Generation of Arbitrary Quadrature-Amplitude Modulated Signals Using a Single Dual-Drive Modulator

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Abstract: *Regardless of complexity, all types of quadrature-amplitude modulated (QAM) signal can be generated using a single dual-drive Mach-Zehnder modulator. Three different quadrature phase-shift keying (QPSK) transmitters are proposed as examples.*

I. Introduction

Recently, multilevel modulation schemes like differential quadrature phase-shift keying (DQPSK) have received renewed attention [1]–[4]. Not only for DQPSK or QPSK, but applicable to general class of quadrature-amplitude modulation (QAM) with and without differential operation, Fig. 1(a) is the traditional method to generate a QAM signal using two Mach-Zehnder modulators (MZMs) within two $\pi/2$-phase difference paths of an Mach-Zehnder interferometer. Intuitively, the two MZMs generate the signal for the two quadrature components with a phase difference of $\pi/2$, i.e., $\cos(\cdot)$ and $\sin(\cdot)$. As shown later, QAM signal can also be generated using a single dual-drive MZM as shown in Fig. 1(b).

II. General Principles

If the two paths of a dual-drive MZM have independent driving voltages of V_1 and V_2, with an input electric field of E_i, the output electric field is

$$E_o = \frac{E_i}{2}\left[\exp\left(j\pi\frac{V_1}{V_\pi}\right) + \exp\left(j\pi\frac{V_2}{V_\pi}\right)\right], \quad (1)$$

where V_π is the voltage to provide a π phase shift of each phase modulator. In additional to operate a MZM

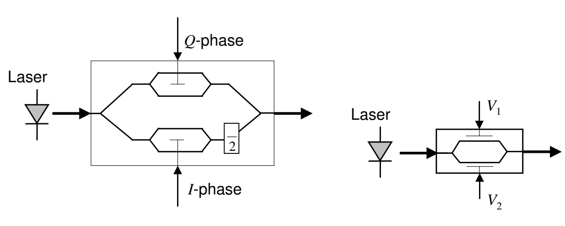

Fig. 1. (a) The traditional QAM transmitter based on two MZMs in an interferometer. (b) A QAM transmitter based on a single dual-drive MZM.

as a phase modulator with $V_1 = V_2$, by choosing both V_1 and V_2 of (1) properly, any quadrature signal can be generated. Assumed an M-ary signal constellation that can be represented as complex numbers of

$$s_i = r_i e^{j\theta_i}, \quad i = 0, \dots, M-1, \quad (2)$$

with a maximum amplitude of $r_{\max} = \max\{r_0, r_1, \dots, r_{M-1}\}$. The input and output relationship of (1) is rewritten in the following normalized form of

$$E_o = \frac{r_{\max}}{2}\left(e^{j\phi_1} - e^{j\phi_2}\right), \quad (3)$$

where $\phi_1 = \pi V_1/V_\pi$ and $\phi_2 = \pi V_2/V_\pi + \pi$. The output electric field of E_o is the difference of two vectors in the circle having a radius of $r_{\max}/2$. The MZM of (3) is biased at the minimum transmission point or the null point and the maximum output electric field has an amplitude of $r_{\max}$ when $V_1 = V_2$.

With two phases of [5], [6]

$$\phi_{i1} = \theta_i + \cos^{-1}(r_i/r_{\max}) \quad (4)$$
$$\phi_{i2} = \theta_i - \cos^{-1}(r_i/r_{\max}) + \pi, \quad (5)$$

we obtain

$$s_i = \frac{r_m}{2}\left(e^{j\phi_{i1}} - e^{j\phi_{i2}}\right), \quad (6)$$

because of $e^{j\cos^{-1} r_i/r_{\max}} + e^{-j\cos^{-1} r_i/r_{\max}} = 2r_i/r_{\max}$. All constellation points of (2) can be generated based on two phase modulators having the phases of (4) and (5), respectively.

Figs. 2 show a 16-QAM constellation and the phases of (4) and (5) for the dual-drive MZM. Instead of representing all 16 constellation points in the same figure, Fig. 2(a) decomposes the 16-QAM signal into two QPSK and one 8-PSK signals. Figs. 2(b)-(d) are the corresponding ϕ_{i1} and ϕ_{i2} of all 16 points according to the decomposition of Fig. 2(a). The empty and solid circles correspond to ϕ_{i1} and ϕ_{i2}, respectively. Fig. 2(b) gives the QPSK signal of Fig. 2(a) with maximum amplitude of $r_{\max}$. The two closest points of Fig. 2(b) are the same but draw differently for the phases of two

