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Abstract. We report experimental demonstration of 8-PAM transmission using an 850 nm VCSEL and 100 m of OM4-type MMF. The 8-level driving signal was generated using a 3-bit DAC, the error rates were measured in real time using a conventional error analyzer. Maximum uncoded bit rate was 37.5 Gbps, which corresponds to 35.2 Gbps with 7% FEC overhead.

Introduction

The growth of the datacenter industry has created a market for low-cost, short-range, high-speed optical interconnects. Most of the interconnects use transmitters based on vertical cavity surface emitting lasers (VCSELs) operating at the wavelength of 850 nm and multimode fiber (MMF), with OM4-type representing the latest generation of commercial graded-index MMF. The throughput of the commercial short-range optical interconnects was steadily increased by faster components and introduction of parallel interconnects (e.g. as defined for 40 Gbps in IEEE 802.3ba). Another method of increasing the throughput is multilevel modulation. For cost reasons, intensity modulation with direct detection is usually considered. Many modulation formats have been investigated, among them 4-level pulse amplitude modulation[1] (PAM), subcarrier modulation with multiple subcarriers[2], single subcarrier[3] and even half-cycle subcarrier[4]. Reports of experimental demonstrations of 8-PAM transmission are limited to applications using polymer optical fibers at relatively low data rates[5,6]. The biggest advantages of PAM are simplicity and reasonable sensitivity, compared to subcarrier formats.

In this paper we present the results of the first experimental demonstration of 8-PAM transmission at data rates up to 35.2 Gbps in a link based on 850 nm VCSEL and up to 100 m of OM4-type MMF. The experiments were performed without off-line processing and the experimental results are also compared with theoretical predictions.

Multilevel PAM

One of the potential advantages of multilevel modulation is increased density of interconnects due to higher throughput in a single fiber. This, however, comes at the cost of worse sensitivity.

The theoretical BER in case of M-level PAM modulation format, where M is the number of levels, is approximately[7]

$$\text{BER} \approx \frac{d_{avg}}{\log_2(M)} \frac{M-1}{M} \text{erfc}\left(\frac{I_{avg}}{(M-1)\sqrt{2}\sigma}\right), \quad (1)$$

where I_{avg} is the average photodetector current and σ is the root mean square (RMS) noise current. The noise is assumed to be white, Gaussian and additive, which is a case in a system dominated by thermal noise and the symbol levels are assumed to be uniformly spaced. The average Hamming distance between the labels of adjacent symbols is denoted d_{avg}. If Gray labeling is used, $d_{avg} = 1$. If natural labeling is used it is[7]

$$d_{avg} = 2 - \frac{\log_2(M)}{M-1}. \quad (2)$$

For 8-level PAM the sensitivity is 8.45 dB worse than OOK at the same symbol rate, or 6.06 dB worse than OOK at the same bit rate.

Experimental setup

The experiments were performed using a directly modulated VCSEL with 16 GHz modulation band-

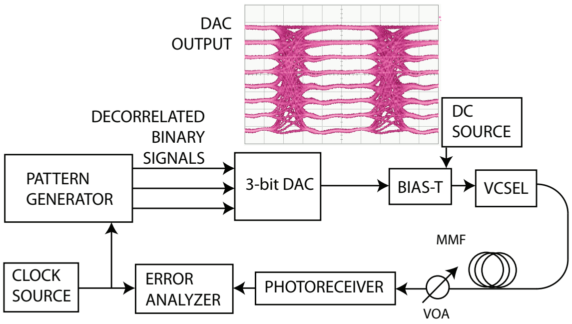

Figure 1. The experimental setup.

