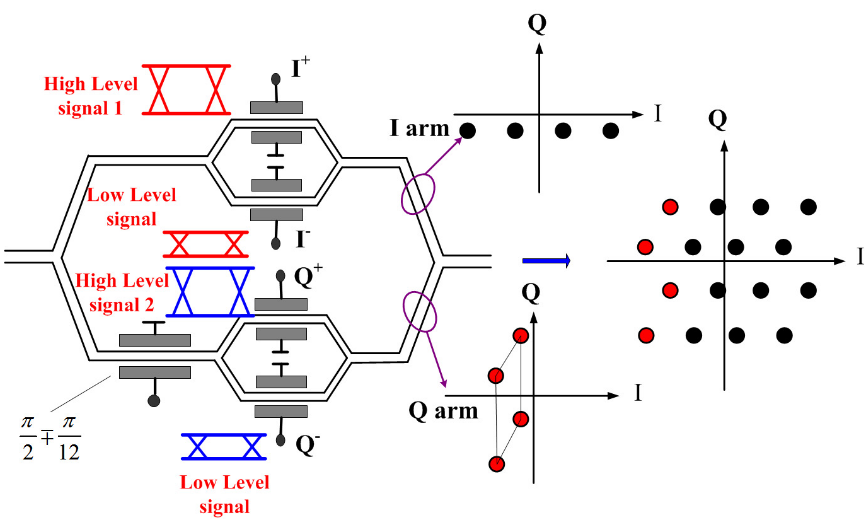

Fig. 5. Operating principle of the proposed Hexagonal 16-QAM transmitter using dual-drive IQ modulator driven by binary signals.

Since the 1980s, hexagonal 16-QAM is known to be the most energy-efficient 2-dimensional constellation with 4 bits/symbol [14] and it theoretically offers a 0.5 dB SNR advantage compared with the standard 16-QAM constellations. Also, as the hexagonal constellation becomes different when rotated by ± 90 degrees, it can potentially be used as a blind and cycle-slip-free modulation format. Binary driving signals together with the same hardware configuration can also be used for hexagonal 16-QAM generation. In this case, the *I*-arm of the IQ modulator is biased at the Null point such that four collinear points are generated as discussed previously. The *Q*-arm, however, will be biased at $v_b = \pm\pi/6$ and the phase

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modulator in this arm is tuned to generate phase shift of $\frac{\pi}{2} \mp \frac{\pi}{12}$. As we will show below, one can generate four signal points in the *Q*-arm that resembles a parallelogram as shown in Fig. 5 and the hexagonal 16-QAM signal can be obtained by adding the *I* and *Q* components.

In order to generate four signals that form a parallelogram, the MZM in the *Q*-arm of IQ modulator is biased at $v_b = \pm\pi/6$. Figure 6 shows the corresponding signals points generated by binary driving signals with different amplitudes.

