2x10 Gbit/s Quaternary Intensity Modulation Generation using an Optical QPSK Modulator

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ABSTRACT

Two 2x10 Gbit/s quaternary intensity modulation signals (4-IM) can be generated using quadrature amplitude modulation (QAM), with unequal modulation amplitudes in two orthogonal quadratures. Two 10 Gbit/s NRZ ASK signals and a QPSK modulator allow to generate 4-IM with the same bandwidth as an NRZ-ASK signal. Measured sensitivity at a BER of 10^{-9} and chromatic dispersion (CD) tolerance are –21.2 dBm and ~ +130 ps/nm, respectively. Two duobinary 10 Gbit/s data streams and a QPSK modulator allow to generate a 9-point QAM signal, with the same bandwidth as a duobinary signal. A stub filter with a frequency response dip at 5 GHz was used to generate the duobinary signals. Detected as a 4-IM, this scheme features a sensitivity and a CD tolerance of –21 dBm and ~ +140 ps/nm, respectively. A polarization and phase insensitive direct detection receiver with a single photodiode has been used to detect all generated QAM signals as 4-IM signals.

Keywords: Quadrature amplitude modulation, QAM, QPSK, Duobinary modulation.

1. INTRODUCTION

Upgrading of existing dense wavelength-division-multiplexed (DWDM) systems to higher bit rates requires wider optical bandwidths per channel or advanced modulation formats with higher spectral efficiency or a combination of both[1,2,3]. Duobinary modulation is important in this context because it is not only spectrally efficient (~0.8 bit/s/Hz) but also simple to implement[4,5,6,7]. So far, differential quadrature phase shift keying (D)QPSK and/or polarization multiplex are needed to increase spectral efficiency beyond that of duobinary modulation, but considerable technical effort at the receive end is needed for their implementation (interferometer and its stabilization, polarization control, two independent photoreceivers to independently detect the two data streams), which reverberates in the cost budget[8,9,10,11]. On the other hand, M-ary amplitude shift keying such as quaternary (4-level) intensity modulation (4-IM) is easy to detect using a direct detection receiver with a single photodiode[12,13]. The 4 levels can be discriminated in 3 D-flip-flops and processed to reconstruct the transmitted data. Although 4-IM doubles the transmission rate, it doesn't have the best spectral efficiency. However, the general class of quadrature amplitude modulation (QAM) can be used to increase the spectral efficiency[14]. In this paper we use an optical QPSK modulator, driven by two 10 Gbit/s *NRZ* data streams, to generate an optical 4-point (2×10Gbit/s) QAM. To further increase the spectral efficiency we replace the NRZ data streams by duobinary data streams to generate a 9-point (2×10Gbit/s) QAM signal. Due to different amplitudes chosen for the two quadratures, both optical QAM schemes allow direct detection as 4-IM signals. These schemes as well as their chromatic dispersion (CD) tolerances will be discussed.

2. QUATERNARY INTENSITY MODULATION GENERATION

2.1 Generation of a 4-QAM signal using an optical QPSK modulator and two 10 Gbit/s NRZ-ASK signals (4-QAM QPSK)

The optical QPSK modulator shown in Figure 1 contains two Mach-Zehnder modulators (MZMs), placed in the two arms of another interferometer that forms a Mach-Zehnder superstructure. The superstructure has quadrature control electrodes in both arms for phase trimming. Throughout the experiments of this paper, a fiber-pigtailed Bookham GaAs/AlGaAs DQPSK modulator[15] was used.

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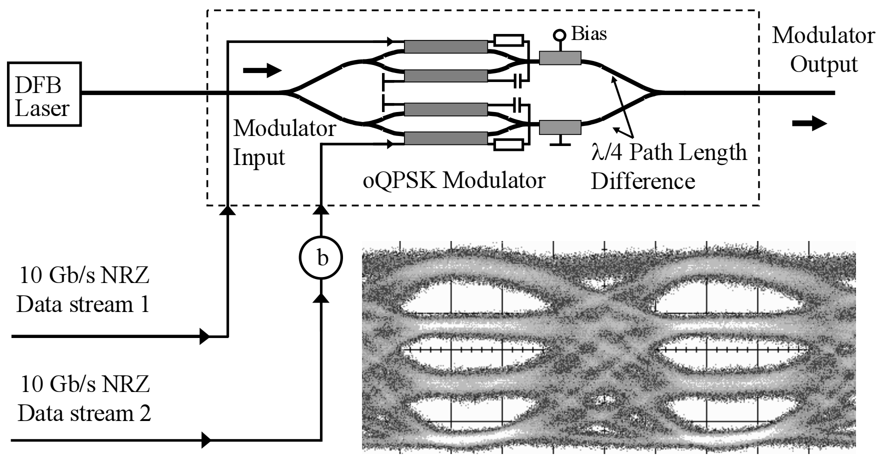