width, emitting at the wavelength of 850 nm, OM4-type MMF and a photoreceiver with 10 GHz bandwidth. The 8-PAM electrical signal, which was used to drive the VCSEL via a bias-T, was generated using a 3-bit digital to analog converter (DAC), model SHF 611A. The DAC inputs were generated with a pattern generator. The 8-level output of the DAC corresponds to natural labeling. Error measurements were performed in real time using an ordinary error analyzer, in a manner similar to the BER measurement for 4-PAM[1]. Only the error rate (ER) between the two middle levels was measured. It was assumed that for equal level spacing and dominating thermal noise, the ERs between all adjacent levels are equal. It was also assumed, that the ERs are dominated by the errors between adjacent levels, e.g. receiving the level third when the fourth level was transmitted and vice versa. The symbol error rate (SER) can be calculated from the ER as

$$\mathrm{SER} \approx (M-1)\mathrm{ER}. \qquad (3)$$

The BER can be calculated from the SER,

$$\mathrm{BER} \approx \frac{d_{avg}}{\log_2(M)}\mathrm{SER}. \qquad (4)$$

With $M = 8$, the result is $\mathrm{BER} \approx (11/3)\mathrm{ER}$.

The test setup overview is presented in Fig. 1. The electrical output of the 3-bit DAC at 10 Gbaud is presented in an insert in Fig. 1, showing very good signal quality. The peak-to-peak amplitude of the electrical 8-PAM signal used to drive the VCSEL was around 700 mV. A back-to-back (BTB) configuration was tested, with only a short MMF patchcord, and a link with 100 m of OM4-type MMF. The measured frequency responses for the two configurations are illustrated in Fig. 2. The –3 dB bandwidth of the system is 9.5 GHz for the BTB case, and 9.4 GHz with 100 m of MMF. Since the main bandwidth limiting

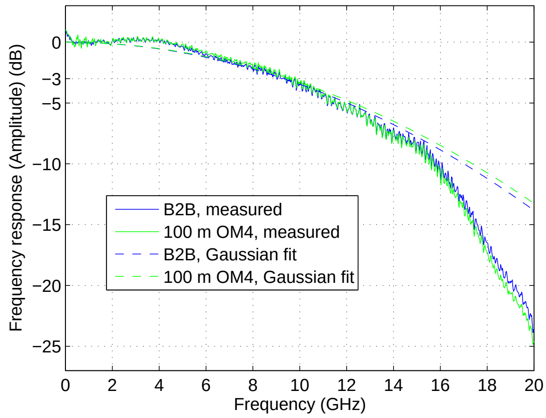

Figure 2. Magnitude of the frequency response of the tested link.

component is the receiver, the shape of the frequency response is approximately Gaussian. Two symbol rates were tested, 10 Gbaud and 12.5 Gbuad, translating into 30 Gbps and 37.5 Gbps uncoded bit rates.

Forward error correction (FEC) was assumed, using the Reed-Solomon code with 255 8-bit symbols long codewords, each with 239 payload symbols, denoted RS(255,239). In case a hard decision bounded distance decoder is used, the required input BER to reach BER=10^{-12} at the output is[8] 1.5×10^{-4}. The introduced FEC overhead reduces the effective bit rates from 30 Gbps to 28.2 Gbps and from 37.5 Gbps to 35.2 Gbps. Current standards concerning datacom applications (e.g. Infiniband or IEEE 802.3ba) do not include FEC, but RS(255,239) is one of the most widely used codes, e.g. used in the ITU-T Recommendation G.709 ”Interfaces for the Optical Transport

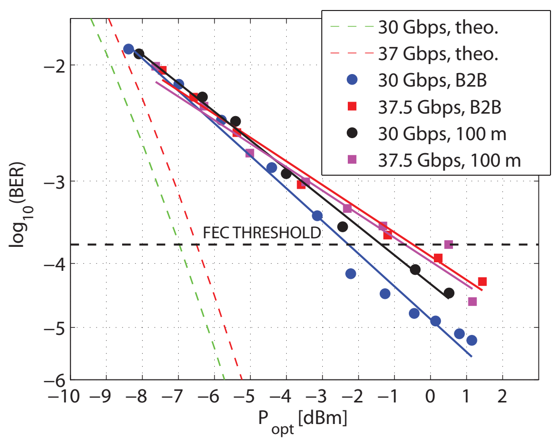

Figure 3. Experimental BER obtained for the 8-PAM for BTB and 100 m at 30 Gbps and 37.5 Gbps uncoded data rates. Theoretical BER with no penalties is included for comparison.