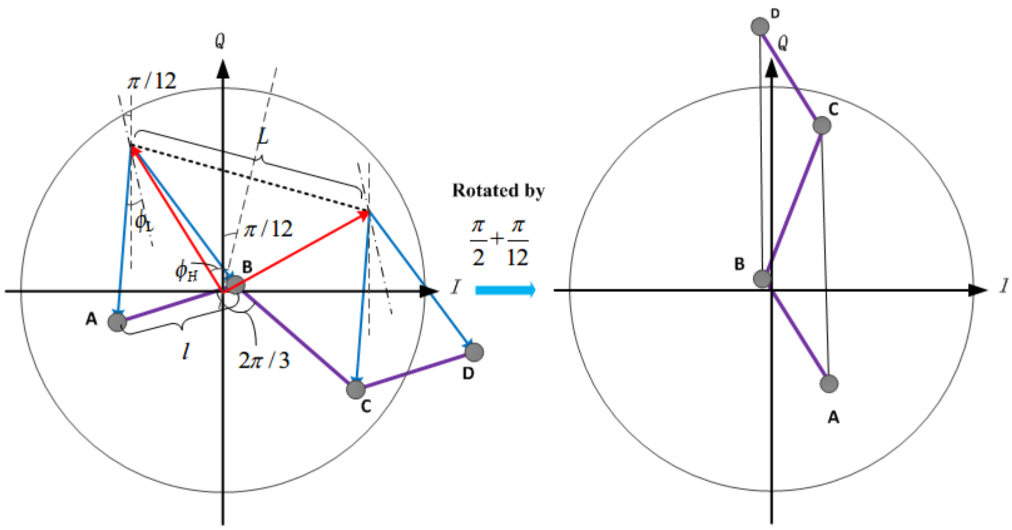

Fig. 6. Constellation points generated by a dual-drive MZM biasing at $v_b = -\pi/6$. By appropriately designing the driving amplitudes V_H and V_L, one can generated 4 signal points A,B,C and D that form a parallelogram.

For hexagonal 16-QAM generation, the following should be satisfied: $|AB| = |BC| = |CD|$ and $\angle ABC = \frac{2\pi}{3}$. The requirements can be expressed as $L = \sqrt{3}l$. As $l = 2\sin(\phi_L) = 2\sin\left(\frac{V_L}{2V_\pi}\pi\right)$ and $L = 2\sin(\phi_H) = 2\sin\left(\frac{V_H}{2V_\pi}\pi\right)$, the relations between the driving voltages in the *Q*-arm become

$$\sin\left(\frac{V_H}{2V_\pi}\pi\right) = \sqrt{3}\sin\left(\frac{V_L}{2V_\pi}\pi\right). \tag{7}$$

Comparing Eq. (7) and Eq. (5), it should be noted that for the case of hexagonal 16-QAM generation, the driving amplitudes V_H and V_L in the *Q*-arm are different in general. Another requirement for the generation of hexagonal 16-QAM is that the parallelogram formed by the four constellation points in the *Q*-arm should be parallel to the *Q*-axis. This can be easily achieved by phase rotating the *Q*-arm (relative to the *I*-arm) by, $\frac{\pi}{2} + \frac{\pi}{12}$ as supposed to the standard phase shift of $\frac{\pi}{2}$. Finally, the generated 4-APSK signals in the *I*-arm will be collinear and by adding the *I* and *Q* signals, hexagonal 16-QAM constellation can be generated with a single IQ modulator as shown in Fig. 5.

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3. Experimental setup and transmission performance

Figure 7 depicts the experimental setup for the proposed 16-QAM signal generation technique. The transmitter is setup according to our proposed scheme. The dual-drive IQ modulators are from Fujitsu (FTM7960EX) with a V_π of about 2.5V and optical bandwidth > 25 GHz. Eight 7 Gbit/s data streams are provided by a Altera FPGA develop board Stratix IV Transceiver SI development board. Then two 4:1 multiplexer (Mux) are used to combine four 7 Gbit/s data streams to 28 Gbit/s binary data streams. These 28 Gbit/s signals with amplitude about 0.5V are used as the low-amplitude (V_L) drive signals. Another two 28 Gbit/s drive signals is generated by a 2:1 multiplexer and two 14 Gbit/s pulse pattern generators (PPG) by Anristu. Two 28 Gbit/s signals from the data and inverse data ports are decorrelated with 1ns delay on one signal. These two 28 Gbit/s signals are used as the high-amplitude (V_H) drive signal with voltage about 0.85V. Then these two pairs of 28Gbit/s driving signals with different amplitudes are used to drive the IQ modulator to generate 16-QAM signals, which are amplified by EDFA and launched into the polarization multiplexing stage. In this stage, the incoming optical signal is first split up in two equally powered tributaries, one of which delayed for de-correlation, and then a polarization beam combiner (PBC) recombines the two tributaries, resulting in 224-Gb/s polarization-multiplexed (PM) 16-QAM signal. A 50-GHz interleaver is used to simulate the various filtering effects in realistic optical networks. Different amount of ASE noise is then added to the 16-QAM signals to realize different OSNR for performance characterization.

