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70 Gbps 4-PAM and 56 Gbps 8-PAM using an 850 nm VCSEL

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Abstract *We present 56 Gbps unequalized 8-PAM real-time transmission over 50 m of MMF and 70 Gbps 4-PAM operation with offline equalization. The experiments were performed with an 850 nm VCSEL with 25 GHz bandwidth and a 22 GHz photoreceiver.*

Introduction

Today's short-range optical communications relies on low-cost vertical cavity surface emitting lasers (VCSELs), multimode fiber (MMF) and direct detection in the receiver. On-off keying (OOK) is the only modulation used in commercial links today. The main reasons for this are cost efficiency and low power consumption of such simple systems, both of which are very important in typical datacom application. The link throughput was historically increased by both faster lasers and parallelization. Today commercial optical interconnects with single-lane data rate of 25 Gbps are becoming available[1].

These approaches have their limits and recently alternative techniques, such as multilevel pulse amplitude modulation (PAM) and equalization have been explored. In[2] 64 Gbps binary transmission over 57 m of MMF was demonstrated using a high-speed VCSEL and custom equalizer circuits. In[3] 60 Gbps operation of 4-PAM was demonstrated. In[4] 4-PAM at 100 Gbps with forward error correction (FEC) and offline processing was demonstrated using a directly modulated 1550 nm VCSEL. The 100 Gbps operation was achieved by use of dual polarization in a single mode fiber, therefore the single-polarization data rate was 50 Gbps.

In this paper we present results of high-speed data transmission experiments using 4-PAM combined with offline equalization and 8-PAM in real-time. The experiments were performed using an 850 nm VCSEL based link. The two modulation formats were tested at symbol rates up to 40 Gbaud for 4-PAM and 25 Gbaud for 8-PAM. It was assumed that FEC can be used since it is gaining support in short-range optical communications, e.g. the most recent version of the Infiniband standard[5] includes FEC.

Experimental setups

Two different test setup configurations were used to generate the 8- and 4-PAM signals. The setups used the same laser, photoreceiver and fiber in both cases. The laser was an in-house developed VCSEL, operating at the wavelength of 850 nm, with 8 micron oxide aperture diameter and around 25 GHz modulation bandwidth. The laser was reported in[6], where 40 Gbps OOK transmission was demonstrated. The VCSEL output was launched into an OM4-type MMF using a lens package. The photoreceiver was a commercially available model with 22 GHz bandwidth and an integrated low-gain linear inverting transimpedance amplifier (TIA). A linear TIA is a requirement for multilevel modulation.

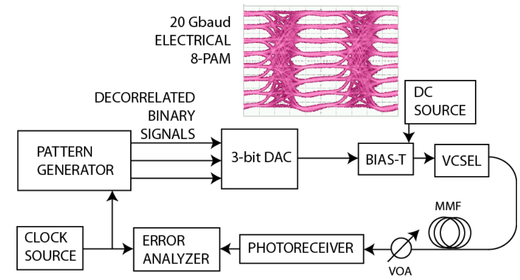

Fig. 1: The experimental setup used for 8-PAM, with an eye diagram of the driving electrical signal included.

The test setups differed by how the electrical signal was generated and how the bit error rate (BER) was evaluated. In the 8-PAM configuration (Fig. 1) a high speed 3-bit digital to analog converter (DAC) was used. The DAC was of the same type as used previously[7], the highest supported symbol rate was 32 Gbaud. It was driven by three decorrelated binary streams, each using a PRBS pattern with length of 2^9-1 bits. An eye diagram of the electrical 8-

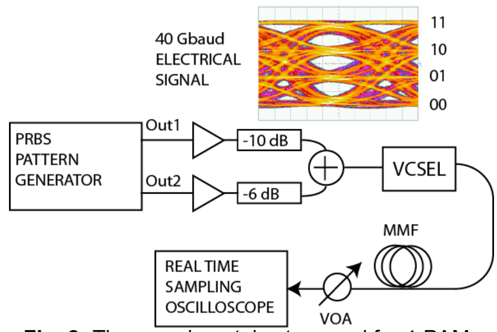

Fig. 2: The experimental setup used for 4-PAM.

