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# 20 G bps Pulse Amplitude Modulation (PAM) Format for Capacity Upgrade in Optical Communications

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**Abstract:** In the fast growing society, communication is broadening so rapidly such that internet users need to access information rapidly and amount of data flowing through internet is very huge. Various techniques for increasing capacity in data centers have drawn lots of attention in recent years. One way of addressing this demand is introduction of advanced optical modulation formats which has been motivated by the demand for high transmission capacity and better system reliability. In this work, two electrical data streams at bit rate of 10 G bps each were combined to produce 20 G bps multilevel system 4-PAM with four levels. One of the four amplitudes represents a combination of two bits (00, 01, 10, 11) per symbol. This therefore transmits two bits in parallel and therefore the data rate is doubled. The generated data was transmitted over 3.21km G.652 fiber at standard BER of $10^{-9}$. This format can be used to simultaneously transmit two bits per symbol per wavelength thereby increasing the overall link transmission speed while maintaining the channel bandwidth. We further demonstrated a digital signal processing assisted receiver to efficiently recover the transmitted signal without employing costly receiver hardware. The ability to use a single photodiode to demodulate the multilevel signal, brings a further reduction in cost on implementing the scheme. This spectral efficient modulation format will achieve even higher data rate per channel when coupled in a Dense Wavelength Division Multiplexing (DWDM) system. This will therefore lead to significant cost saving of capital investment and easing the system management and hence an efficient utilization of bandwidth.

**Keywords:** 4-Pulse Amplitude Modulation, Fiber, Dense Wavelength Division Multiplexing, Bit Error Rate

## 1. Introduction

With the explosive growth of internet based services such as internet of things, cloud computing, the existing standardized 10 G bps passive optical networks (PON) systems might not be enough in the coming years [1]. This rapid increase of bandwidth demanding applications such as on-line games, virtual reality (VR)/augmented reality (AR), cloud computing et al require high speed data transmission between and inside data centers [2]. This rapid and ever growing demand for optical communication and communication systems has been necessitated by the ever

growing demand for bandwidths. To meet the increasing capacity requirement in data centers and high performance computers, advanced optical interconnection is highly desired with simple implementation, large bandwidth, high modulation efficiency, long transmission distance and low cost [3]. Commercial deployment of optical fibers started only as a backbone for long haul transmission systems, but today the deployments have extended to metro and even access networks. 75 percent of total metro traffic will be terminated within the metro network, while only 2 percent of the traffic needs to traverse through the backbone network according to Xu et al (2015) [4]. With this high demand,

continuous research to develop technologies that meet the intended data rates has been inevitable. Improvement in capacity and reach relies on increase in spectral efficiency, increase in total available bandwidth and reduction in signal impairments accumulated per bits per symbol. Spectral efficiency can be improved by using techniques that transmit more bits per symbol but is limited by noise and other distortions thus reducing the sensitivity per bit [5, 6]. The conventional binary modulation format Non Return to Zero (NRZ) is a two level amplitude shift keying (ASK) technique in which the signal levels are switched between '0' and '1'. In order to deploy higher data rate access network with lower cost, high spectrally efficient modulation format should be introduced [1]. Multilevel pulse amplitude modulation is a more spectral efficient technique in which more levels are assigned to the amplitude of the signal. Each amplitude level is assigned a number of bits. The number of bits transmitted per symbol determines the number of levels the signal can have. A system with two bits per symbol results in a 4-ary ASK signal. The four level signals will be referred to as 4 level pulse amplitude modulation (4-PAM). The 4-PAM signal is the result of adding up two 2-PAM signals, with double amplitude of one respect to the other [7]. PAM has a unique advantage because it does not require extra lasers or a costly overhaul of optical fiber cablings within the existing infrastructure [8]. Upgrading network capacity, spectral and power efficiency at low installation costs, as well as extending the reach between hyper-scale data centre network nodes are still key challenges facing current long reach high capacity optical interconnects. To meet the data tsunami demands from global Internet users, service providers have continuously worked towards upgrading the network transmission layer to higher lane rates and more parallel architectures [9]. A higher data rate achieved using either higher-order modulation format or higher symbol rate, places tremendous pressure on the component in terms of SNR requirement or bandwidth requirement. To relieve the burden on the hardware, advanced DSP techniques can be applied [10].

