Generation of Square or Hexagonal 16-QAM Signals Using a Single Dual Drive IQ Modulator Driven by Binary Signals

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Abstract: A simple square or hexagonal 16-QAM generation technique using a commercially available dual drive IQ modulator driven by 4 binary signals is proposed. Square or hexagonal polarization multiplexed (PM) 16-QAM signals at 25Gbaud/s are experimentally demonstrated.
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1. Introduction

Thanks to the advances of digital signal processing (DSP), high-order modulation format signals with coherent detection technologies can provide more spectrally efficient optical transmission systems. Dual polarization (DP) quadrature phase shift keying (QPSK) operating at 100 Gb/s with DSP are now commercially available [1]. 16-ary quadrature amplitude modulation (16-QAM), which doubles the spectral efficiency (SE) further to 4 bit/s/Hz [2], become the potential candidate for next generation optical transmission system beyond 100Gb/s per channel.

Consequently, extensive researches have been done for 16-QAM signal generation. 16-QAM signals could be generated with tandem-QPSK transmitter by cascading IQ modulator, Mach-Zehnder Modulators (MZM) and phase modulators (PM) [3], or cascading two IQ modulators [4]. Such transmitters were driven by binary electrical signals, simplifying the drive electronics. However, the several discrete modulators in such transmitter lead to a large insert loss. The long term stability became a big issue. Another approach for 16-QAM generation was to integrate several modulators in parallel structure, such as two IQ modulators, or several MZM modulators [5][6]. However, the complex modulator structures made it hard to fabricate. Another practical method to realize 16-QAM transmitter was to use four-level signals to drive an single drive IQ modulator [2][7][8]. Comparing to typical binary signals, four-level signals were relatively difficult to generate and process. Thus, expensive digital-to-analog converters (DAC) were usually used for four-level signal generation. Dual drive MZM modulator also was able to be used for 16QAM generation [9], however arbitrary waveform signals generated using a look-up table and a high-resolution DAC were needed.

In this paper, we propose and experimentally demonstrate a 25 Gbaud/s square 16-QAM transmitter using a commercially available dual drive IQ modulator driven by four binary signals. We also demonstrate the generation of hexagonal 16-QAM signals with the same setup. Hexagonal 16-QAM has a triangular lattice. The compact constellation diagram makes it more energy efficient than square 16- QAM. To the best of our knowledge, it is the first time a hexagonal 16-QAM signal is generated with an IQ modulator [10].

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. Each MZM in the dual-drive IQ modulator is a dual-drive MZM (DD-MZM), driven by two binary signals with different amplitudes. As a result, two independent four-level amplitude- and phase-shift keying (4-APSK) signals are 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(a).

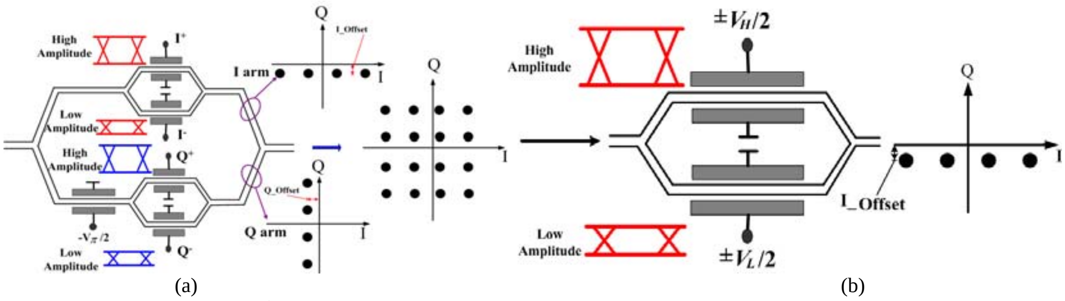


Fig.1 Operating principle of the proposed 16-QAM transmitter using dual-drive IQ modulator driven by binary signals.
(a) 16-QAM generation with IQ modulator; (b) 4-APSK generation with DD-MZM using binary signals with different amplitudes