At the receiver, the signal are filtered out using another interlever with 50GHz grid size and subsequently de-multiplexed to the coherent receiver. The PM 16-QAM signal is mixed with a local oscillator (LO) with 100-kHz linewidth in an integrated coherent receiver from Fujistu (FIM24704) consists of a polarization-diversity 90∘optical hybrid, 4 sets of balanced receivers and transimpedance amplifiers (TIA). The four outputs of the coherent receiver are sampled using a 50 GSample/s real-time digital sampling scope (DSA72004B). A sequence of 500 K samples is stored and post-processed off-line. The digital signal processing algorithms comprises of re-sampling up to 56 GSa/s, four fractionally-spaced (T/2) 13–taps time-domain finite impulse response (FIR) adaptive filters for timing phase recovery, polarization de-multiplexing, differential group delay (DGD) mitigation and down sampling to one sample per symbol [15], frequency offset compensation, carrier phase estimation [16], symbol detection and bit error ratio (BER) calculation.

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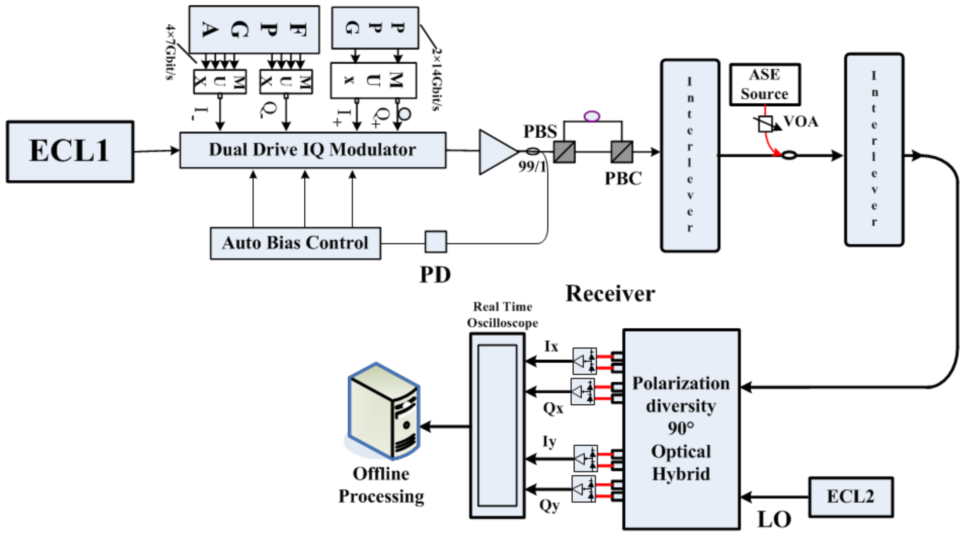

Fig. 7. Experimental setup for the proposed 16-QAM signal generation technique. De-correlated 28Gb/s binary data streams with different amplitudes are used to drive the dual-drive IQ modulator. PD: photo-detector; PBS: polarization beam splitter; PBC: polarization beam combiner; polarization division multiplexing; VOA: variable optical attenuator; ECL: external cavity laser.

Figure 8(a) shows the eye diagram of the 28 Gbaud 16-QAM signal detected by photo diode (PD) and oscilloscope. The corresponding optical spectrum is shown in Fig. 8(b). The optical spectrum of over-filtered 28 Gbaud 16-QAM signal is also shown in Fig. 8(b) for comparison. The 3dB bandwidth is 0.127 nm and the 20dB bandwidth is 0.384 nm. In our setup, the V_H / V_π level of the driving signal is about 0.34. So, small peak in the center of the optical spectrum can be observed due to the residual carrier.