Figure 1: Optical 4-QAM (2×10Gbit/s) generation in an optical QPSK modulator, and resulting quaternary intensity eye diagram for QAM signal (electrical attenuator setting b = 1/2).

The two MZMs are driven by two electrical 10 Gbit/s NRZ signals. The drive amplitude of the NRZ signal in one of the MZMs equals $\sim V_\pi$. This generates an in-phase optical field Re(E) with normalized field amplitudes {0, +1}.

The other MZM is driven by an NRZ-ASK signal with a $\sim V_\pi/2$ amplitude, which is accomplished by electrical attenuation. With suitable phase trimming assumed, it generates a quadrature optical field Im(E) with normalized field amplitudes {0, $+a$}. The total output electric field is $E_O = \mathrm{Re}(E) + j\,\mathrm{Im}(E)$.

The modulation constellation diagram is shown in Figure 2. The generated fields are {0, +ja, +1, and +1+ja}. The four different constellation points results in four different intensities {0, a^2, 1, $1+a^2$}. For a=$1/\sqrt{2}$, corresponding to 6 dB of electrical attenuation (b = 1/2), the intensities are equidistant and are now labeled as "0", "1", "2", "3".

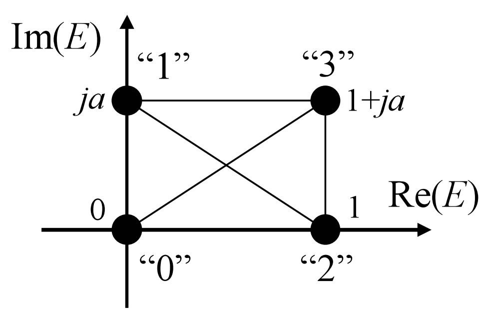

Figure 2: Electrical field modulation constellation (a=$1/\sqrt{2}$). A quaternary intensity modulation results from this 4-QAM.

Figure 1 shows also the 4-level eye diagram of the quaternary intensity modulated signal, detected at the modulator output at 10 Gbaud (20 Gbit/s). The 4-QAM constellation represents a 4-IM but the spectrum is just as broad as for NRZ modulation although the capacity is doubled. Suitable decoding is needed at the receiver side[12].

Figure 3 shows the heterodyned electrical spectrum of the 10 Gbaud optical 4-QAM. There exists a carrier in the spectrum, and it is equivalent to the spectrum of a 10Gbit/s NRZ-ASK signal.

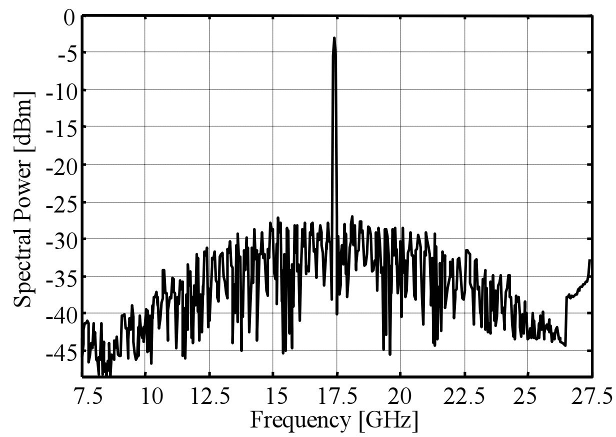

Figure 3: Heterodyned electrical spectrum of the 2x10Gbit/s 4-Point QAM = 4-IM signal

2.2 Generation of a 9-QAM signal using an optical QPSK modulator and two 10 Gb/s duobinary signals (9-QAM QPSK)

We use the setup of Figure 1, but replace the NRZ by duobinary data streams (Figure 4). Since differential encoding was not available, two mutually delayed 10 Gbit/s NRZ electrical signals were lowpass-filtered (LPF) to generate the duobinary signals. The lowpass filters are constructed using open stubs with single-path delays of 50 ps and 25 Ohm characteristic impedance and are inserted into each 50 Ohm modulator drive cable.