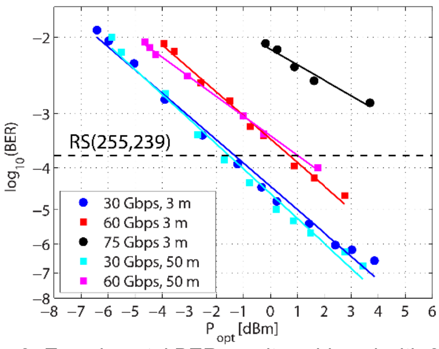

Fig. 3: Experimental BER results achieved with 8-PAM with the FEC threshold for reference.

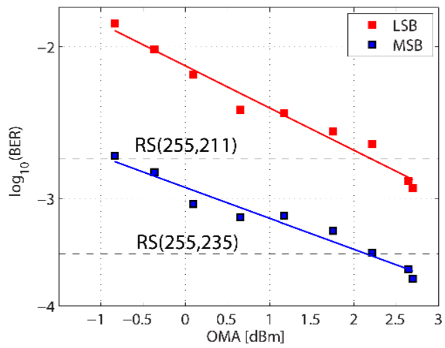

Fig. 5: Experimental BER versus optical modulation amplitude (OMA) for 40 Gbaud 4-PAM experiments, separated between the MSB and the LSB with respective FEC thresholds.

PAM signal at 20 Gbaud is shown in an inset to Fig. 1. The signal, with an amplitude of 842 mV, was fed through a bias-T to the VCSEL, biased at 7.6 mA. The BER was measured in real-time using an ordinary error analyzer designed for OOK, similarly to our previous work[7] on 8-PAM. The overall BER was derived from the error rate (ER) on the middle threshold. Under assumption that the ERs at all decision threshold are the same, the overall BER is equal to[7] (11/3)·ER.

In the 4-PAM test setup (Fig. 2) the electrical driving signal was generated by coupling together two decorrelated binary signal, each being a PRBS pattern of length 2^7-1. The binary signals were amplified and adjusted in amplitude so that one of the signals had half of the amplitude of the other and combined in a high bandwidth resistive 3 dB coupler. An eye diagram of the electrical signal is shown in an inset to Fig. 2. The VCSEL was biased at 12 mA and the electrical signal amplitude was around 1.2 V. A 3 m OM4 patchcord was used for transmission. The signal from the photoreceiver was acquired using a real-time sampling oscilloscope with 33 GHz bandwidth and 100 Gsps sampling rate and processed offline. The offline processing included a simple static equalizer designed to emphasize the signal frequencies in the 20–40 GHz range. The equalizer filter was a linear phase FIR filter with length corresponding to 5 symbols for signal at 40 Gbaud. The purpose of the equalizer was to emulate a static analog equalizer which could be placed in the receiver, but which we did not have capacity to implement in hardware. In a system with a digital equalizer, in case when the filter taps are symbol-spaced, the number of taps would be dramatically lower than in the presented case, where the taps are sample-spaced.

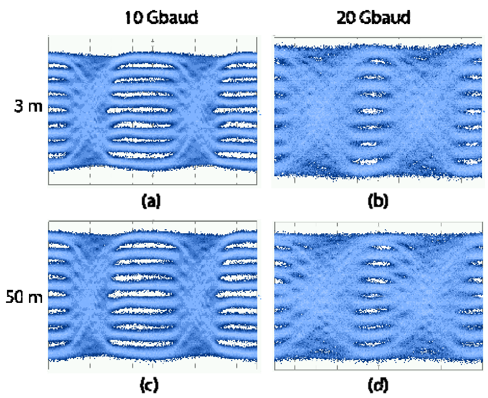

Fig. 4: Eye diagrams of 8-PAM at after 3m of fiber at 10 Gbaud (a), 20 Gbaud (b) and after 50 m of fiber at 10 Gbaud (c) and 20 Gbaud (d).

Because of the differences between the test setups, a direct comparison of the 8-PAM and 4-PAM results is not possible. The purpose of the experiments was rather to expand the envelope of what can be achieved using multilevel modulation.

