726.7-Gb/s 1.5-µm Single-Mode VCSEL Discrete Multi-Tone Transmission over 2.5-km Multicore Fiber

J. Van Kerrebrouck[1], L. Zhang[2,3], R. Lin[2,5], X. Pang[2,4], A. Udalcovs[4], O. Ozolins[4], S. Spiga[6], M. C. Amann[6], G. Van Steenberge[7], L. Gan[5], M. Tang[5], S. Fu[5], R. Schatz[2], S. Popov[2], D. Liu[5], W. Tong[8], S. Xiao[3], G. Torfs[1], J. Chen[2], J. Bauwelinck[1] and X. Yin[1]

[1] IDLab, INTEC, Ghent University – imec, Gent, Belgium. Email: xin.yin@ugent.be
[2] KTH Royal Institute of Technology, Kista, Sweden
[3] SE-IEE, Shanghai Jiao Tong University, Shanghai, China
[4] Networking and Transmission Laboratory, RISE Acreo AB, Kista, Sweden
[5] Huazhong University of Science and Technology, Wuhan, China, tangming@hust.edu.cn
[6] Walter Schottky Institut, Am Coulombwall 4, Garching
[7] CMST, INTEC, Ghent University – imec, Belgium
[8] Yangtze Optical fiber and Cable Joint Stock Limited Company, Wuhan, China

Abstract: A 107Gb/s net-rate DMT optical signal was generated using a single-mode long-wavelength VCSEL with a modulation bandwidth of 23GHz. We experimentally demonstrated a total net-rate up to 726.7Gb/s at 1.5µm over 2.5km 7-core dispersion-uncompensated MCF.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications

1. Introduction

Low-cost transmission systems at data rate of 100 Gb/s and beyond are highly demanded to meet the increasing capacity requirements in datacenter applications. Intensity modulation and direct detect (IM/DD) systems are preferable for large deployment because of its low complexity and cost, especially for intra-datacenter short-reach optical links up to 2 km.

Currently, vertical-cavity surface-emitting laser (VCSEL) based optical links are among the simplest solutions to realize cost-effective and power-efficient for high performance computing (HPC) and datacenters. 100 Gb/s transmissions were experimentally demonstrated employing short-wavelength VCSELs and multimode fibers (MMF), together with advanced modulation formats, such as pulse amplitude modulation (PAM), discrete multi-tone (DMT), or carrier-less amplitude and phase modulation (CAP) [1-3]. However, the bandwidth of MMF prohibits a sufficiently long transmission distance, restraining the transmission reach to a few hundred meters. Meanwhile, long-wavelength (LW) single-mode (SM) VCSELs have gained a lot of interests thanks to the lower power consumption and losses in silica-based optical fibers [4], which is desired in long term to support future mega-datacenter fiber plants. A 74.8 Gb/s net-rate LW SM VCSEL link was demonstrated in real-time with 3-level duo-binary (EDB) modulation [5]. Xie et al. achieved a net data rate of 87.5 Gb/s over 500-m SSMF (79.2 Gb/s over 4 km) at 20% overhead HD-FEC with DMT using a 1.5 µm VCSEL [6]. And recently, 81.6-Gb/s net-rate PAM-4 transmission was demonstrated over 1.6-km SSMF, with a 20-GHz bandwidth SM VCSEL at 1525 nm [7].

Another promising technique to meet high-capacity required by datacenters is multicore fiber (MCF). MCF can provide much more capacity within a single fiber, and significantly reduce network capital expenditure (CapEx)[8]. In this paper, we have demonstrate DMT of 107 Gb/s net-rate (gross 114 Gb/s) using a 1.5 µm SM VCSEL, with direct modulation bandwidth of 23GHz. After 2.5 km SSMF transmission, the maximum achieved net-rate is 105 Gb/s (gross 112.3 Gb/s). To the best of our knowledge, this is the highest DMT net bit-rate ever achieved with a single SM LW-VCSEL. Moreover, with a combination of the new 23-GHz SM LW-VCSEL device and a 7-core dispersion-uncompensated MCF, we have shown that a total net-rate up to 726.7 Gb/s (gross 777.5 Gb/s) over 2.5 km transmission distance is achievable.