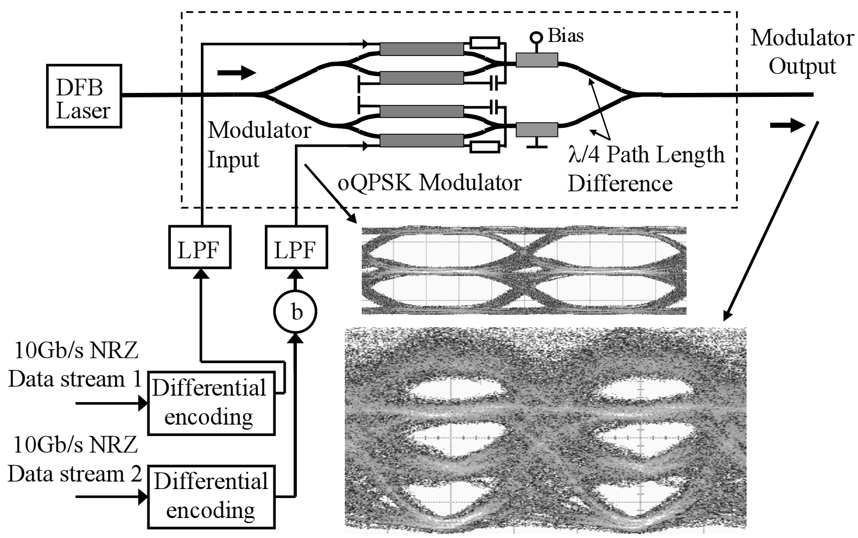

Figure 4: Principle of optical 9-QAM modulation using duobinary low pass filtering (LPF) and a QPSK modulator (electrical attenuator setting b = 1/2). The resulting quaternary intensity eye diagram (bottom) and the electrical duobinary eye diagram (top) are also shown.

Each stub filter (LPF) responds to an impulse by two impulses of equal height and 100 ps mutual delay, thereby forming an idealized duobinary filter[4]. The simulated frequency response of the LPF stub used in this experiment had a ~ 35dB dip at the frequency 5 GHz. A duobinary signal with a full ~ $2V_\pi$ total swing generates in one MZM the in-phase optical field Re(E) with normalized field amplitudes {–1, 0, +1}. The other arm MZM is driven with a duobinary signal with a V_π total swing and generates the quadrature component Im(E) with normalized field amplitudes {–a, 0, +a}. The total output field is again $E_O = \mathrm{Re}(E) + j\,\mathrm{Im}(E)$.

The modulation constellation is shown in Figure 5. The generated fields are {0, $\pm ja$, ±1, $\pm 1 \pm ja$}, corresponding to four different intensities {0, a^2, 1, $1+a^2$}. Illustrating the case $a=1/\sqrt{2}$ (b = 1/2), the intensities are again labeled "0", "1", "2", "3".

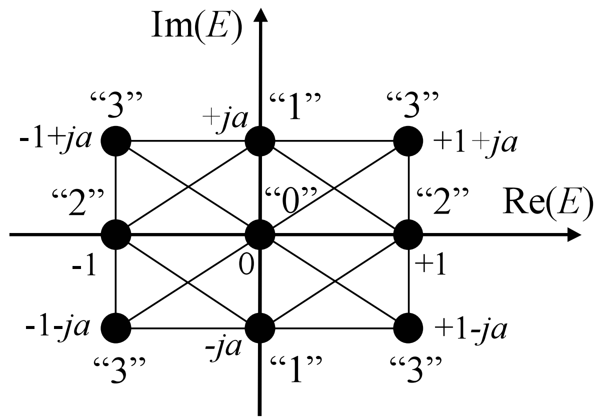

Figure 5: Electrical field modulation constellation ($a = 1/\sqrt{2}$) of 9-QAM. The two quadratures have orthogonal phases in one polarization (Re(E), Im(E)). A quaternary intensity modulation results from the 9-QAM.