## 2. Theory

Q-factor characterizes the quality of a digital signal from an analog point of view, therefore it is judged as a signal/noise ratio [11].

System performance is often reported using the quality (Q) factor method, where the noise distribution is assumed to follow Gaussian distribution [12]. The decision circuit in a fiber optical communication receiver demodulates the signal by comparing the sampled voltage $V(t)$ to a reference value called the optimum decision threshold. An assumption is made that the additive white Gaussian noise (AWGN) is the dominant cause of erroneous decisions, and then the statistical probability of making such decisions can be calculated. To determine the probability of error, the probability density function (PDF) for '0' and '1' levels must be known or the probability that the signal level will fall below or above the decision threshold. The PDF is given by.

$$PROB\left[v(t), \sigma_x\right] = \frac{1}{\sqrt{2\pi\sigma_x^2}} e^{-\frac{1}{2}\left(\frac{v(t)-v_s}{\sigma_x}\right)^2} \qquad (1)$$

Where $V_s$ is the voltage sent by the transmitter (the mean value of the density function), $V(t)$ is the sampled voltage value in the receiver at time t, and $\sigma$ is the standard deviation of the noise.

The BER is determined by the standard deviation of the noise for zero (low) level $\sigma_L$ and one (high) level $\sigma_H$ and the voltage difference between the zero level $V_L$ and one level $V_H$. The Q-factor which defines the optical signal to noise ratio (OSNR) for a binary optical communication system is expressed as [13]

$$Q_{(1,0)} = \frac{V_H - V_{TH}}{\sigma_H} = \frac{V_{TH} - V_L}{\sigma_L} \qquad (2)$$

From equation (2) the Q factor can also be given as

$$Q = \frac{V_H - V_L}{\sigma_H + \sigma_L} \qquad (3)$$

For a four level system such as 4-PAM, threshold for each level and their respective standard deviations must also be computed. Considering a 4-PAM modulation format, three signal levels are practically applicable. The mean peak to peak voltage for zero and one level of each of the three eyes is calculated together with their respective standard deviations. The threshold levels for each eye are estimated based on the mean and standard deviation of symbol. The signal quality factor (Q-factor) parameter is then calculated from mean peak to peak voltages and the standard deviation. This leads to the final stage of computing for the actual BER value using the already calculated Q-factor [14]. The total BER of such a system is the cumulative error rate measurements done on each individual threshold values [15]

$$BER_{4-PAM} = BER_1 + BER_2 + BER_3 =$$

$$\frac{1}{2}erfc\left[\frac{\mu_1 - \mu_0}{\sqrt{2}\left(\sigma_1 + \sigma_0\right)}\right] + \frac{1}{2}erfc\left[\frac{\mu_2 - \mu_1}{\sqrt{2}\left(\sigma_2 + \sigma_1\right)}\right] +$$

$$\frac{1}{2}erfc\left[\frac{\mu_3 - \mu_2}{\sqrt{2}\left(\sigma_3 + \sigma_2\right)}\right] \qquad (4)$$

## 3. Materials and Methods

The setup in figure 1 below is a multilevel optical transmission link comprising of an electrical transmitter, medium and the optical receiver. The complementary, P data output arm and N data output arms of the pattern generator (PPG) generates the pseudo random bit sequence (PRBS) ($2^7$-1), which after combining directly modulates the vertical cavity surface emitting laser (VCSEL) 1310nm laser. The VCSEL biasing was performed by varying the current using the laser diode controller (LDC) and directly modulating the VCSEL with the 10 G bps

