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Abstract: 100 Gb/s optical fiber transmission link with a single 1.5 um VCSEL has been experimentally demonstrated using 4-level pulse amplitude modulation
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1. Introduction

The rapid growth of Internet and cloud computing applications drives data centers to upgrade their links from the 10 Gb/s commonly used today to 100 Gb/s and beyond in the near future [1] with little or no increase in carbon and real-estate footprint [2]. These two counteracting demands leads to a quest for higher data capacity on short range optical communication systems employing directly modulated (DM) vertical cavity surface emitting lasers (VCSELs); a laser type that is rapidly becoming the preferable laser source for interconnect applications due to an attractive combination of attributes, including high bit rates [3,4], low drive voltage [5], and the capability of array integration [6].

The existing 100 Gb/s standard for short range interconnects (100GE-SR10) specifies the use of 10 wavelengths each operated at 10 Gb/s while the next generation standard (100GE-SR4) employs 4 lasers each operated at 25 Gb/s [7]. Increasing the data modulation of each laser to 100 Gb/s paves the way for a) an increase the total link capacity to 400 Gb/s or to b) a reduction in footprint and complexity of the 100 Gb/s links since they could be operated with a single laser.

In this paper, we report on research investigation on the capabilities of using a single VCSEL to achieve 100 Gbit/s speed transmission. We have performed directly modulation of a VCSEL by employing a 4-levels pulse amplitude modulation (4-PAM) at 25 Gbaud and polarization multiplexing to achieve a total bitrate of 100 Gb/s link with a single VCSEL. Forward error correction coding has been implemented with an effective bit rate of 86.5 Gb/s. Error free transmission in the experiment with $1.6 \cdot 10^{8}$ bits of FEC decoding. This is, to the author knowledge, the largest transmission capacity reported for a single VCSEL source.

2. Experimental Setup

Figure 1 shows the setup of the transmission experiment. Two uncorrelated 25 Gb/s subrate channels of an SHF 12103 A pulse pattern generator (PPG) are added to form a 50 Gb/s 4-PAM signal. The link is analyzed with pseudorandom binary sequences (PRBS) and with 2 different forward error correction (FEC) patterns. The PRBS sequence has a pattern length of 2^{11}-1. The FEC codes have a length of 1138489 bits with 7% overhead, and 152881 bits with 20% overhead. We choose the product code with shortened BCH (Bose – Chaudhuri - Hocquenghem) components [8] as FEC codes in our experiments.

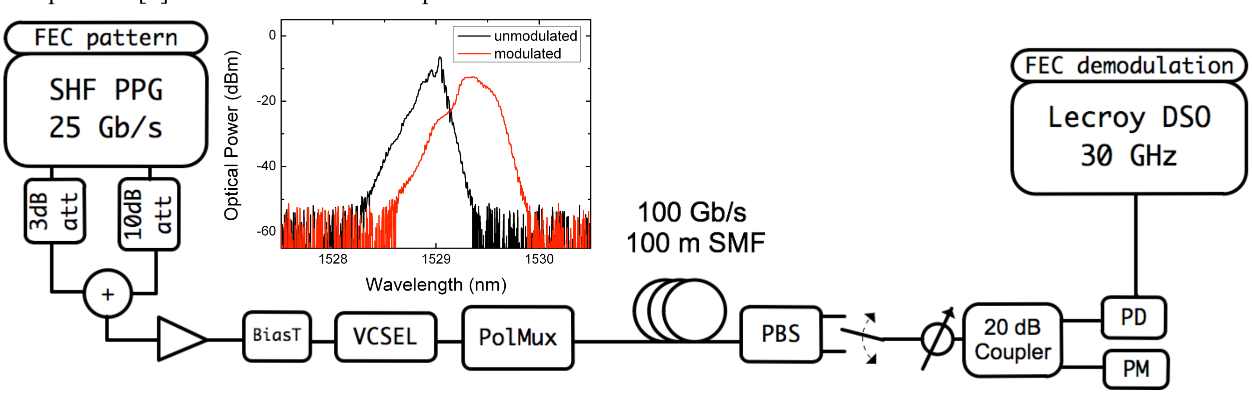

Figure 1. Setup. Pulse pattern generator (PPG), Photodetector (PD), Variable optical attenuator (VOA), Low pass filter (LPF), Power meter (PM), Single mode fiber (SMF), Polarization beam splitter (PBS).

The subchannel addition system is optimized to reduce reflections, and is composed of a 10 dB and a 3 dB electrical attenuator, and a 6 dB electrical combiner. A high-linearity amplifier from SHF is used to amplify the electrical signal up to 1 Vpp in order to utilize the linear region of the VCSEL I-P characteristic curve. L-I-V curve of the VCSEL is shown in Fig. 2.a. The VCSEL used is a high-speed short-cavity VCSEL with 1.55 μm emission wavelength and 3-dB modulation bandwidth of 18 GHz at 20°C. The spectrum of the modulated VCSEL with the 4-PAM signal is shown embedded in Fig. 1. Detailed description of the specific VCSEL characteristics can be found in [9]. The bias of the VCSEL is set to 10 mA for optimum performance. The optical signal from the VCSEL is launched into a polarization multiplexing system with an optical delay between branches to emulate orthogonal polarization transmission uncorrelated at 100 Gb/s. The signal is transmitted over 100 m of standard single mode fiber (SMF). On the receiver side, polarization beam splitter (PBS) separates the two polarizations. Each polarization is detected independently by a 40 GHz photodiode. A Lecroy 30 GHz, 80 Gsa/s digital storage oscilloscope (DSO) is used to store the received signal for offline demodulation. The offline signal demodulation includes bit synchronization and adaptive decision threshold gating.

