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30 Gbps 4-PAM transmission over 200 m of MMF using an 850 nm VCSEL

Krzysztof Szczerba,[1,*] Petter Westbergh,[1] Johnny Karout,[2] Johan Gustavsson,[1] Åsa Haglund,[1] Magnus Karlsson,[1] Peter Andrekson,[1] Erik Agrell,[2] and Anders Larsson[1]

[1] *Department of Microtechnology and Nanoscience, Chalmers University of Technology, 412-96 Gothenburg, Sweden*

[2] *Department of Signal and Systems, Chalmers University of Technology, 412-96 Gothenburg, Sweden*

[*] *krzysztof.szczerba@chalmers.se*

Abstract: We present high speed real time, error free 4-PAM transmission for short range optical links based on a VCSEL operating at 850 nm, a multimode fibre and a simple intensity detector. Transmission speeds of 25 Gbps and 30 Gbps are demonstrated, and the maximum fibre reaches were 300 m and 200 m, respectively. The 4-PAM is also compared with OOK transmission at 25 Gbps, and we find that at this bit rate 4-PAM increases the error free transmission distance in the multimode fibre by 100 m, compared to OOK.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.4080) Modulation; (060.2360) Fiber optics links and subsystems; (140.7260) Vertical cavity surface emitting lasers.

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1. Introduction

The growing demand for increased transmission speed in applications such as optical interconnects and local area networks motivates the development of fast and low cost optical solutions using vertical cavity surface emitting lasers (VCSELs) and multimode fiber (MMF). Graded index MMF was used to reduce the impact of modal dispersion and extend the reach compared to legacy MMF, but recent development of VCSELs capable of operating at bit rates of up to 40 Gbps at the wavelength of 850 nm [1] and 44 Gbps at the wavelength of 980 nm [2], shows that the transmission distance at these high bit rates is very limited if on-off keying modulation (OOK) is used. Multilevel modulation, with higher spectral efficiency, is a way of extending the reach of multimode fiber at high bit-rates. Because of cost constraints, intensity modulation and direct detection (IM/DD) are appealing in short range optical networks. There are two main possibilities for spectrally efficient modulation formats in IM/DD links, pulse amplitude modulation (PAM), and subcarrier modulation (SCM). The 4-PAM was investigated theoretically up to 20 Gbps and experimentally at 10 Gbps for use with directly modulated lasers [3]. In [4], 4-PAM eye diagrams with electronic predistortion at 32 Gbps are reported, proving the feasibility of 4-PAM at high data rates. Single cycle subcarrier modulation with 16 level quadrature amplitude modulation was also demonstrated in links using VCSELs and MMF [5], with real time transmitter and was off-line processing in the receiver. Discrete multitone modulation was demonstrated at 30 Gbps for the same type of link [6], with off-line processing.

There are constraints for modulation formats complexity in short range optical links, especially those used for data communication, e.g. in supercomputing and data center applications. The limitations come from power consumption, heat generation, and spatial density requirements. 4-PAM offers the lowest implementation complexity of all the modulation formats with spectral efficiency of 2 bits/second/Hz. Real-time hardware for transmitters and receivers for 4-PAM are already developed [7, 8]. In laboratory conditions, 4-PAM modulation can be generated in real time. The bit error rate (BER) measurement can also be done in real time.

In this paper, we present transmission at 25 Gbps and 30 Gbps using 4-PAM over 300 and 200 meters of MMF, respectively. The 4-PAM signal generation and BER measurements were performed in real time. We also compared 4-PAM and OOK modulation at 25 Gbps, and demonstrated that an increase in transmission distance can be achieved by using 4-PAM instead of OOK at the same bitrate. No equalization was used in the receiver, nor was any predistortion used in the transmitter.

2. Experimental setup

2.1. 4-PAM signal generation

The main advantage of the 4-PAM modulation format is its simplicity. The experimental bit error rate measurement of 4-PAM modulation can be done with standard BER test equipment designed for OOK. In our experiments the 4-PAM signal was generated from two binary PRBS data signals of length $2^7 - 1$, at 12.5 Gbps and 15 Gbps for 25 Gbps and 30 Gbps 4-PAM, respectively. With this method, only natural mapping of bits to symbol is possible. The amplitudes of the binary signals were approximately 900 mV and 450 mV, but they were tuned slightly to adjust the resulting 4-PAM signal level spacing. The two binary signals were decorrelated by half of the PRBS pattern length, to reach all possible level transitions in the resulting 4-PAM

