Nonlinear Effect of IQ Modulator in a Realtime Synchronous 16-QAM Transmission System

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Abstract-- Different operation points of a 16-QAM modulator are tested in realtime. An optimal condition is found which minimizes BER. The FEC threshold was reached for a receiver input power below −30 dBm.

I. INTRODUCTION

Multi-level modulation formats and coherent detection have become a promising technology to reach transmission rates of 112 Gb/s and above. Among the possible formats the 16ary quadrature amplitude modulation (16-QAM) which carries 4 bit/symbol is an attractive candidate. Recently, simulations, offline and realtime experiments with this modulation format have been performed [1], [2]. There are several possible setups for an optical square 16-QAM transmitter [3]. The one which has been selected in this experiment is the conventional IQ transmitter, since the squared envelope (normalized power) during symbol transitions and the chirp is small compared to other 16-QAM transmitter setups. Based on that scheme we present results of a 2.5 Gb/s realtime transmission experiment with synchronous digital detection of a 16-QAM constellation. Signals were processed digitally in realtime on a field-programmable gate array (FPGA).

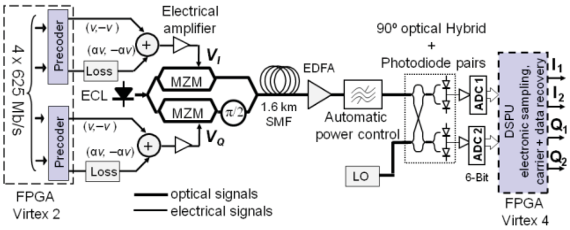

Fig. 1. Self-homodyne 2.5 Gb/s 16-QAM transmission setup with realtime synchronous coherent digital I&Q receiver.

II. EXPERIMENTAL SETUP

Four 625 Mb/s pseudo-random binary sequence (PRBS) signal with a length of (2^7-1) are generated by an FPGA with output voltage levels of $\pm v$. Two of the four data streams are attenuated ($-20\log(\alpha)$ (dB)) to have voltage amplitudes $\pm\alpha v$ $(0 < \alpha < 1)$ and are combined with the other unattenuated signal using resistive summers. This results in two 625 Mbaud quaternery data streams containing four-level signals with the amplitudes of $\pm(1+\alpha)v$ and $\pm(1-\alpha)v$. These I&Q data streams are Gray-encoded to form a quadrant number, which is modulo 4 differentially encoded to determine the quadrant of the optical phase. Each quaternary data signal is applied to modulator driver with output voltages V_I and V_Q. For the generation of 16-QAM we use a dual-parallel Mach-Zehnder modulator (DPMZM) consisting of two Mach-Zehnder interferometers (MZI) with an extinction ratio of 50 dB. The DPMZM synthesizes the 16-QAM optical signals from these I&Q data streams. Fig. 2 shows the characteristic response of the MZM when driving voltage is applied and when the DC bias voltage (V_{bias}) is set to null position. The transfer characteristic equation as a function of the applied voltage is

$$\frac{\left|E_{out}\right|^2}{\left|E_{in}\right|^2} = \sin^2\left(\frac{\pi}{2}\frac{V_d(t)}{V_\pi}\right). \qquad (1)$$

where $E_{in}(t)$ is the input field, $E_{out}(t)$ is the output field, and $V_d(t)$ is the electrical driving voltage waveform. The voltage to turn the modulator from minimum to maximum transmission is V_π. If we define the voltage amplitude as $V_d(t) = \Delta V_\pi$ $(0 < \Delta \le 1)$, the output intensity of the MZM shown in Fig. 2 can be described by

$$P_1 = \sin^2\left(\frac{\pi}{2}\cdot\Delta\right) \,\&\, P_2 = \sin^2\left(\frac{\pi}{2}\cdot\frac{(1-\alpha)}{(1+\alpha)}\Delta\right). \qquad (2)$$

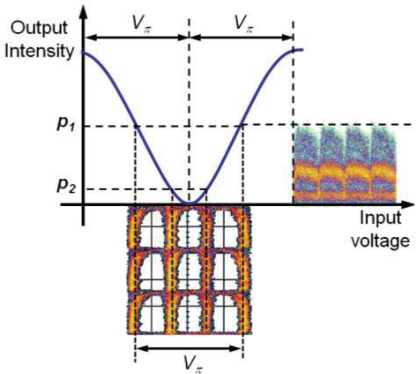

Fig. 2. MZM transmittance.

An external cavity laser (ECL) is employed in a self-homodyne transmission setup. The specified linewidth is 150 kHz. One part of its output signal is fed into the DPMZM for transmission. After transmission through 1.6 km of a standard single-mode fiber (SMF) the signal is passed to an Erbium-doped optical amplifier (EDFA) and a bandpass filter with a bandwidth of ~20 GHz for noise filtering. The other part of the ECL output signal is used

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as a local oscillator signal. The two optical signals are superimposed in a $LiNbO_3$ 90° optical hybrid and detected with two differential photodiode pairs. The resulting electrical signals are amplified and sampled with 6-bit analog-digital converters (ADCs). The ADC outputs are connected to a Xilinx Virtex 4 FPGA that contains the digital carrier and data recovery [4].

III. MEASUREMENT RESULTS

Fig. 3 shows typical constellation maps and the eye diagrams of the 16-QAM patterns in the transmitter (electrically before the modulator) for different attenuators values. The amplitude of the constellation map is affected severely when α is changed. In Fig. 4 the optical signal before transmission is plotted for different α and Δ values.