3. Results

Digital upsampling of the signal to oversampling 10 has been used for better demodulation. Figure 2.b shows the histograms of the optimum sample point of the received signal for different received powers. The histograms show 5000 bits. The minimum points of the histogram for each received power are taken as the symbol decision thresholds. The least significant bit (LSB) and most significant bit (MSB) of each symbol are two uncorrelated patterns. After demodulation, error counting of received LSB and MSB is done independently comparing each bit-stream with the corresponding pattern.

Figure 3.a shows the bit error rate (BER) curve for MSB after 100 m and with back-to-back (B2B) configuration. Figure 3.b shows the BER curves for LSB. We can observe worst performance in LSB as it was expected due to its higher error probability on the symbol. We have used gray mapping to facilitate error correction.

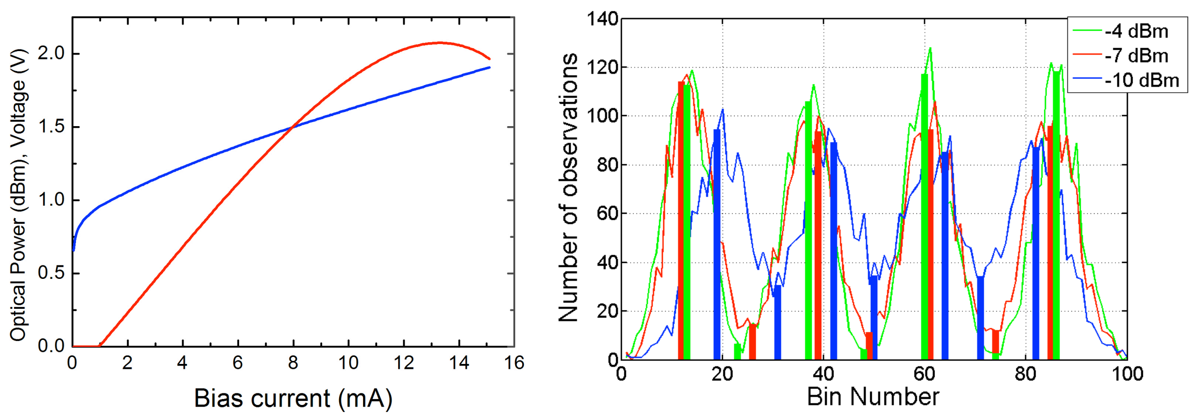

Figure 2. a) LIV curve at 35 °C; b) histogram of optimum sample from received signal

Adaptive FEC:

The theoretical pre-FEC thresholds of 7% overhead and 20% overhead FEC, aiming for after-FEC BER of 10^{-15}, are $4.8\cdot10^{-3}$ and $1.3\cdot10^{-2}$ [10], while in the FEC performance simulation thresholds are approximately $4.4\cdot10^{-3}$ and $1.1\cdot10^{-2}$, respectively, due to BCH decoding errors. The 7% overhead FEC is applied to MSB and the 20% overhead FEC is applied to LSB based on the BER results returned from PRBS sequence tests. Figure 3.a and 3.b show with a blue line the FEC limits for 7% and 20%, respectively. Transmissions below the FEC limit can be decoded without errors. By applying different FEC codes to LSB and MSB, the received power sensitivities for error free demodulation coincide. We processed $1.6\cdot10^{8}$ bits for the FEC decoding for both channels and got error free after the offline demodulation and FEC decoding at -4 dBm received power sensitivity. The adaptive FEC maximizes the effective bitrate for error free transmission. The 7% and 20% overhead of MSB and LSM, respectively, result in a total effective bitrate of 86.5 Gb/s. Due to the limited number of FEC frames we can save on the DSO, we theoretically calculated the error probability in a longer sequence. Based on the theory in [11], as we had 0 errors in the experiment after several FEC decoding iterations, we have, with 90% confidence, that the BER of less than $2.02\cdot10^{-6}$ is expected in repeated experiments. These errors are expected to be corrected after 1 or 2 more iterations due to the small FEC error floor of less than 10^{-15}. Therefore an error free transmission is still expected in a longer time measurement.