Non-Return-to-Zero (NRZ) PRBS ($2^7$-1) PPG via a Bias-Tee (BT). The VCSEL was biased above the threshold current at 5.5m A. The two decor related P and N PRBSs ($2^7$-1) each at 10 G bps are differentially attenuated before combining and doubling the transmission data rates to 20 G bps. The different electrical attenuations on the two outputs guarantee the existence of two data signals with different voltage levels (different amplitudes). The N output attenuated at 13dB has the electrical data sequence delayed in time by an integer multiple of a bit period (100 p s), decor relating the two complemented bit sequences. On mixing in the power combiner, the two decorrelated data sequences interfere constructively and destructively, producing a four level data signal (4-PAM). The mixing doubles the transmission data rate from 10G bps to 20G bps. The multilevel transmitter therefore codes two bits in one symbol prior to modulation and transmission through the fiber.
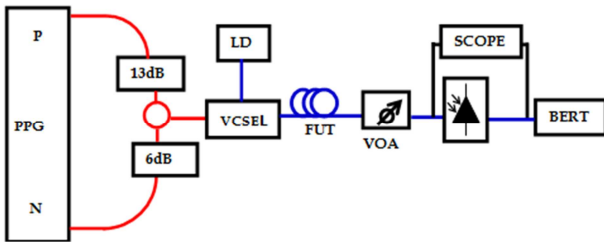


**Figure 1.** *Experimental modulation setup for 4-PAM.*

The VCSEL at 1310 nm was directly modulated at a bit rate of 20 G bps by a NRZ PRBS signal and analysis was done for Back-to-back (B2B) and 3.21km G.652 single mode fiber (SMF) transmission. The PIN photodiode demodulates and converts the optical signal back to electrical data signal. The receiver comprises of a sampling oscilloscope that captures and stores the received signal. Sampling oscilloscopes have an inherent noise floor that is very low compared to real-time oscilloscopes having comparable bandwidth, and as a result, will often yield the most accurate characterization of a PAM-4 signal. For optical PAM-4 systems, the sequence generator used provides up to 2 optical channels per module. The captured eye diagrams were then transferred to an offline digital signal processing (DSP) for analysis. The developed DSP MATLAB algorithm utilizes the loaded eye data information from the oscilloscope as the input data. Three optimum threshold values are accurately determined thereby demodulating the four signal symbols generated at the transmitter. Mean peak to peak voltage for zero and one level of each of the three eyes is calculated together with their respective standard deviations. The Q factor is calculated from the mean peak to peak voltage for zero and one level of each of the three eyes is calculated together with their respective standard deviations. The final and most important DSP stage is the determination of the bit error rate (BER) values using the calculated Q factor. The performance of the multilevel high speed optical communication system was evaluated through BER calculation at the standard acceptable BER of $10^{-9}$.

# 4. Results and Discussion

## 4.1. VCSEL Biasing and Tune-Ability

The VCSEL was biased above its threshold current to give sufficient output power as shown in figure 2 (a). The emission wavelength was tuned between 1303.48nm to 1307.58 nm by increasing the bias current from 3.5 to 8.5 m A in figure 2 (b). This implied that by biasing the VCSEL with 3.5-8.5 m A, a 4.1nm (512.01GHz) wavelength tune ability range was achieved. Therefore, we can create 10 G bps tune-able channels operating within a 512.01GHz bandwidth using VCSEL which can allow 10 DWDM channels at 50GHz spacing. This characteristic of the VCSEL makes it an important component for DWDM and flexible spectrum applications and in systems where wavelength tuning is required.
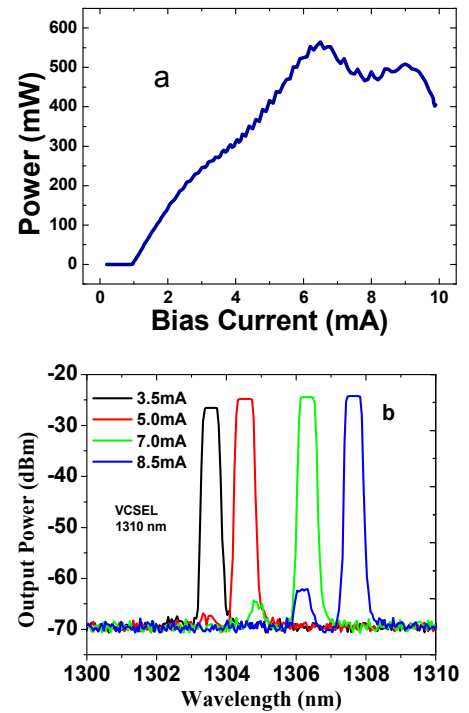