We will take the MZM in I arm of the IQ modulator to illustrate the 4-APSK generation in more detail. The MZM is operated in push-pull mode and biased at the Null point. The drive signals are two binary signals with amplitude V_H and V_L ($V_H > V_L$), thus generating four possible states corresponding to driving signal levels of: $\pm V_H/2$ and $\pm V_L/2$, for the upper arm and low arm of MZM respectively. Neglecting insertion loss, the transfer function of the dual drive MZM is given by

$$\frac{E_{out}(t)}{E_{in}(t)} = \frac{1}{2}\left(e^{j\left(\frac{\pm V_H \pi}{2V_\pi}+\frac{\pi}{2}\right)} + e^{-j\left(\frac{\pm V_L \pi}{2V_\pi}+\frac{\pi}{2}\right)}\right) = -\sin\frac{\pm V_H \pm V_L}{4V_\pi/\pi}\cos\frac{\pm V_H \mp V_L}{4V_\pi/\pi} - j\sin\frac{V_H + V_L}{4V_\pi/\pi}\sin\frac{V_H - V_L}{4V_\pi/\pi}. \quad (1)$$

According to (1), the four modulated points will move away from the I-axis due to an extra phase offset.

$$I_{offset} = \left|\operatorname{Im}\left(\frac{E_{out}(t)}{E_{in}(t)}\right)\right| = \sin\frac{V_H + V_L}{4V_\pi/\pi}\sin\frac{V_H - V_L}{4V_\pi/\pi}. \quad (2)$$

The offset value depends on the driving voltage and the half-wave voltage (V_π). In addition, to keep the four modulated points with equal spacing along the I-axis, the amplitudes of the driving binary signals should be adjusted to satisfy

$$\tan\left(\frac{\pi(V_H + V_L)}{4V_\pi}\right) = 3\tan\left(\frac{\pi(V_H - V_L)}{4V_\pi}\right). \quad (3)$$

In this case, four constellation points along the I-axis direction with a small offset from I-axis can be obtained in the I-arm of the IQ modulator as shown in Fig.1(b). Likewise, four constellation points can also be obtained along the Q-axis in the Q-arm of the IQ modulator and the overall 16-QAM signal can be generated by adding the two 4-APSK signals in the I and Q components. The resulting 16-QAM constellation diagram shows an offset from the origin of the complex (IQ) plane, and therefore, some residual carrier will be present in the generated 16-QAM signals. Nonetheless, such offset can be easily eliminated by normalization process at the receiver digital signal processing (DSP) unit.

In addition to square 16-QAM generation using binary signals, when we adjust the bias of one sub-MZM away from the ideal null point, the generated four constellation points in that particular arm will not have a constant offset, but scatter like the shape of an italicized "N". With the other arm's MZM is still biased in null points, a hexagonal 16-QAM signal can be generated.

3. Experimental Results

Figure 2 shows the experimental setup for the proposed 16-QAM signal generation technique. Two 25Gbit/s binary data streams are generated by multiplexing two 12.5Gbit/s signals. With splitters and delay lines, 4 de-correlated 25Gbit/s binary data streams are generated to drive a dual drive IQ modulator. Each DD-MZM in both arms of the IQ modulator is driven by two binary data streams with different amplitudes. A variable attenuator is used to adjust the amplitudes of the low-level signals to satisfy equation (2). An ECL laser with linewidth about 150 KHz is used as the transmitter and local oscillator.

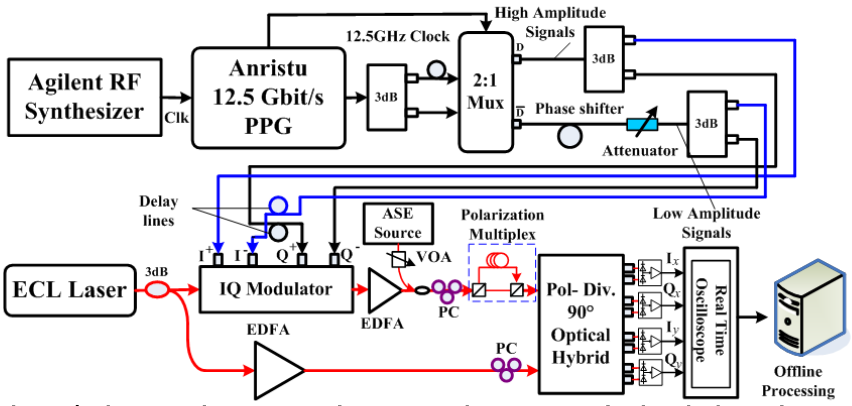
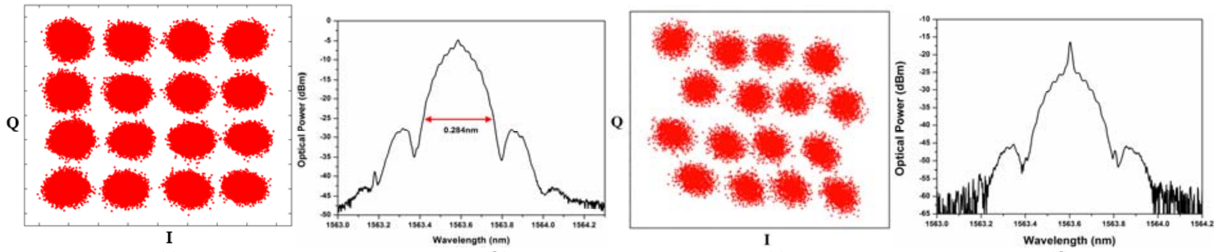