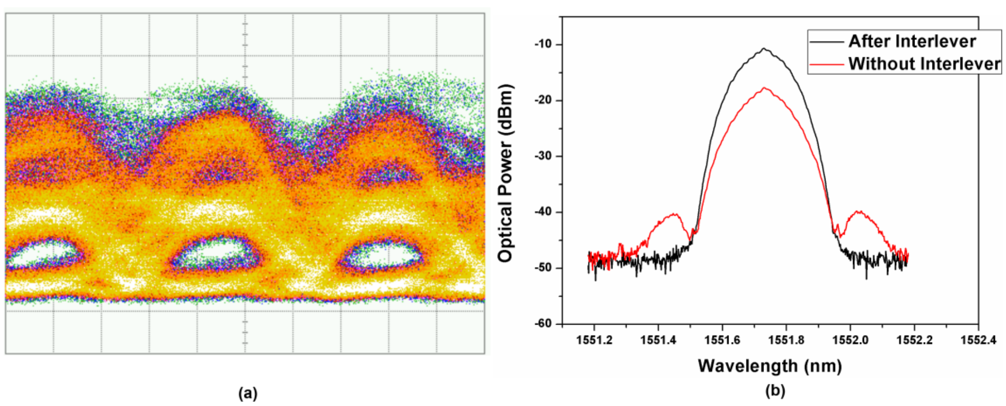

Fig. 8. Eye diagram (a) and optical spectra (b) with/without interlever of 28 Gbaud 16-QAM signals

With coherent detection and the off-line processing algorithms described above, the recovered signal distributions of the square 16-QAM signals with an OSNR of 32dB is shown in Fig. 9.

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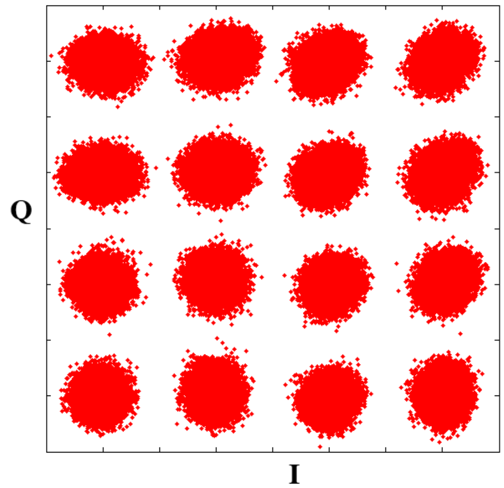

Fig. 9. Received signal distributions for the 28 Gbaud 16-QAM signal.

The back-to-back performance of the 224-Gb/s 16-QAM signal on a 50 GHz grid as a function of the OSNR is shown in Fig. 10. At a BER of 1E-3, the required OSNR for single polarization 28 Gbaud 16-QAM signal is 20.6dB, 3.6dB away from the theoretical OSNR requirement. With polarization-multiplexing, the required OSNR of 28 Gbaud PM 16-QAM signal increased to 24.9 dB, incorporating a 4.9 dB penalty from the theoretical limit. Without using four-level signals, the performance of our proposed 16-QAM generator is comparable with other‘s experiments [4, 17].