2. 23-GHz 1.5 µm SM VCSEL and experimental setup

The experimental probing setup and VCSEL structure are shown in Figure 1. The 1.5 µm SM InP-based VCSEL uses an ultra-short semiconductor cavity (~1.5 µm) and two distributed Bragg reflectors (DBRs) to enhance its bandwidth [4]. The optical gain is provided by an active region with seven AlGaInAs quantum wells and current confinement is achieved by a p+ –AlGaInAs/n+ –GaInAs buried tunnel junction (BTJ). The reduced cavity length allows us to minimize the photon lifetime by maintaining single-mode operation, and an involved doping profile has been used to overcome parasitic limitations and thermal issues. Figure 1 (a) and Figure 1 (b) show the measured P-I-V curves of the VCSEL and the small-signal S21 responses. This 1.5 µm SM VCSEL shows an impedance of 54Ω @ 10 MHz and 63Ω @ 10 GHz. The threshold current is ~1.5 mA. The maximum bandwidth of 23.3 GHz and an optimum flat response is reached with a bias current of around 7-8 mA, where however the VCSEL optical output power starts to degrade due to saturation, Figure 1 (a).

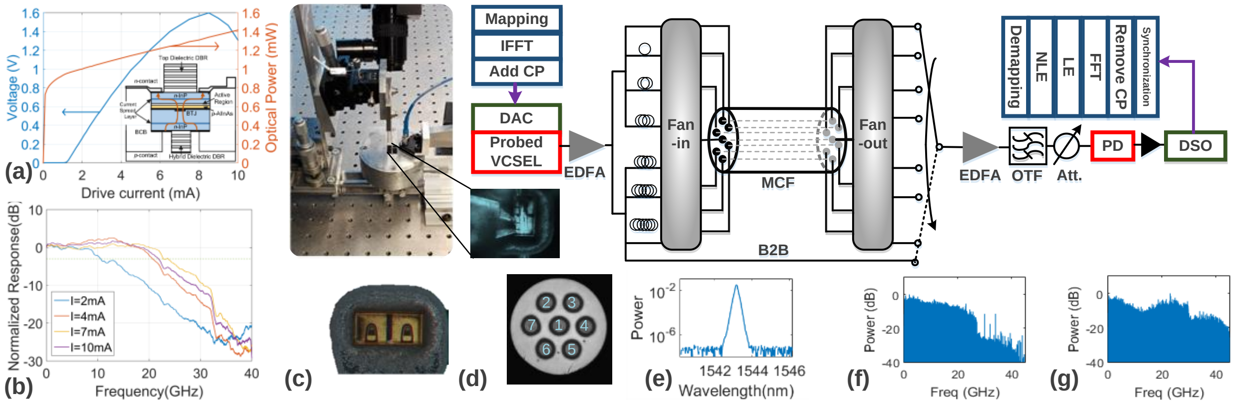

Figure 1 Experimental Setup (a) VCSEL structure and power-current-voltage (PIV) characteristic, (b) VCSEL S21 measurements for different bias currents (c) VCSEL chips, (d) 7-core MCF, (e) filtered optical spectrum, (f) received electrical spectrum of DMT signal at optical B2B case, (g) received electrical spectrum of DMT signal after 2.5km MCF transmission.

The digital signal processing (DSP) flow of the experiments is also shown in Figure 1. The DMT signals were generated with MATLAB and loaded into 92 GSa/s digital to analog converter (DAC, Keysight AWG M8196A). The length of the inverse fast Fourier transform (IFFT) and cyclic prefix were set to 1024 and 16, respectively, and the first subcarrier was set to null. The linear channel equalization (LE) pilot ratio was 3.3%. Volterra nonlinear equalization (NLE) was used to compensate the VCSEL nonlinearity and the algorithm memory length was 10. The clipping ratio was set to 0.7 to improve the output signal to noise ratio (SNR) from the DAC. The output amplitude of the DAC was 720 mV (peak-to-peak).

The VCSEL (Figure 1 (c)) bias current was set to 7.8 mA as a trade-off between bandwidth, linearity and output optical power. There was no temperature controller (TEC) used in the setup. The measured central wavelength was 1543.2 nm and the captured output power of VCSEL was 1 dBm. The VCSEL on its probing platform is shown in the inset of Figure 1. The directly modulated signal was fed into the booster Erbium-doped optical fiber amplifier (EDFA) with 14.8dBm power output. The signal was split in a custom fan-in module (-55 dB crosstalk) of a 2.5 km 7-core MCF (The cladding diameter of the hexagonal MCF is 150 μm and the core pitch is set as 42 μm, inset (d) of Figure 1) using one 1:2 optical coupler cascaded with two 1:4 optical couplers, where the last port was used for optical back-to-back (B2B) measurements. The optical delay lines were used to decorrelate the signals to emulate a practical system using seven independently modulated VCSELs. The multi-core crosstalk of the MCF is around -45 dB/100 km, the loss is less than 0.20 dB/km at 1550 nm, and the dispersion is 17.1 ps/nm/km.

