A single DFB laser with multilevel directly modulated signal for high speed optical fibre communication system

T V Chabata, E K Rotich Kipnoo, R R G Gamatham, A W R Leitch, and T B Gibbon

Physics Department, Nelson Mandela Metropolitan University, P. O. Box 77000, Port Elizabeth 6031, South Africa. Tel: +27 41-504-2141; Fax: +27 41-504-2573.
Email: Tichakunda.Chabata@nmmu.ac.za

Abstract. A multilevel modulation format that meets the high bandwidth requirements and increases the bit rate is experimentally investigated. A single distributed feedback (DFB) laser at 1550 nm is used to transmit a total of 20 Gb/s of data over a single mode optical fibre link. The data rate is doubled from binary 10 Gb/s by employing a multilevel technique. An economical, all electrical multilevel signal generation technique was designed. The multilevel format transmitter codes two bits in one symbol. This enables an increase in the bit rate of the system, though at the expense of receiver complexity. The two bits coded in a single symbol generate a four level signal that has to be decoded at the receiver. The designed complex receiver section utilizes the offline digital signal processing algorithms to evaluate the system performance through bit error rate (BER) measurements. The system performance was experimentally evaluated on back-to-back transmission.

1. Introduction

The current increase in the use of cloud based services, high definition (HD) TV streaming, on-line gaming and sharing of photos, videos and other files has greatly congested the already operational 10 Gb/s intensity modulation direct detection (IM/DD) optical networks . There is therefore a need to developed new technologies which can potentially provide the required increase in data capacity while maintaining the bandwidth and the form of existing links. A cost effective alternative is one based solely on optical amplitude modulation format allowing the use of existing receivers [1]. A technique to achieving high spectral efficiency in IM/DD optical links is to increase the number of amplitude levels in the signal. This modulation format is commonly referred to as M-level pulse amplitude modulation (M-PAM), where M refers to the number of levels in the signal. Each optical symbol will carry $\log_2(M)$ bits of information. Recently a 4-PAM modulation of a vertical cavity surface emitting laser (VCSEL) at 50 Gbps was reported [1].

In this paper, a multilevel signal transmitter and analyzer at the receiver is demonstrated. The advanced modulation technique employing 4 -pulse amplitude modulation (4-PAM) that doubles the transmission rate is designed and implemented using a directly modulated distributed feedback (DFB) laser. The narrow linewidth of the DFB laser is of importance in the design of the high speed optical link. The magnitude of temporal dispersion of the signal is directly proportional to the length of the fibre and the linewidth of the laser source. The generated multilevel signal is transmitted using a single DFB laser at 1550 nm at an effective data rate of 20 Gb/s. An offline digital signal processing (DSP), multilevel signal analyzer was developed to evaluate the quality of the received optical signal using the Q factor approach. The ultimate quality measure in an optical communication links is the bit error rate (BER) [2]. The quality factor and probability density function are the important parameters in analyzing and estimating the BER from an eye diagram plot.

2. Theory

Figure 1 shows the probability density function (pdf) of a received binary signal with symbol S_0 and symbol S_1 [3]. In the derivation, we assume that the pdf is Gaussian and is given by:-

$$P_n(x) = \frac{1}{\sigma_n\sqrt{2\pi}}\exp-\left[\frac{x^2}{2\sigma_n^2}\right] \qquad [1]$$

The erroneous received bit is the overlapping region between pdf of symbol S_0 and symbol S_1. The probability of error when S_O is transmitted is the shaded area under the curve (blue) and is given by:-

$$P_{\left(e/s_0\right)} = \frac{1}{\sqrt{2\pi}\sigma_0}\int_{Th_1}^{\infty} e^{-\left(\frac{Th_1-U_0}{\sqrt{2}\sigma_0}\right)^2} = \frac{1}{2}erfc\left[\frac{Th_1-U_0}{\sqrt{2}\sigma_0}\right] \qquad [2]$$

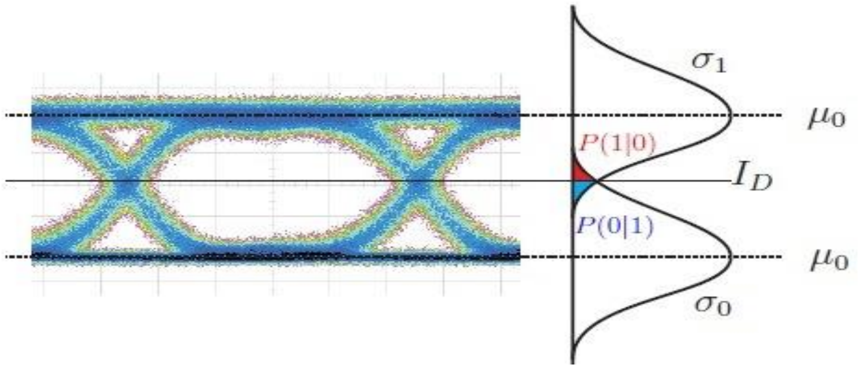

Figure 1: The Probability density functions of a received binary signal [3].