Fig.2 Experimental setup for the proposed 16-QAM signal generation technique. De-correlated 25Gb/s binary data streams with different amplitudes are used to drive the dual-drive IQ modulator

The generated 25Gbaud/s (200Gb/s) 16-QAM signal is amplified by EDFA and different amount of ASE noise is added to realize different OSNR. Polarization controllers (PC), polarization beam splitter/combiner (PBS/PBC) and optical delay line is used to realize polarization multiplexing. On the receiver side, the signals are coherently detected with a polarization-diverse receiver. A part of the CW light of the ECL is used as the local oscillator after amplification, thus realizing self-homodyne detection and avoiding the need for estimation of frequency offset between transmitter and local oscillator. The electrical signals are then sampled for analog-to-digital (A/D) conversion using a real-time oscilloscope and processed offline to perform normalization, polarization demultiplexing [11], carrier-phase estimation [12], symbol detection and bit-error rate (BER) estimation.



(a) (b) (c) (d)

Fig.3 (a) Received signal distribution for the proposed square 16-QAM generator; (b) corresponding optical spectrum. (c) Received signal distribution for the proposed hexagonal 16-QAM generator; (d) corresponding optical spectrum.

Fig.3 shows the received signal distributions and the corresponding optical spectra of square and hexagonal 16-QAM signals with an OSNR of 32dB. The 20dB bandwidth of the square 16-QAM is about 0.284nm. A residual optical carrier is present in the optical spectrum, which increases the output power of the transmitter by about 7%.

The back-to-back performance of the proposed square 16-QAM generation technique is investigated by adjusting the system OSNR and calculating the corresponding BER and the results are shown in Fig.4. About 20.3dB of OSNR are required for a BER of 1e-3, which is about 3.7dB from the theoretical limit.

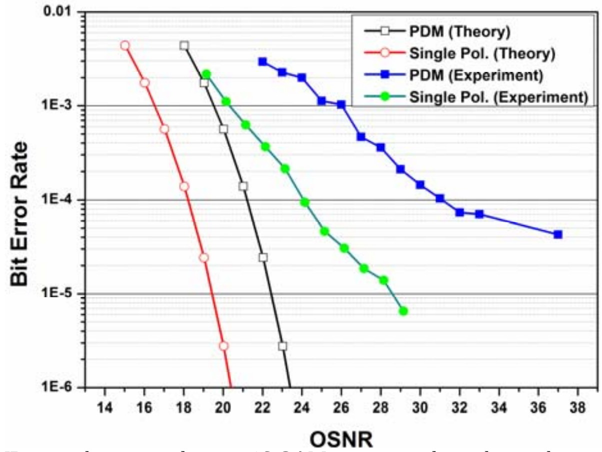


Fig.4 Back-to-back BER vs. OSNR using the proposed square 16-QAM transmitter driven by two binary signals with different amplitudes.

4. Conclusions

We demonstrate a simple square or hexagonal 16-QAM signal generation technique using four simple binary electrical signals to drive a dual-drive IQ modulator. Experimental results for a 25Gsymbols/s (200Gb/s) system demonstrated the technique's feasibility and the potential for simple and practical implementation of 16-QAM transmitters in future coherent communication links.

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