Figure 4 also shows the 4-level 10 Gbaud (20Gbit/s) intensity eye diagram, detected at the modulator output. Not only differential encoding is needed at the transmitter side, but also 4-IM decoding at the receiver side.

The spectrum of the generated 9-QAM (4-IM) is just as broad as for duobinary modulation although capacity is doubled. Figure 6 shows the heterodyned electrical spectrum of the 10 Gbaud optical 9-QAM signal. There exists no carrier in the spectrum, and it is equivalent to the spectrum of an idealized duobinary signal (also generated with help of a stub filter).

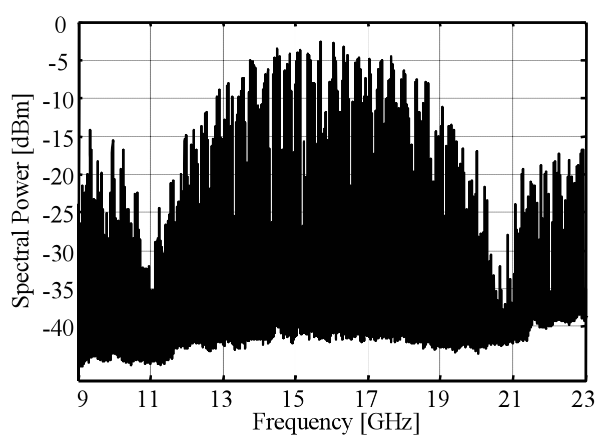

Figure 6: Heterodyned electrical spectrum of the 2x10Gbit/s 9-QAM = 4-IM signal using a QPSK modulator (9-QAM QPSK)

3. QUATERNARY INTENSITY MODULATION DETECTION

The 9-QAM and the 4-QAM each represent a 4-IM signal. The 4-IM signal contains three eye openings corresponding to three different patterns. These patterns {Q1, Q2, Q3} can be detected at the receiver using a single photodiode (direct detection) and three decision circuits (D-flip-flops) as shown in Figure 7. Suitable decoding is needed to recover the two data streams from the three detected patterns[12]. The schematic of the decoding logic circuit is shown in Figure 7 in addition to its corresponding truth table.

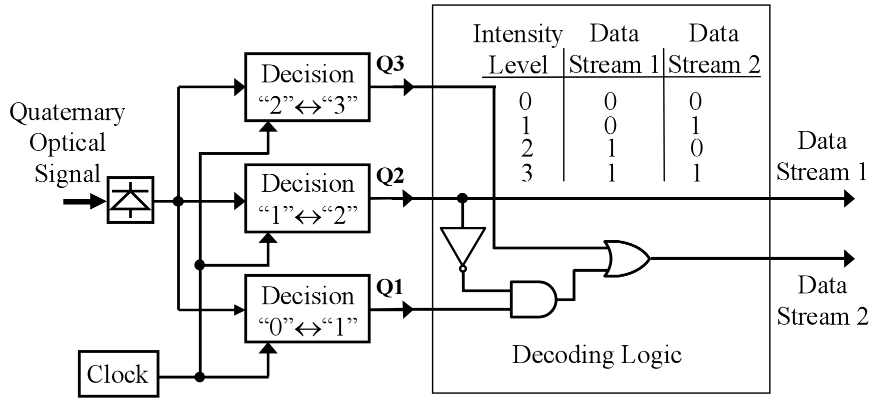

Figure 7: A schematic of a 4-IM receiver with decoding logic diagram and corresponding truth table.

4. TRANSMISSION SETUP

Figure 8 shows an experimental 2×10Gbit/s transmission setup used for the different QAM generation schemes. The distributed-feedback laser (DFB) transmitter laser has a frequency of 193.5 THz. Two 2^7-1 PRBS are transmitted. A mutual delay of 31 bit durations decorrelates the patterns. The encoding function for the duobinary case is not implemented. The receiver employs an optical preamplifier followed by a dense wavelength division multiplexing (DWDM) Arrayed Waveguide Grating (AWG) Demultiplexer (DEMUX) of Gaussian type with 100 GHz spacing of its 40 channels, which acts as a narrow band pass optical filter. A variable optical attenuator (VOA) placed before the optical preamplifier is used for sensitivity and optical signal to noise ratio (OSNR) measurements. The detected photocurrent of an optical front end PIN photodiode with transimpedance amplifier (PIN-TIA) is stabilized by a feedback loop (not shown) that controls the pump current of the last EDFA for automatic power control (APC). An electrical amplifier amplifies the received signal before it feeds an oscilloscope or an error detector. The error detector is programmed, using different thresholds and patterns, to receive all the three patterns, corresponding to the top, middle, and bottom eye diagram. Proper Bit Error Rate (BER) averaging is performed to represent the mean BER of the received patterns.