Results of transmission with 8-PAM

The BER results from the 8-PAM experiments are shown in Fig. 3. The tested bit rates were 30 Gbps, 60 Gbps and 75 Gbps, over a 3 m OM4-type MMF patchcord and 50 m of OM4-type MMF. There is about 3 dB sensitivity penalty between the 30 Gbps and 60 Gbps, which is mostly due to the intersymbol interference (ISI). The effects of ISI for 30 Gbps and 60 Gbps cases can be seen in the eye diagrams shown in Fig. 4. As the bit rate is increased, they eyes start to close, both horizontally and vertically, which is reflected in the BER results. The ISI penalty in case of 8-PAM increases quickly with the ratio of the symbol rate to the channel bandwidth. The channel had around 20 GHz bandwidth, limited mostly by the photoreceiver and 60 Gbps, (corresponding to 20 Gbaud) is the highest bit rate for which the BER goes below the FEC threshold.

Because the lowest measured BER was well above 10^{-12}, use of FEC would be necessary. For example, a popular Reed-Solomon (RS) code with 8 bits long symbols, 255 symbols long

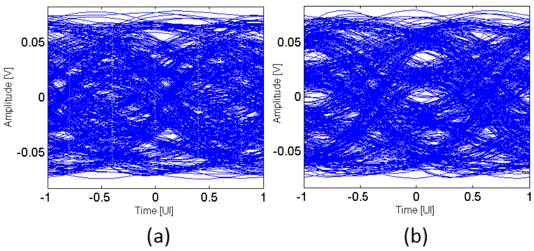

Fig.6: Eye diagram of 4-PAM signal at 40 Gbaud before (a) and after (b) equalization.

codeword and 239 payload symbols in a codeword would suffice. For this code the input BER threshold to reach 10^{-12} at the output is $1.8 \cdot 10^{-4}$. The code has 7% overhead and therefore the effective transmission bit rates with this code, for the 30 Gbps and 60 Gbps would be, respectively, 27.9 Gbps and 55.8 Gbps. In the 75 Gbps case the measured BER does not fall below the FEC threshold of the RS (255, 239).

Results of transmission with 4-PAM

The BER results obtained with 4-PAM at 80 Gbps are shown in Fig. 5. An eye diagram of the captured signal before equalization is shown in Fig. 6a. The symbol rate of 40 Gbaud was twice the channel approximate −3 dB bandwidth and therefore the ISI effects are severe. The symbol levels cannot be distinguished in the signal before equalization. An eye diagram of the signal after off-line equalization is shown in Fig. 6b. The signal quality is improved enough to distinguish the signal levels. The BER results are presented separately for the most-significant bit (MSB) and the least-significant bit (LSB). Because of the natural labeling used, the error probability on the MSB is lower than on the LSB. The labeling is illustrated in the inset to Fig. 2. The value of the MSB (which is the leftmost bit in Fig. 2) changes only between the middle two levels, the value of the LSB changes between every adjacent pair of levels and therefore every symbol error results in an LSB error. Because of the different BER values on the LSB and MSB, they should be coded with different FECs, similarly to what was done in[4]. The MSB and LSB can be coded for example with RS (255, 235) and RS (255, 211). The RS (255, 235) code has 8% overhead and requires input BER of less than $3.3 \cdot 10^{-4}$ to reach output BER below 10^{-12}. The RS (255, 211) code has 17% overhead and the input BER threshold is $2 \cdot 10^{-3}$. With the FEC overhead the effective data rate would be 70 Gbps.

Conclusions

High speed operation of 8-PAM and 4-PAM was demonstrated in a short-link built with an 850 nm VCSEL. It is clear that increased number levels reduces the robustness to ISI and in case of 8-PAM, without equalization, the required system bandwidth is equal to the symbol rate. Equalization of 8-PAM was, however not studied but it would likely enable increased data rates. In case of equalized 4-PAM it was possible to increase the symbol rate to twice the system bandwidth. This shows that a combination of multilevel modulation, equalization and FEC may be a promising approach in the future. If a photoreceiver with larger bandwidth and higher gain integrated amplifier was available, the data rates could be increased.

The RS FEC is a popular choice in many applications. However, in short-range optical communications energy consumption, latency and complexity are important considerations. The RS codes are good at correcting burst errors, because they correct entire symbols which are a few bits long. This is not necessary in typical short-range interconnects. Potentially, binary codes with simpler decoders, and therefore lower power consumption could be used. Latency requirements prevent use of very long codes.

Acknowledgements

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