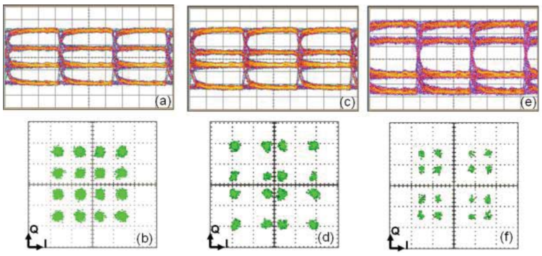

Fig. 3. Electrical eye digrams and constellation maps of 625 Mbaud 16-QAM. (a&b) α = 0.5; (c&d) α = 0.7 and (e&f) α = 0.35.

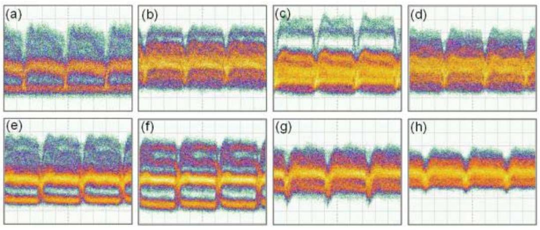

Fig. 4. Intensity patterns of 625 Mbaud 16-QAM behind DPMZM. (a) α = 0.5, Δ = 0.5; (b) α = 0.5, Δ = 1; (c) α = 0.5, Δ = 0.35; (d) α = 0.5, Δ = 0.7; (e) α = 0.7, Δ = 0.5; (f) α = 0.7, Δ = 1; (g) α = 0.35, Δ = 1 and (h) α = 0.35, Δ = 0.5.

Fig. 5 shows the received constellation maps after optical transmission over 1.6 km of SMF for −20 dBm preamplifier input power for different α and Δ values. Using the parameters α = 0.5 and Δ = 0.5, the constellation is aligned orderly as shown in Fig. 5-(a), and this gives the best BER. As Δ is increased to 1, the constellation shows severe phase distortions as shown Fig. 5-(b). In Fig. 5-(c-h), the amplitude and the phase deviate from the values needed for ideal constellation.

We measured the bit error ratio (BER) of all I&Q subchannels of the 2.5 Gb/s 16-QAM signal received behind 1.6 km of SMF versus preamplifier input power for various α and Δ values (Fig. 6). From the BER curves, we deduced the dependence between α and Δ. The lowest BERs were measured at α = 0.5 and Δ = 0.5. A BER floor was observed, below the threshold of a state-of-the-art forward-error correction (FEC) (7% overhead). For a given α = 0.5, corresponding Δ was varied with steps of~0.2. The BER changed as a function of Δ in the given range, especially when Δ is far away from the optimal condition (ie. Δ = 1). The reason for this is that the nonlinear transmittance of MZM is affected severely when Δ is increased. According to the results, the parameter α should be in the range of 5 dB to 6 dB. In this case variations of Δ can be tolerated in the range of 0.4...0.6 for BER less than the FEC limit at receiver input power below −30 dBm.

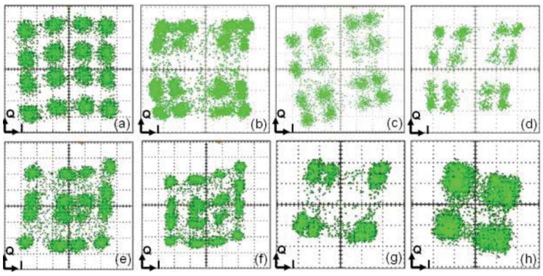

Fig. 5. 16-QAM constellation after optical transmission for −20 dBm. (a) α = 0.5, Δ = 0.5; (b) α = 0.5, Δ = 1; (c) α = 0.5, Δ = 0.35; (d) α = 0.5, Δ = 0.7; (e) α = 0.7; Δ = 0.5; (f) α = 0.7, Δ = 1; (g) α = 0.35, Δ = 1 and (h) α = 0.35, Δ = 0.5.

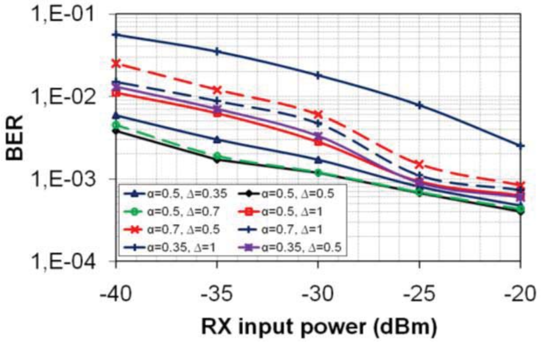

Fig. 6. Measures PRBS-7 BER curves for laser-linewidth-times-symbol-rate product $\Delta f \cdot T = 0.00048$, averaged over all 4 subchannels (I1, Q1, I2 and Q2).

IV. SUMMARY

The influence of nonlinear effects related to the IQ modulator of a 16-QAM coherent transmission system has been investigated in a realtime transmission. The amplitudes of the MZM in the IQ modulator need to be carefully adjusted to obtain a good pattern and avoid phase distortions. Optimal operating conditions are found to guarantee a BER floor below the threshold of a state-of-the-art FEC.

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