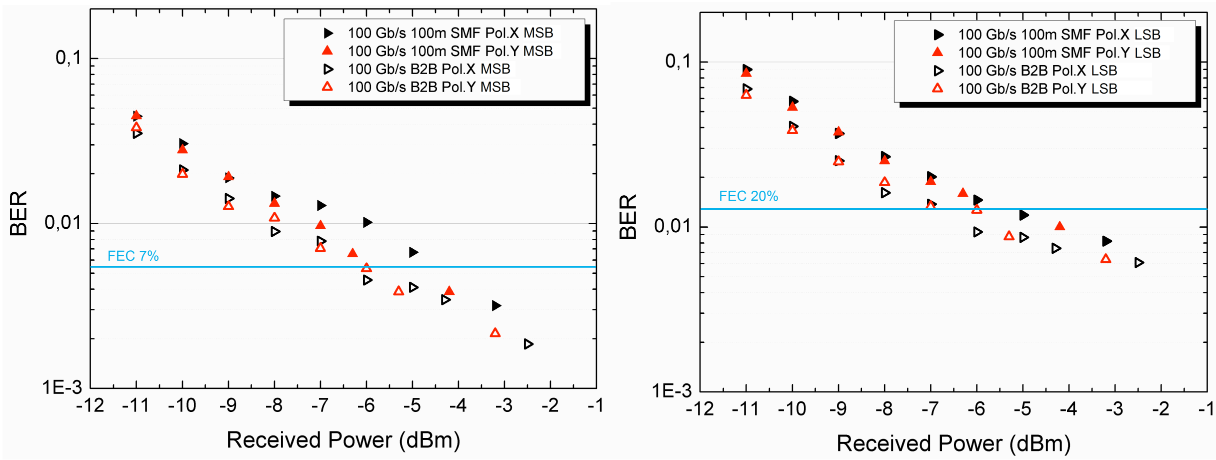

Figure 3. a) BER curves at 100 Gb/s after 100 m SSMF and B2B for MSB, b) BER curves at 100 Gb/s after 100 m SSMF and B2B for LSB

4. Conclusion

Ultimate capacity transmission with a single VCSEL has been investigated by multilevel pulse amplitude modulation and polarization multiplexing over 100 m SMF. We have demonstrated 100 Gb/s transmission with error free transmission after forward error correction with an effective bitrate of 86.5 Gb/s by using adaptive FECs.

5. Acknowledgements

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6. References

[1] Hong Liu; Lam, C.F.; Johnson, C.; , "Scaling Optical Interconnects in Datacenter Networks Opportunities and Challenges for WDM," *High Performance Interconnects (HOTI), 2010 IEEE 18th Annual Symposium on* , vol., no., pp.113-116, 18-20 Aug. 2010.

[2] Strategies for Solving the Datacenter Space, Power, and Cooling Crunch: Sun Server and Storage Optimization Techniques. Oracle White paper, March 2010.

[3] Hofmann, W.; Müller, M.; Wolf, P.; Mutig, A.; Gründl, T.; Böhm, G.; Bimberg, D.; Amann, M.-C.; , "40 Gbit/s modulation of 1550 nm VCSEL," *Electronics Letters* , vol.47, no.4, pp.270-271, February 17 2011

[4] Hofmann, W.; Moser, P.; Wolf, P.; Mutig, A.; Kroh, M.; Bimberg, D.; , "44 Gb/s VCSEL for optical interconnects," *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference* , vol., no., pp.1-3, 6-10 March 2011

[5] Moser, P.; Hofmann, W.; Wolf, P.; Fiol, G.; Lott, J.A.; Ledentsov, N.N.; Bimberg, D.; , "83 fJ/bit energy-to-data ratio of 850-nm VCSEL at 17 Gb/s," *Optical Communication (ECOC), 2011 37th European Conference and Exhibition on* , vol., no., pp.1-3, 18-22 Sept. 2011

[6] Hofmann, W.; Gorblich, M.; Bohm, G.; Ortsiefer, M.; Xie, L.; Amann, M.-C.; , "Long-wavelength 2-D VCSEL arrays for optical interconnects," Lasers and Electro-Optics, 2008 and 2008 Conference on Quantum Electronics and Laser Science. CLEO/QELS 2008. Conference on , vol., no., pp.1-2, 4-9 May 2008

[7] Cole Chris, "Next generation 100G client optics," *Optical Communication (ECOC), 2011 37th European Conference and Exhibition on* , workshop 13, 18-22 Sept. 2011

[8] Bomin Li, Knud J. Larsen, Darko Zibar and Idelfonso Tafur Monroy, "Over 10 dB Net Coding Gain Based on 20% Overhead Hard Decision Forward Error Correction in 100G Optical Communication Systems," in Proc. 37th European Conf. and Exhibition on Optical Communication, Geneva, 2011.

[9] M.-C. Amann, E. Wong, M. Mueller, "Energy-efficient High-Speed Short-Cavity VCSELs", Proc. OFC/NFOEC, paper OTh4F, Los Angeles, Ca, USA March 2012.

[10] J. Justesen, "Performance of Product Codes and Related Structures with Iterated Decoding" in IEEE Trans. Commun. 59, 2, 407-415 (2011).

[11] J. L. Massey, "Comparison of Rate One-Half, Equivalent Constraint Length 24, Binary Convolutional Codes for Use with Sequential Decoding on the Deep-Space Channel", Technical Report No. EE-762, University of Notre Dame, Indiana 46556, USA, 1976