For similar threshold value, the probability of error when S_1 is transmitted is also the area under the curve (red) and is given by:-

$$P_{\left(e/s_1\right)} = \frac{1}{\sqrt{2\pi}\sigma_1}\int_{-\infty}^{Th_1} e^{-\left(\frac{U_1-Th_1}{\sqrt{2}\sigma_1}\right)^2} = \frac{1}{2}erfc\left[\frac{U_1-Th_1}{\sqrt{2}\sigma_1}\right] \qquad [3]$$

where, P (e/s_0) and P (e/s_1) are contributing to total probability of error. The probability of error for binary (2 level signal, with unbalanced noise distribution, ($u_1 \neq u_0$) is given by:

$$BER = P_e = P_{s0}P_{\left(e/s_0\right)} + P_{S1}P_{\left(e/s_1\right)} = \frac{1}{2}\,erfc\left[\frac{Q_0}{\sqrt{2}}\right] + \frac{1}{2}\,erfc\left[\frac{Q_1}{\sqrt{2}}\right] = \frac{1}{2}erfc\left[\frac{u_1-u_0}{\sqrt{2}(\sigma_1+\sigma_0)}\right] \qquad [4]$$

The Q- factor term is given by:-

$$Q = \frac{u_1-u_0}{\sigma_1+\sigma_0} \qquad [4.1]$$

The same reasoning can be extended to any M-ary modulation format to estimating the BER.
For a 4 level modulation format, three optimum threshold decision values are applicable, each of the threshold values being between a pair of two adjacent symbols levels. The total error rate is driven from error rate measurements done on each of the threshold values [4].

$$BER = ER_1 + ER_2 + ER_3 = \frac{1}{2}erfc\left[\frac{u_1-u_0}{\sqrt{2}(\sigma_1+\sigma_0)}\right] + \frac{1}{2}erfc\left[\frac{u_2-u_1}{\sqrt{2}(\sigma_1+\sigma_2)}\right] + \frac{1}{2}erfc\left[\frac{u_3-u_2}{\sqrt{2}(\sigma_2+\sigma_3)}\right] \qquad [5]$$

3. Research design

The schematic diagram shown in Figure 2 is a complete multilevel optical transmission link comprising of an electrical transmitter, the medium and the optical receiver. The complimenting, P and N, arms of the programmable pattern generator (PPG), generates the pseudo random bit sequence (PRBS),(2^7-1), which on combining directly modulates the (DFB) laser. The different electrical attenuations on the two outputs guarantee the existence of two data signals at different power levels. The N output attenuated at 13 dBm has the electrical data sequence delayed in time by an integer multiple of a bit period, decorrelating the two complemented bit sequences. After mixing the two decorrelated data sequences interfere constructively and destructively, producing a four level data sequence. The mixing doubles the transmission data rate from 10 Gb/s to 20 Gb/s. The multilevel transmitter therefore codes two bits in one symbol prior to modulation and transmission through the fibre.

The DFB laser signal at 1550 nm is directly modulated at a bit rates of 20 Gb/s by a Non-Return-to- Zero (NRZ) Pseudo-Random Binary Sequence (PRBS) signal and is transmitted through a back to back single mode fibre. The power meter (PM) measures the optical power at the back-end of the receiver after the optical signal power has been attenuated by a variable optical attenuator (VOA). The direct intensity modulated signal is directly detected (DD) by the photodiode (PD). The photodiode (PD) demodulates and converts the optical signal back to an electrical data signal. The front-end of the receiver comprises of an oscilloscope that captures and stores the received signal. The captured data is transferred to an offline digital signal processing (DSP) circuit. An Offline digital signal processing algorithm was developed to monitor and evaluate the performance of the designed multilevel optical link.

The developed DSP analyser utilises the loaded eye diagram 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 voltages and the standard deviation as given in equation [4.1]. The final and most important stage is the determination of the BER values using the already calculated Q- factor, utilizing equation [5].