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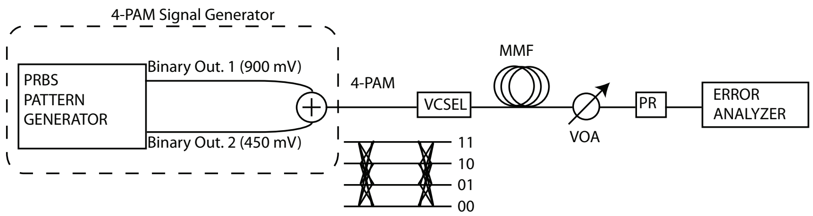

Fig. 1. The experimental setup. The outputs of the pattern generator are individually adjustable with regard to amplitude and delay and also phase matched.

signal. The OOK signals were phase matched before being coupled together. The 4-PAM generator along with bit to symbol mapping are illustrated in Fig. 1.

2.2. *The optical link - VCSEL, fibre and photodetectors used in the experiments*

The generated 4-PAM signal was fed to a VCSEL through a bias-T. The VCSEL, having approximately 20 GHz modulation bandwidth, was described in an earlier publication [9]. The VCSEL bias and modulating signal amplitude were experimentally optimized for the best performance, the optimal bias current was found to be 7 mA for the driving signal peak to peak voltage of 1.35 V. The modulation current could not be easily and reliably measured. The VCSEL was operated at room temperature without cooling. Between the VCSEL and the photoreceiver, an OM3+ graded index multimode fiber was used, with a bandwidth-distance product of 4700 MHz·km. A variable optical attenuator was used to vary the optical power. At the receiver, an amplified photoreceiver (PR) with 12 GHz bandwidth was used, which was the most bandwidth-limiting component in the experiment, apart from the transmission fiber.

2.3. *Real time bit error rate measurement*

The BER measurement was performed using an error analyzer (EA) designed for conventional OOK modulation. For the 4-PAM modulation three decision levels are applicable, each of the levels being between a pair of two adjacent symbol levels. The total symbol error rate was derived from error rate measurements done on each of the 4-PAM threshold levels. Given that we have four symbols denoted as S_0, S_1, S_2 and S_3, there are three decision levels between the adjacent symbols: L_1, L_2 and L_3. A symbol error is detected when a symbol S_i is transmitted and a symbol S_j is received, where i is not equal to j. The conditional probability of receiving S_j when S_i was transmitted is denoted with P_{ij}. In the high signal to noise ratio (SNR) case (which corresponds to low BER), when it can be assumed that only errors between the nearest neighboring symbols happen, and given that natural bit to symbol mapping, the total BER is given by

$$BER = \frac{1}{8}(P_{01} + P_{10} + 2P_{12} + 2P_{21} + P_{23} + P_{32}). \tag{1}$$

The high SNR region of operation is the most interesting one, because a practical links would be operated in this fashion. Forward error correction would have to be implemented to enable operation in the low SNR region, which would probably be challenging in the targeted applications of short range optical links. The error rate measurements ER_1, ER_2, ER_3 at each of the consecutive decision levels L_1, L_2 and L_3 can be expressed in terms of P_{ij} as follows:

$$ER_1 = \frac{1}{4}(P_{01} + P_{10}), \quad ER_2 = \frac{1}{4}(P_{12} + P_{21}), \quad ER_3 = \frac{1}{4}(P_{23} + P_{32}). \tag{2}$$

The error rates at each of the levels were measured with the EA pre-programmed with a pattern corresponding to each of the levels. The aggregate BER can thus be obtained from

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$$BER = \frac{1}{2}ER_1 + ER_2 + \frac{1}{2}ER_3 \tag{3}$$

The complete experimental setup for 4-PAM measurements is shown in Fig. 1.