After the MCF transmission, the signals were detected individually after a fan-out module and there was no dispersion compensation fiber after the MCF. It was amplified by an EDFA and an optical tunable filter (OTF) was utilized to filter out the amplified spontaneous emission (ASE) noise; the filtered optical spectrum is shown in inset (e) of Figure 1. A 90-GHz PIN photodetector (PD) was used at the receiver. A variable optical attenuator (VOA) was used before the PD for bit error rate (BER) curves. In a real implementation, the EDFA and VOA can be omitted when a TIA with a sufficient gain is used. The electrical signal from direct-detection was captured by a 160 GS/s digital storage oscilloscope (DSO) and amplified by a 65 GHz linear electrical amplifier with 11-dB gain. The samples from the oscilloscope are processed offline. The received electrical spectrum of the DMT signal for the optical B2B case and for 2.5 km MCF transmission are shown as insets (f)-(g) in Figure 1.

3. Results and discussions

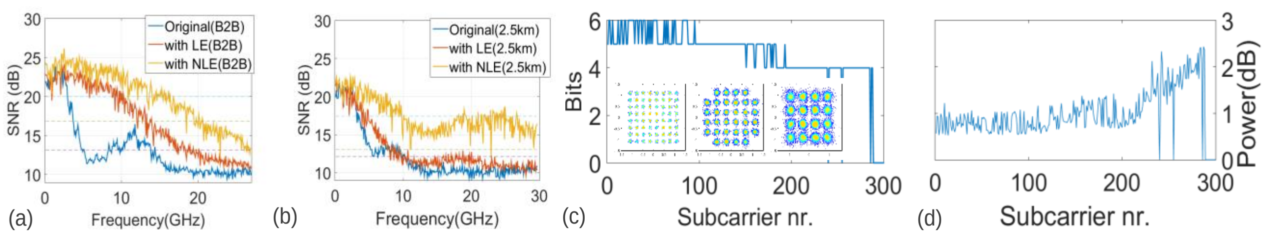

Figure 2 (a) SNR versus frequency with equalizations for B2B, (b) SNR for 2.5km, (c) Bit loading profile, (d) power loading profile at B2B.

The SNR without and with MCF transmission were probed by sending 16-QAM modulated DMT signals with 300 and 330 subcarriers, respectively. The SNR of the optical B2B case with 7 dBm received optical power is shown in

Figure 2 (a) and the SNR of the MCF's worst core (core 4) after 2.5 km transmission is shown in Figure 2 (b). The average SNR of the B2B case is 13.16 dB and it is improved to 16.87 dB after LE and further improved to 20 dB after NLE. Comparatively, the average SNR of 2.5km MCF transmission is 12.1 dB and it is improved to 13.1 dB after linear equalization and to 17.4 dB after NLE. Thus, NLE is effective in compensating the link nonlinearities which otherwise cause inter-subcarrier mixing.

From the results of Figure 4 (a,b), it can be observed that the B2B case is a low-pass channel with more than 10dB attenuation. Thus, bit-power loading can help with improving the system capacity and spectrum efficiency. By contrast, there is only ~ 5 dB of SNR variation of 2.5 km MCF and the jitter of SNR is severe. So, bit-power loading will not help much and 16QAM with 330 subcarriers were used for demonstration. The bit-power loading profile of the B2B case is shown in Figure 2 (c,d). The B2B net rate is increased from 94.3 Gb/s (gross 100.9 Gb/s) to 106.9 Gb/s (gross 114.4 Gb/s).

In Figure 3, it can be seen that the performance with NLE for the VCSEL link is significantly improved compared to the ones without equalization and with LE. The constellations of the worst core without equalization, with LE and NLE are shown in the insets (b)-(d) of Figure 3. The measured BER in function of the received optical power (RoP) at the PD input is shown in Figure 3 (a). The BER Lower than the threshold of the 7% HD-FEC of 3.8E-3 is achieved with NLE. The achieved gross bit rate is 114.4 Gb/s for the B2B case. As shown in Figure 3 (e), for 2.5 km MCF transmission, we have achieved gross-rates of 110.9-Gb/s, 112.3-Gb/s, 112.3-Gb/s, 109.3-Gb/s, 110.9-Gb/s, 110.9-Gb/s, and 110.9-Gb/s, respectively. The total system capacity with 2.5-km MCF is about 777.5 Gb/s (net rate 726.7 Gb/s).