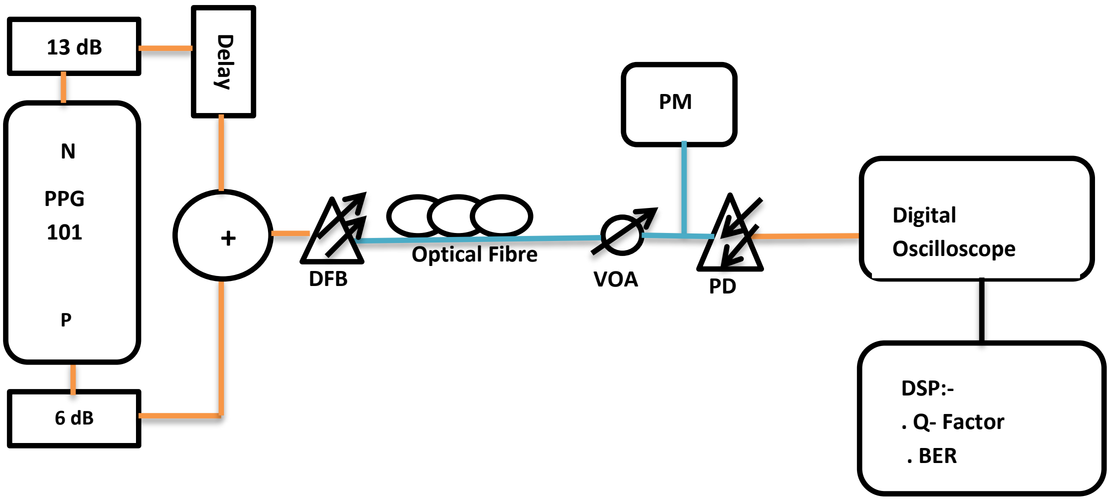

Figure 2: Experimental setup for a 4- Level pattern generator with differentially attenuated outputs and an integer bit period delay:

PPG: programmable pattern generator. DFB: distributed feedback laser. VOA: variable optical attenuator power PM: power meter. PD: photodiode and a DSP: digital signal processing circuit. BER: bit error rate, Quality factor technique.

4. Results and discussion

Two decorrelated P and N pseudo random bit sequences (2^7- 1) each at 10 Gb/s are differentially attenuated before combining and doubling the transmission data rate to 20 Gb/s. Figure 3 shows the individual P and N signal before mixing and the combined signals after mixing . After mixing each of the four symbol comprises of two bits each (00; 01;10 and 11). The graph clearly shows that the combined signal (red) is a result of the interference of the two individual signals (blue and black).

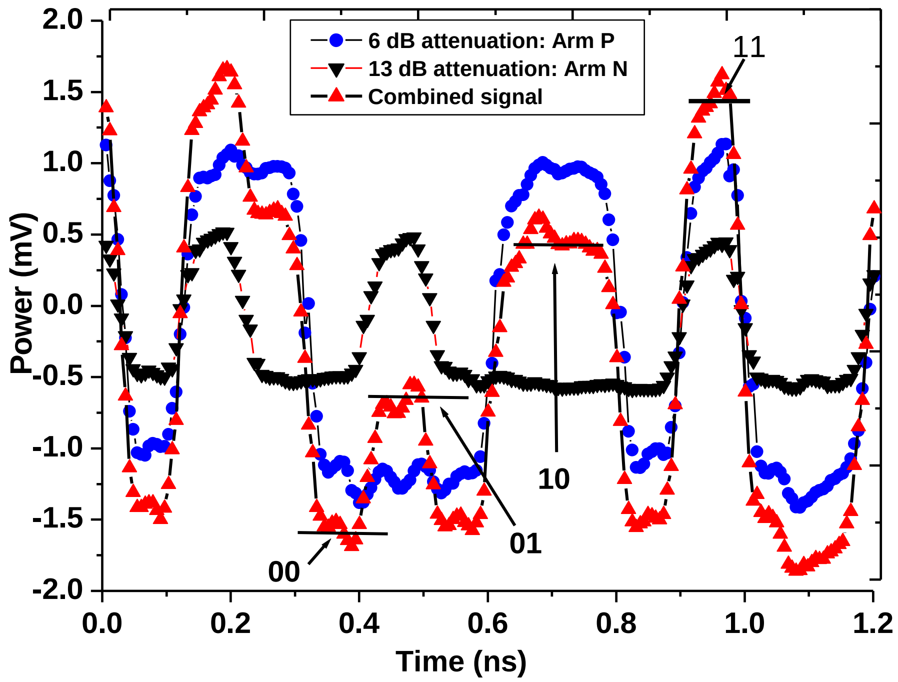

Figure 3: The individual and combined waveforms of the signal out of the multilevel transmitter.