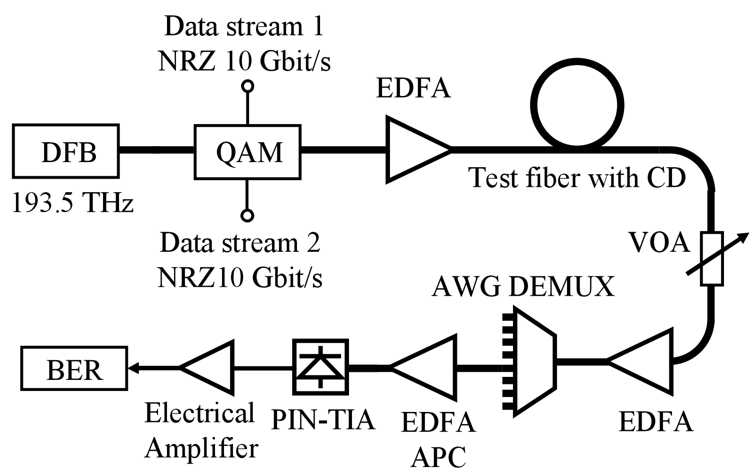

Figure 8: 20 Gbit/s QAM (4-IM) transmission setup

The sensitivity measured for a BER of 10^{-9} for binary 4-QAM (4-QAM QPSK) and duobinary 9-QAM with QPSK modulator using LPF stubs with 5-GHz dip (9-QAM QPSK) are –21.2 dBm and –21 dBm respectively.

The measured BER curves for the different QAM signals are shown Figure 9. The top eye, which represents the intensity levels “2” and “3”, dominates the overall BER in all three cases.

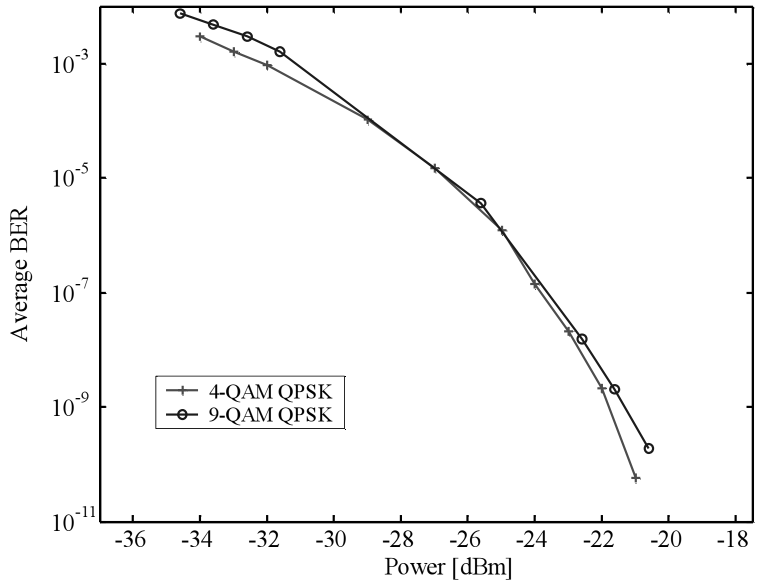

Figure 9: Back-to-back receiver sensitivity for QAM-based quaternary intensity modulation.

The chromatic dispersion (CD) tolerance was measured for all generated QAM signals. Figure 10 shows the ONSR after the optical preamplifier needed for a BER of 10^{-9} versus CD. An optical attenuator was used to vary the ONSR. The 1-dB tolerances at a BER of 10^{-9} are ~130ps/nm and ~140ps/nm for 4-QAM QPSK and 9-QAM QPSK respectively.