**Figure 2.** *(a) Un-modulated VCSEL bias characteristics (b) VCSEL tune ability.*
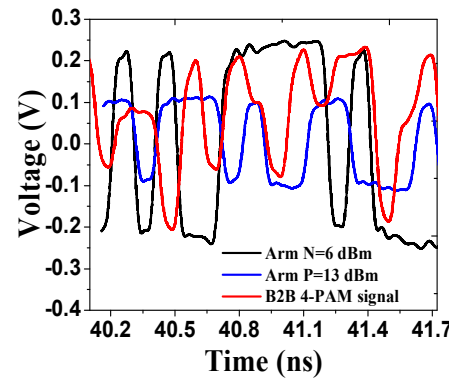
## 4.2. 4-Pulse Amplitude Modulation



**Figure 3.** *Arm P, Arm N electrical signal and combined 4-PAM electrical data signal.*

The figure 3 above shows electrical data signal waveform for arm P and arm N before mixing and the combined electrical data signal waveforms. After mixing the electrical signals from the two arms, a 4-PAM electrical is generated with four levels. Each of the four symbols comprises of two bits each (00; 01; 10 and 11). Arm N is attenuated to 6 dB while arm P is attenuated to 13dB. The attenuation in both arms reduces the effects of reflection from mismatch in the transmission line.

The figure 4 shows clear electrical eye diagram for a 4-PAM illustrating the three levels of the signal with three eyes. These three levels each of which represents a combination of two bits (00, 01, 10, 11) where each level is clocked on a rising or falling edge of a clock signal. When one of the four amplitudes is transmitted in a symbol period there are two bits transmitted in parallel, therefore the data rate is doubled.
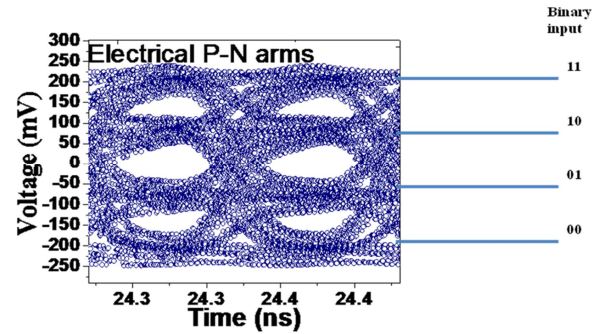