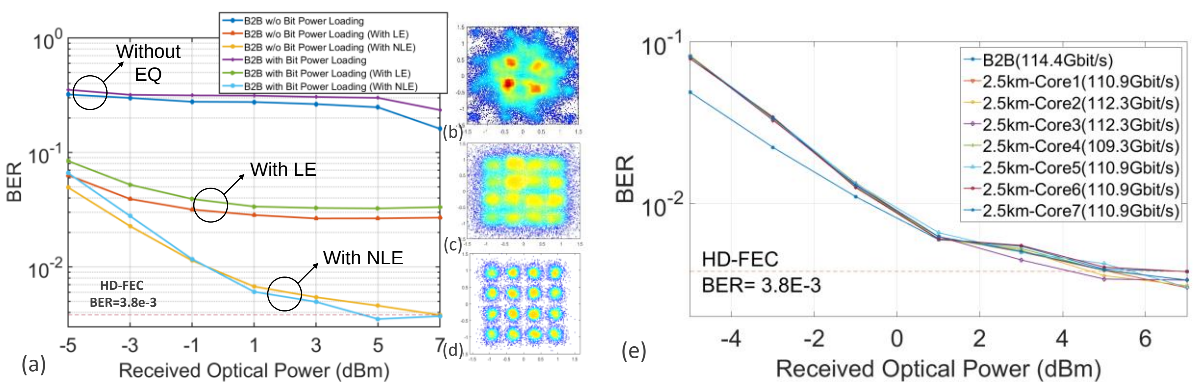

Figure 3 Performance comparison: (a) BER versus received optical power (Rop) with various equalizations.(b) constellation diagram without any equalization, (c) with LE and (d) with NLE. (e) BER versus RoP with and without 2.5km MCF transmission.

4. Conclusions

We experimentally demonstrated that a long-wavelength single-mode VCSEL transmitter can be used for data transmission up to a record net rate of 107 Gb/s, with DMT and direct detection. Using a 7-core dispersion-uncompensated MCF, the achieved maximal aggregated net data rate, excluding the 7% FEC overhead, is 726.7 Gb/s (gross 777.5 Gb/s) over 2.5 km at 1543 nm.

5. Acknowledgements

This work was partly supported by the European Commission through the FP7 project MIRAGE (ref.318228), Swedish Research Council (VR), the Swedish Foundation for Strategic Research (SSF), Göran Gustafsson Foundation, and Swedish ICT-TNG.

6. References

[1] F. Karinou et al., "112 Gb/s PAM-4 Optical Signal Transmission over 100-m OM4 Multimode Fiber for High-Capacity Data-Center Interconnects," M2C.2, ECOC 2016.
[2] C. Kottke et al., "High Speed 160 Gb/s DMT VCSEL Transmission Using Pre-equalization," W4I.7, OFC 2017.
[3] W. Bo et al., "Single-Lane 112Gbps Transmission over 300m OM4 Multimode Fiber Based on A Single-Transverse-Mode 850nm VCSEL," Th2P2SC4, ECOC 2016
[4] S. Spiga et al., "Single-Mode High-Speed 1.5-µm VCSELs," JLT, vol. 35, no. 4, pp. 727-733, 2017.
[5] X. Yin et al., " Towards efficient 100 Gb/s serial rate optical interconnects: A duobinary way," 2017 IEEE Optical Interconnects Conference (OI), pp. 33-34.
[6] C. Xie et al., " Single-VCSEL 100-Gb/s short-reach system using discrete multi-tone modulation and direct detection," OFC 2015, pp. 1-3.
[7] N. Eiselt et al., " Experimental Demonstration of 84 Gb/s PAM-4 Over up to 1.6 km SSMF Using a 20-GHz VCSEL at 1525 nm," JLT, vol. 35, no. 8, pp. 1342-1349, 2017.
[8] Y. Li et al., "CapEx advantages of multi-core fiber networks," Photonic Network Communications, Vol. 31, pp 228–238, 2016.