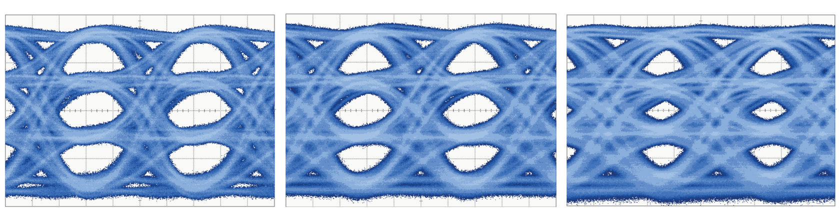
2.4. OOK experimental setup

For the experiments with OOK at the bitrate of 25 Gbps the setup was simplified. The same bit pattern generator and error analyser were used, but without generating the 4-PAM signal. The peak to peak amplitude of the signal driving the VCSEL was the same as for the 4-PAM case, which was 1.35 V. Because an amplified photoreceiver for the wavelength of 850 nm with sufficient electrical bandwidth for 25 Gbps OOK operation was not commercially available at the time, a non-amplified photodetector having 25 GHz bandwidth was used. A discrete amplifier was used to amplify the signal from the photodetector. Although this receiver configuration has higher bandwidth that the photoreceiver used for 4-PAM, it has somewhat worse noise performance. The main reason is that a photodiode is a current source and the discrete amplifier is a voltage amplifier, so the power transfer between these two components is not optimized.

3. Results of 4-PAM experiments

The quality of the 25 Gbps 4-PAM signal in the back-to-back (B2B) configuration is illustrated by the eye diagram in Fig. 2a. No predistortion or equalization was done to the signal. The eye diagram of the signal after propagation through 200 m and 300 m of MMF is illustrated in Fig. 2b and Fig. 2c. In Fig. 3a, the eye diagram of the 30 Gbps signal in the B2B case is illustrated, and in Fig. 3b for propagation over 200 m of MMF. Note that because the transimpedance amplifier in the photoreceiver was inverting, the modulation level one having the highest power is lowest in the eye diagrams of the figures.

The B2B eye diagrams for both 25 Gbps and 30 Gbps do not show any distortion related to non-linearities of the VCSEL itself. In many of the reported 4-PAM experiments the modulation amplitude of the signal driving the VCSEL is adjusted to stay in the linear region of the output power to driving current relationship (the P-I relationship). One has to keep in mind however, that the semiconductor lasers have much more linear performance for high frequency signals, for which the thermal effects are much less pronounced [10]. In general the spurious free dynamic range (SFDR) increases with the bias current, and may continue to increase beyond the thermal roll-over point of the static P-I characteristics [11]. Therefore, we have experimentally optimized the driving signal to obtain the best eye opening. Typical SFDR, for the batch from which the VCSEL used for the experiment came, was above $90\text{dB}\cdot\text{Hz}^{2/3}$, and degraded significantly above the -3 dB point.



(a) (b) (c)

Fig. 2. Eye diagrams at 25 Gbps, after B2B (a) and after propagation over 200 m of MMF (b) and 300 m of MMF (c). The eye diagrams were taken at around 0 dBm received optical power.

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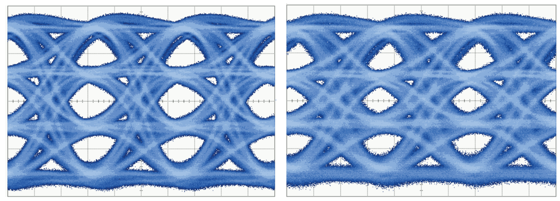


(a) (b)

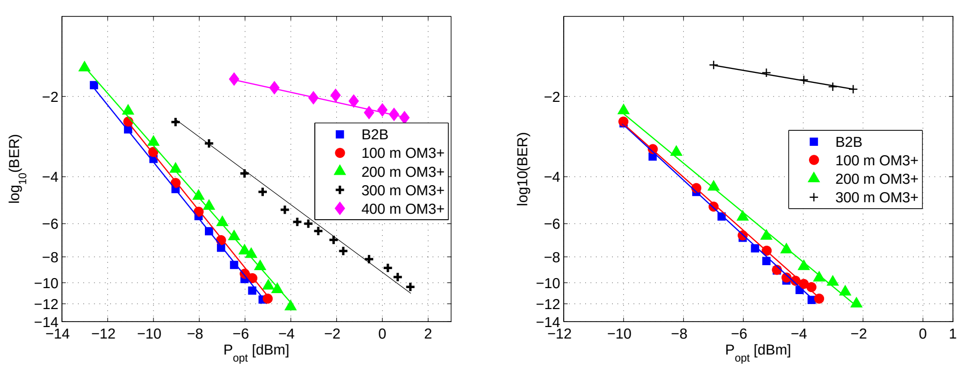
Fig. 3. Eye diagrams at 30 Gbps, after B2B (a) and after propagation over 200 m of MMF (b), taken at around 0 dBm received optical power.