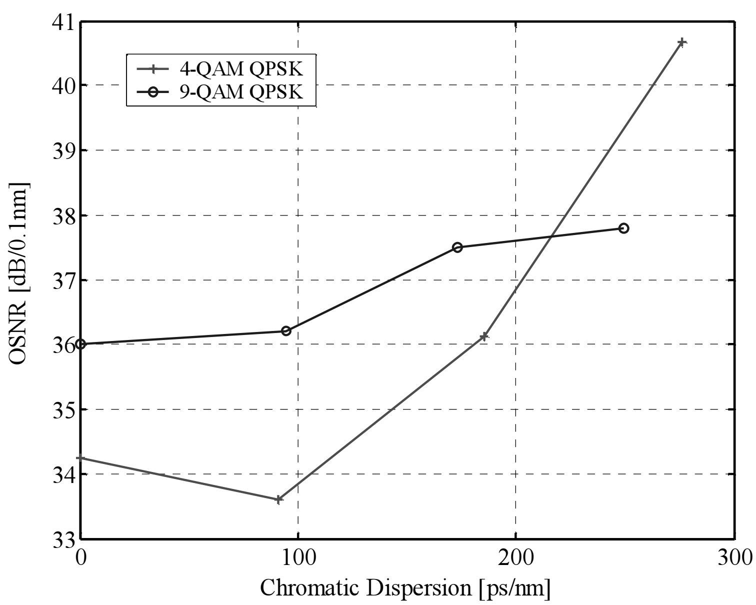

Figure 10: OSNR needed for a BER of 10^{-9} versus CD in ps/nm.

5. DISCUSSION

According to Figure 10, the 9-QAM scheme is superior to the 4-QAM scheme, due to the reduced bandwith of the duobinary modulation. The 9-QAM QPSK signal is affected by the fact that one of the Mach-Zehnder modulators is driven with a V_π voltage swing where the limiting functionality of a fully driven modulator is reduced by a factor $\sqrt{2}$. In the presence of electrical intersymbol interference this results in a non-optimal optical duobinary signal in that modulator. A solution to this problem is to place an optical attenuator in one of the QPSK modulator branches and drive both Mach-Zehnder modulators with a full $2V_\pi$ voltage swing, where optical duobinary signal quality is best. The two quadratures with duobinary modulation need not necessarily belong to the same polarization. Figure 11 shows as an alternative duobinary modulation in two polarizations using a polarization division multiplex transmission setup. It is of course also possible to generate 4-QAM with polarization division multiplex.
In principle, QPSK and PolDM could even be combined to generate 16-ary intensity modulation (16-IM) by binary (16-QAM) or duobinary (81-QAM) modulation in 4 quadratures with relative field amplitudes of 1, $\sqrt{2}$, 2, $2\sqrt{2}$.

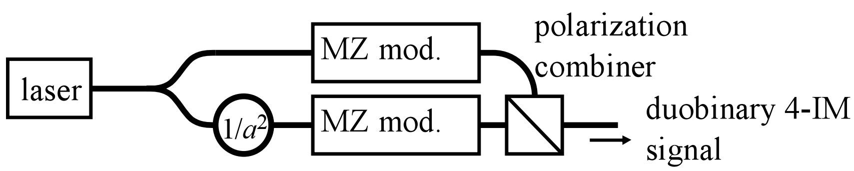

Figure 11: Alternative generation of duobinary 9-QAM by using quadratures belonging to different polarizations ($a = 1/\sqrt{2}$)

For comparison we have generated an electrical quaternary intensity modulated signal at 10 Gbaud by superimposing two mutually delayed 10 Gbit/s electrical data streams. It was used to drive one Mach-Zehnder modulator. The thereby generated optical 4-IM signal was detected with the same receiver as for the QAM schemes (Figure 7). Even though the relative amplitudes of the two superimposed electrical signals as well as the modulator bias point were set for optimum sensitivity the achieved sensitivity was only –12.8 dBm, worse than for the other QAM methods.

6. CONCLUSION

Optical 4-QAM and 9-QAM signals have been generated using an oQPSK modulator, and detected in a simple receiver. The duobinary 9-QAM scheme is believed to represent intensity modulation with the narrowest reported spectrum reported to date.

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