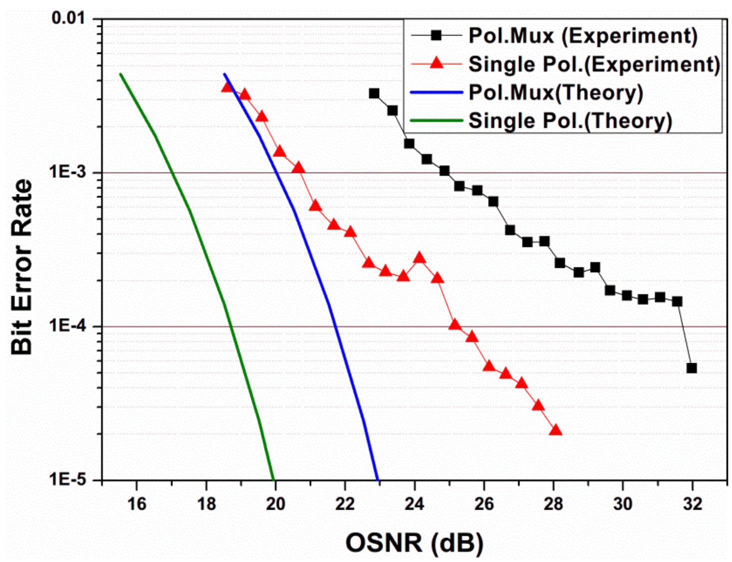

Fig. 10. Back-to-back BER vs. OSNR using the proposed square 16-QAM generation technique driven by two binary signals with different amplitudes. The OSNR is measured in 0.1 nm bandwidth.

Similar experimental setup is used for hexagonal 16-QAM generation. The baud rate of the transmitter is 25Gbaud. The amplitudes of the driving binary electrical signals are set according to the requirements of Eq. (5) and Eq. (7) for the *I*-arm and *Q*-arm MZM. In the I-arm of the IQ modulator, the MZM is biased at the null points, and in the Q-arm, the MZM is

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biased at the $v_b = -\pi/6$. The bias voltage for the phase modulator in Q-arm are adjusted to introduce phase shift about $\pi/2+\pi/12$. Self-homodyne detection is used to avoid using carrier phase estimation (CPE) in digital signal processing units. Figure 11 shows the received signal distribution and optical spectrum of the generated hexagonal 16-QAM signals. The necessary DSP and symbol decision strategies have not yet been optimized and detail experimental studies on hexagonal 16-QAM for optical communications will be topics of future research. To the best of our knowledge, it's the first time to generate hexagonal 16-QAM signals optically using a commercially available IQ modulator and we hope that this simple hexagonal 16-QAM generation technique will enable more research in hexagonal 16-QAM for optical communication systems.

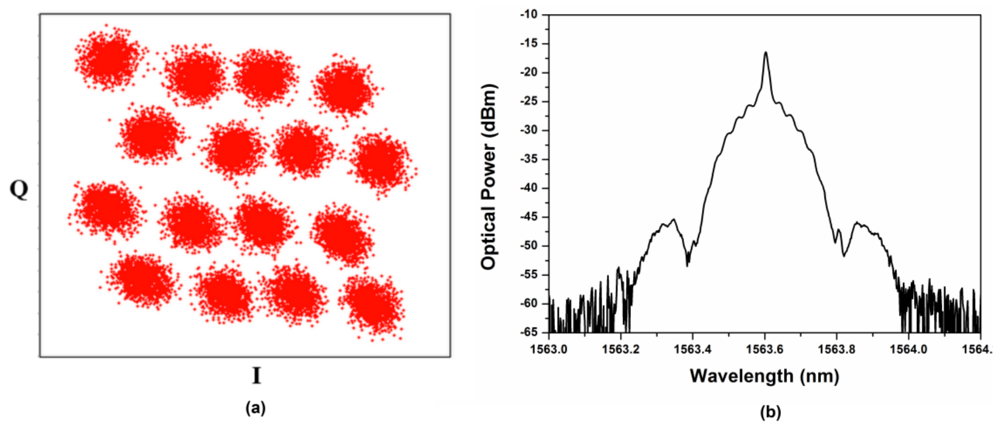

Fig. 11. (a) Received signal distribution using the proposed hexagonal 16-QAM generation technique; (b) corresponding optical spectrum.

4. Conclusions

In this paper, we demonstrated a simple 16-QAM signal generation technique by using four simple binary electrical signals to drive a dual-drive IQ modulator. By analyzing the modulator transfer function and designing the amplitudes of the binary electrical driving signals, both square and hexagonal 16-QAM signals are experimentally generated. The back-to-back performance of the 28 Gbaud square PM-16-QAM signals show similar performance with other generation techniques. In addition, hexagonal 16-QAM signals are generated with binary driving signals for the first time, thus providing a practical way to study the more-optimal hexagonal modulation formats for future optical communication systems.

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