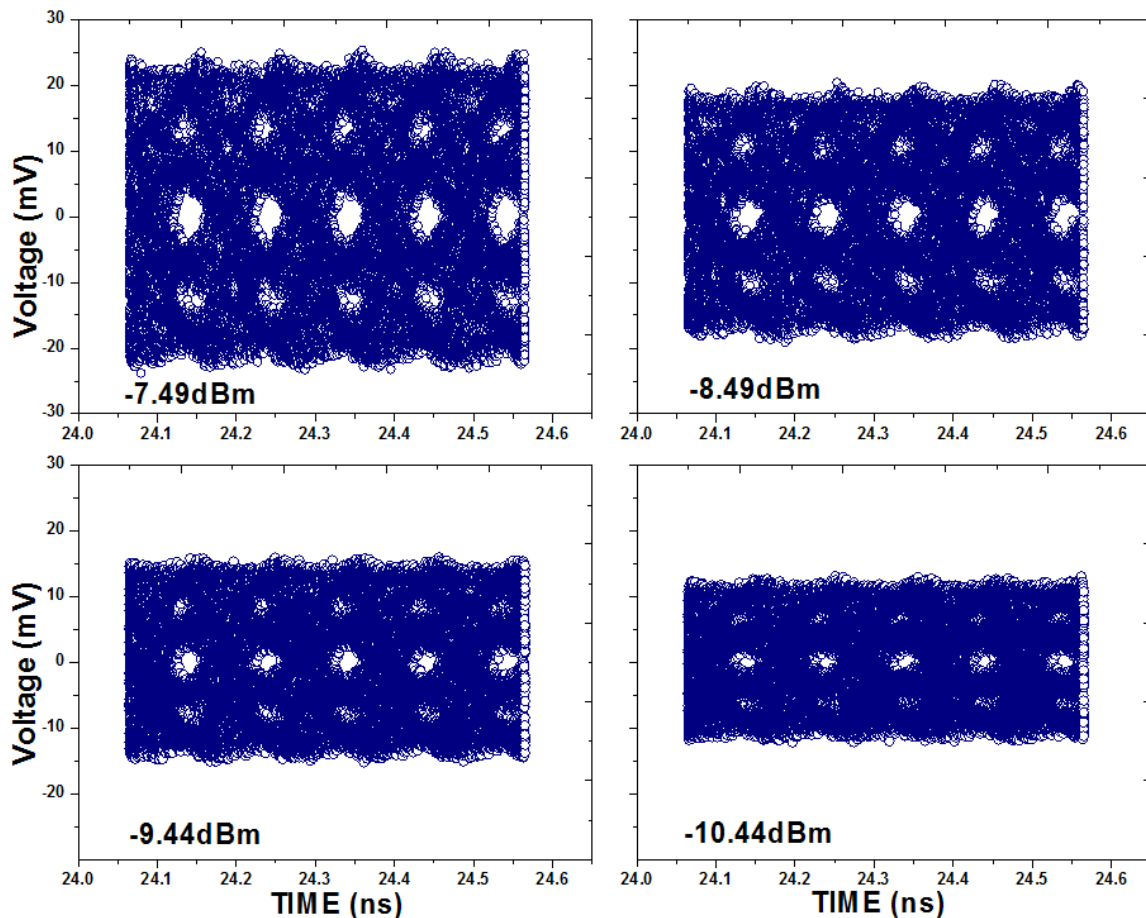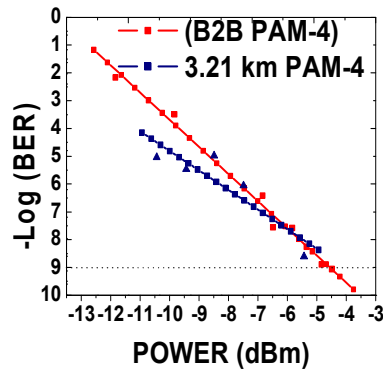Figure 4. B2B electrical 20 G bps 4-PAM eye diagram.





Figure 5. BER curve and eye diagrams for PAM-4 signal.

The figure 5 shows the BER versus output power for a 1310nm VCSEL at 20 G bps after B2B and 3.21km transmission on a G.652 fiber. For the B2B case the output power sensitivity is observed at approximately-4.542dB at ITU standard BER threshold of $10^{-9}$. After transmission of 3.21km on a G.652 SMF was obtained to be approximately-3.817dB, indicating a corresponding power penalty of 0.725dB. The eye diagrams after the 3.21km SMF transmission, visible degradation of the eye-diagrams can be observed which is due to ISI. As the power also decreases the eyes tend to close. The main advantage of 4-PAM is the double throughput, using the same components. In a case where there is bandwidth constraint, 4-PAM allows one to double the bit rate. In this work, signal processing to demodulate the 4-PAM signal was performed offline using MATLAB by utilizing the eye diagrams. From the eye diagrams for a 4-PAM format, the eyes close at every power decrement. This indicates that 4-PAM requires high optical power resulting in higher power penalty and is manifested in the closure of the eye.

## 5. Conclusions

Successful transmission of 20 G bps PAM-4 modulated VCSELs was demonstrated over 3.21km on G.652 fibers with BER of $10^{-9}$. The devised higher modulation technique can be suitably applied to the already deployed optical communication links by only modifying the transmitter without affecting the deployed fiber. The DSP algorithm developed, using the PDF and BER technique is a technology used to evaluate and monitor the performance of a high order modulation scheme in the absence of the relevant hardware. The multilevel transmitter and the offline DSP can help alleviate the ever growing demand for transmission speeds in many optical interconnects and local area networks. The developed multilevel DSP algorithms can be used in any other high modulation formats with small modifications based on the number of levels thereby promoting a cost effective way of evaluating the performance of any high speed optical communication link. This results show that combination of PAM-4 modulation and DSP method can increase the reach, achieve higher capacity and support connectivity for the next generation of data centers.

## Acknowledgements

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