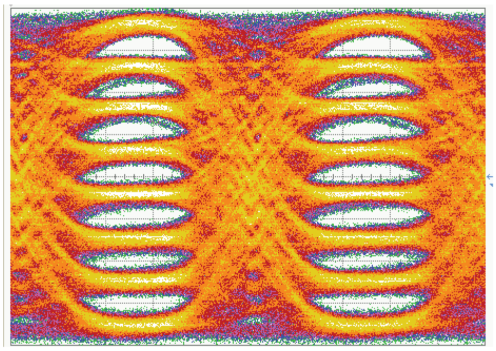

Figure 4. 10 Gbaud 8-PAM eye diagram, after transmission over 100 m of MMF. The vertical scale is 700 mV per division.

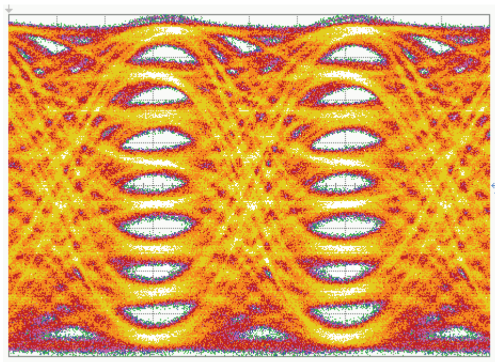

Figure 5. 12.5 Gbaud 8-PAM eye diagram, also after transmission over 100 m of MMF. The vertical scale is the same as in Fig 4.

Network (OTN)".

Results

The system performance was quantified with a measurement of the BER versus the received optical power. The results are presented in Fig. 3. For comparison, theoretical BER curves, obtained using (1), are included. Eye diagrams for the 10 Gbaud and 12.5 Gbaud 8-PAM after transmission over 100 m of OM4-type MMF are shown in Figs. 4 and 5.

There is a considerable implementation penalty at the FEC threshold, compared to the theory. Expected sensitivity at the FEC threshold was about –7 dBm, but in the experiments it turned out to be around –2.5 dBm for 10 Gbaud BTB and –1 dBm at 12.5 Gbaud BTB. The sensitivity penalty between BTB and 100 m transmission is small, which is reasonable given how close the frequency responses of the B2B setup and 100 m link are.

The main reason for the implementation penalty is insufficient modulation signal amplitude which ideally should be around 1.4 V peak to peak, rather than the 700 mV which was available in this experiment. The lower electrical signal amplitude translates to a degradation of the extinction ratio of the optical output of the VCSEL. Assuming that at 1.4 V driving signal amplitude the extinction ratio is near perfect, at 700 mV amplitude the extinction ratio penalty should be around 3 dB[9,Ch. 5.4]. This largely explains the penalty observed in the experimental results.

The eye diagrams show that the eye openings are uniform between each pair of adjacent levels, giving credibility to the assumption that the ERs between each pair of level are similar. Intensity dependent noise cannot be observed in the eye diagrams, which is expected, since the laser has very low relative intensity noise (RIN) of -155 dB/Hz. No ringing or overshoot is present in the eye diagrams and ISI does not seem to contribute greatly to the penalties at 10 Gbaud. In the 12.5 Gbaud case the ISI starts to become limiting factor and the horizontal eye opening is significantly lower than at 10 Gbaud.

Conclusions

We have experimentally demonstrated 8-PAM transmission using a directly modulated VCSEL at up to 35.2 Gbps over 100 m of OM4-type MMF. Because of the implementation penalties, use of FEC would be necessary to provide error free transmission. The sensitivity at the FEC threshold was around –1 dBm at 35.2 Gbbs. The implementations penalties can be reduced by increasing the driving signal amplitude and better co-optimization of the VCSEL bias and the driving signal.

Acknowledgements

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