There are however other impairments, which are visible in the eye diagrams. The highest power modulation level is the most broadened. It could be due to the relative intensity noise (RIN) or modal noise, since more modes are excited in the VCSEL as the output power increases. There is also level splitting at the top level. More detailed analysis is required to accurately determine the origin of these impairments.

The BER results for the 25 Gbps transmission are illustrated in Fig. 4a. The maximum practical distance of the OM3+ MMF over which error free transmission can be achieved is 300 m. For the length of 400 m, there is an error floor, due to the modal dispersion. The BER for 30 Gbps transmission is shown in Fig. 4b. In this case, the maximum propagation distance is 200 m of the same MMF, and there is an error floor for 300 m of MMF.

4. Experimental comparison with OOK

The BER results for experiments with OOK at 25 Gbps are illustrated in Fig. 5a. Sensitivities at BER of 10^{-9} for all measured modulation formats are illustrated in Fig. 5b. The absolute sensitivity, which is around -5 dBm at BER of 10^{-9}, is around 1.5 dB worse that the result achieved with 4-PAM at the same bitrate (25 Gbps). The reason for that is that different receiver configurations were used for each of the modulation formats. For 4-PAM a 12 GHz photoreceiver with an integrated transimpedance amplifier (TIA) was used, but for OOK a 25 GHz photodetector and a discrete voltage amplifier was used. Theoretically, it is expected, that the 4-PAM modulation would require 4.8 dB more optical power at the same symbol rate [12]. At



(a) (b)

Fig. 4. BER results for 4-PAM transmission at 25 Gbps (a) and 30 Gbps (b).

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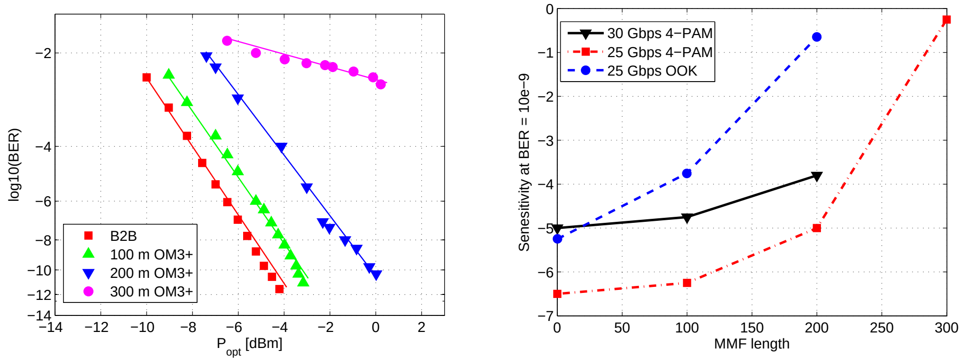

(a) (b)

Fig. 5. BER results for OOK transmission at 25 Gbps (a) and comparison of sensitivities for the three tested cases (b).

the same bit rate 4-PAM should require only 3.3 dB more optical power [13], because of the bandwidth being reduced by half, compared to OOK. This is however offset by the fact, that the configuration of a photodetector and a discrete voltage amplifier has worse noise performance than a photoreceiver with an integrated TIA which was available for 4-PAM because of the reduced symbol rate. The propagation penalties in the multimode fibre are higher for OOK than for 4-PAM. While 4-PAM performance degradation after 100 m of the used MMF is negligible, OOK degrades by 1 dB. After 200 m of the MMF, OOK degrades by 5 dB, while 4-PAM degrades only by around 1 dB. This is also the maximum propagation distance for OOK, i.e. 100 m less than for 4-PAM at the same bit rate.

5. Conclusions

We show 25 Gbps and 30 Gbps, error free, 4-PAM transmission over 300 m and 200 MMF respectively using directly modulated VCSELs. The BER is measured in real time down to 10^{-12} and there is a large power margin for error free operation. The VCSEL itself is not a limiting factor but the lack of photoreceivers with sufficient bandwidths is limiting the high-bandwidth performance. In this situation, 4-PAM is a viable alternative. Due to the better spectral efficiency of 4-PAM the transmission distance in MMF is improved over what would be expected from transmission using OOK. The 4-PAM format has also lower complexity than subcarrier formats, which were demonstrated at a higher bitrate [5], but with only the transmitter working in real time. We have also showed that 4-PAM has significant benefits compared to OOK at the same bit rate. The transmission distance in MMF is significantly extended, and the hardware requirements are relaxed, so that existing components with lower bandwidth can be used.

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