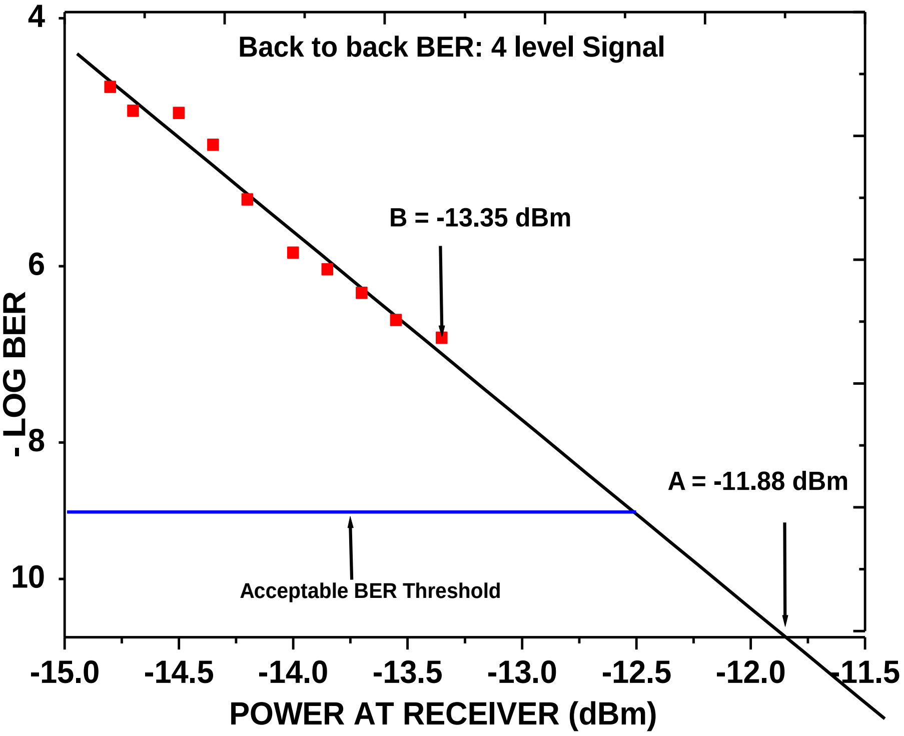

Figure 4: Back to back bit error rate (BER) for the four level signal

Figure 4 shows the BER curve for back to back transmission obtained using the statistical probability density function (pdf), given in equation (5). The equation uses the analogue information from the signal (Q factor) to accurately estimate the BER. A receiver sensitivity of -12.47 dBm at the acceptable BER of 10^{-9} is obtained, with a penalty of 7 dB compared to a two level signal reported in [6]. The penalty is brought about by modulating an additional bit within the same modulation depth prompting the need for a more sensitive receiver to demodulate the two bits per symbol.