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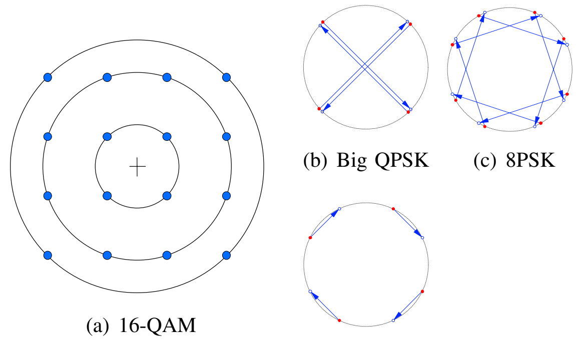
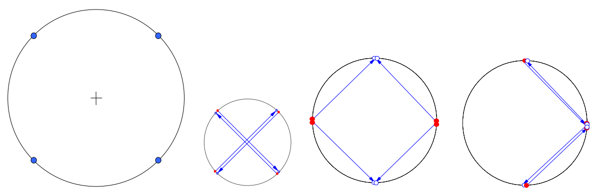


(a) 16-QAM (b) Big QPSK (c) 8PSK (d) Small QPSK

Fig. 2. (a) 16-QAM constellation and its decomposition into two QPSK and an 8-PSK signals, (b), (c), (d) are the two phases of ϕ_1 (empty circles) and ϕ_2 (solid circles) to generate the 16-QAM signals.



(a) QPSK (b) 4 level (c) 2 level (d) 3 level

Fig. 3. (a) QPSK constellation and its generation using a (b) four-, (c) two-, and (d) three-level drive signal.

different signals. Fig. 2(c) generates the 8-PSK signal of Fig. 2(a). Fig. 2(d) gives the QPSK signal of Fig. 2(a) with the smallest amplitude.

From Fig. 2, the generation of a 16-QAM signal using a dual-drive MZM requires the usage of a 16-level drive voltage and thus very complicated drive circuits. Compared with the transmitter of Fig. 1(a), the simplification of the optical components using a single dual-drive MZM creates a high complexity in the electronic circuits. With the allowance of higher modulator loss, as shown later, the number of drive levels can be reduced.

III. Generation of (D)QPSK Signals

The dual-drive MZM transmitter of Fig. 1(b) can use to generate either QPSK or DQPSK signals with a constellation of Fig. 3(a). Similar to that of Fig. 2(b), Fig. 3(b) is the trivial case of operating the dual-drive MZM as a phase modulator with $V_1 = V_2$. The four phases of Fig. 3(a) is given by a four-level drive signal. A QPSK signal may be generated with higher loss but smaller number of levels if the four constellation points are generated with phases of ϕ_1 or ϕ_2 the same as one another. With only two values of ϕ_1 and ϕ_2, Fig. 3(c) drives the dual-drive MZM in Fig. 1(b) with a two-level signal. Fig. 3(d) has three different values of ϕ_1 and ϕ_2 and requires a three-level drive signal. Comparing Figs. 3(c) and (d) with Fig. 3(b), the schemes using two and three level drive signal have 3-dB extra loss than that of

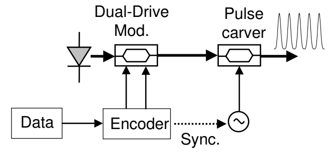


Fig. 4. A RZ-DQPSK transmitter

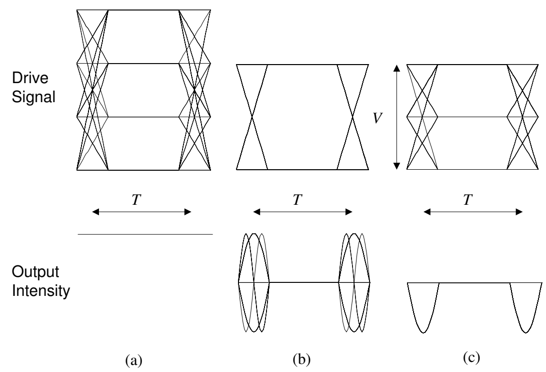


Fig. 5. The eye-diagram of the drive signal and output intensity between two modulators of the transmitter of Fig. 4 when (a) 4, (b) 3, (c) 2 drive signals are used.

Fig. 3(b). Both the peak-to-peak drive voltage and the number of drive levels are reduced in Figs. 3(c) and (d).

However, both the two- and three-level transmitters of Figs. 3(b) and (c) do not have constant intensity between consecutive symbols. Fig. 4 shows a RZ-DQPSK transmitter using a dual-drive MZM followed by a phase craver. After the phase craver, the intensity is a constant pulse train. However, Figs. 5 show the eye-diagram of the drive signal and the intensity before the phase craver. With two or three levels of drive signal, the output intensity of the dual-drive MZM has some ripples between consecutive symbols. The simplest two-level scheme of Fig. 3(c) and 5(b) has a peaking ripple doubling the output intensity. The two- and three-level drive signals of Fig. 3(c) and (d) are applicable for RZ but not NRZ signals. The peak-to-peak drive voltage is reduced from $1.5V_\pi$ for four-level signal to V_π for two- and three-level drive signals.

IV. Conclusion

Using 16-QAM and QPSK signals as example, we show that a single dual-drive MZM can be used to generate all types of QAM signals.

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