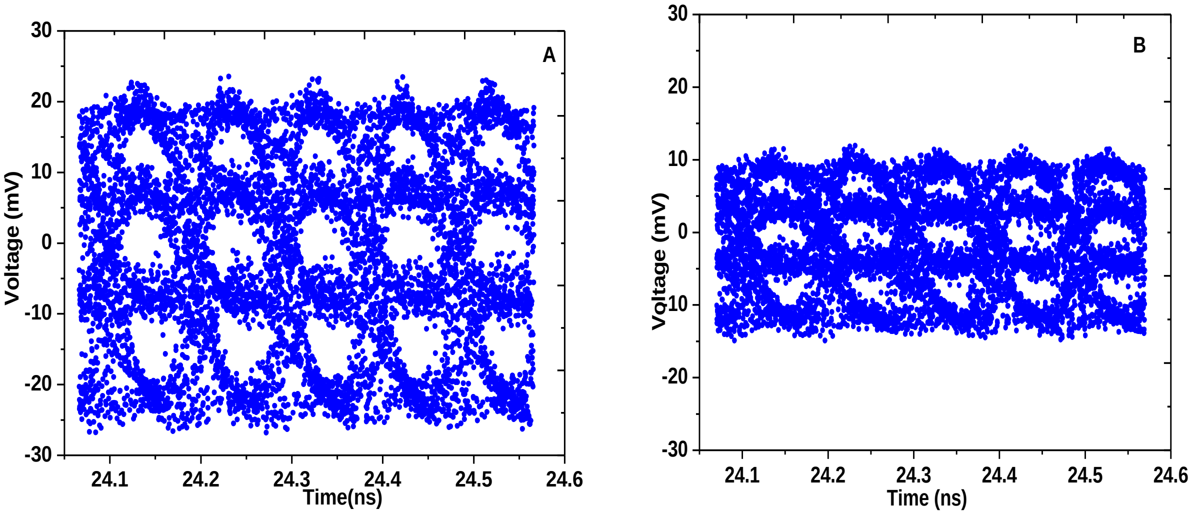

Figure 5 (A and B): Eye diagrams at -11.88 dBm and – 13.35 dBm respectively.

Figure 5 shows the open eye diagrams at different receiver powers. The diagram has three open eyes and four signal levels. The eye closure is attributed to the attenuation of the signal in the back to back single mode fibre transmission link. The DSP algorithm developed, using the pdf and Q factor is an attractive technology to evaluate and monitor the performance of a high order modulation scheme in the absence of the relevant hardware.

5. Conclusion

In this paper a four level signal analyser has been successfully implemented. The multilevel transmitter and the offline signal analyser designed and experimentally implemented are technologies that can help alleviate the ever growing demand for transmission speed in many optical interconnects and local area networks. The developed multilevel DSP algorithms signal analyser can be used in any M-ary modulation formats thereby promoting a cost effective way of evaluating the performance of any high optical communication link.

Acknowledgement

We are grateful for Research Funding from: Telkom, Dartcom, Ingoma, NRF, CSIR, THRIP, and Scholarship Funding from ALC and NMMU.

References

[1]. J B Jensen, M I Olmeido and I T Monroy, (2013), "Modulation Formats for Beyond-100Gbps Ethernet Optical Links – A Review of Research", *DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark*

[2]. E Lach, W Idler 2011, "Modulation formats for 100G and beyond", Elsevier. Opt. Fib. tech. 17, pg 377-386

[3]. W Freude, R Schmogrow1, B Nebendahl, M Winter, A. Josten, D Hillerkuss1, S Koenig, J Meyer, M Dreschmann, M Huebner, C. Koos, J Becker, 2012. " Quality Metrics for Optical Signals: Eye Diagram, Q-factor, OSNR, EVM and BER", *Institute of Photonics and Quantum Germany, ICTON,*

[4]. M F L Abdullah, R Talib .2012, "Multilevel signal analyzer tool for optical communication system". *Department of communication Engineering. University Tun Hussein Onn Malaysia. Institute of Advanced engineering and science.*

[5]. S Krzysztof, W Pette, G Johan, H Åsa, K Johnny, K Magnus, A Peter; A Erik and L Anders, 2011, "30 Gbps 4-PAM transmission over 200m of MMF using an 850 nm VCSEL", *European Conference and Exposition on Optical Communications (ECOC), OSA.*

[6]. T V Chabata, R R G. Gamatham , H Y S Kourouma, E K Rotich Kipnoo, A W R Leitch, and T B Gibbon (2013) , " Digital Signal Processing Algorithm for Signal Reconstruction and Performance Measurement for a Single Photo Detector Optical Communication System". *Proc. 16th annual Southern Africa Telecommunication Networks and Applications Conference (SATNAC) Spier, Stellenbosch, Western Cape, South Africa, pg 27-30, 1-4th Sept 2013.*

[7]. T.B. Gibbon, K. Prince, T.T. Pham, A. Tatarczak, C. Neumeyr, E. Rönneberg, M. Ortsiefer, "VCSEL transmission at 10 Gb/s for 20 km single mode fibre WDM-PON without dispersion compensation or injection locking", *Elsevier. Opt. Fib. tech*. 17, pg 41-45 (2011).

[8]. G P AGRAWAL .2007 Non Linear Fibre Optics Academic Press 4th Edition,

[9]. HFAN -9.0.2 Application note (04/08), "Optical signal to noise ratio and the Q-Factor in Fiber Optic Communication Systems".

[10]. R Rodes, J Estaran, B Li, M. Mueller, J B. Jensen, T Gründl, M. Ortsiefer, C Neumeyr, J Rosskopf, K J Larsen, M C Amann, and I T Monroy (2012), "100 Gb/s single VCSEL data transmission link", *DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, DK2800 Kgs. Lyngby, Denmark"*, OSA