Up to 600 Gbit/s data transmission over 100 m of single multi-mode fiber using 4×λ 850-940 nm VCSELs

N. Ledentsov Jr.[1,2], C. Kottke[3], Ł. Chorchos[1,2], V.A. Shchukin[1], O. Yu. Makarov[1], M. Bou Sanayeh[1], V.P. Kalosha[1], V. Jungnickel[3], R. Freund[3], J. P. Turkiewicz[2], N. N. Ledentsov[1]

1 VI Systems GmbH, Hardenbergstr. 7, 10623 Berlin, Germany, nikolay.ledentsov-jr@v-i-systems.com
2 Warsaw University of Technology, Nowowiejska 15/19, 00-661 Warsaw, Poland
3 Fraunhofer Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin, Germany

Abstract: We demonstrate parallel high speed data transmission over single multimode fiber using VCSELs operating in the SWDM wavelength range (850 nm – 940 nm). Total demonstrated throughput of such system reaches 500 Gbit/s with 4-PAM modulation and 600 Gbit/s with DMT modulation.

OCIS codes: (060.2330) Fiber Optic Communications; (060.2360) Fiber Optic Links and Subsystems; (140.7260) VCSELs

1. Introduction

Growth in datacenter and cloud computing demands an increase in the density and throughput of optical interconnects. Wavelength division multiplexing is broadly applied in telecom systems since 1990s [1]. In short reach interconnects, an emergence of OM5 wideband fiber [2] opened an opportunity to use Short Wavelength Division Multiplexing (SWDM) in the 850-940 nm wavelengths range. State-of-the-art directly modulated 850 nm VCSELs can achieve up to 224 Gbit/s single channel data transmission with Discrete Multi-Tone (DMT) modulation [3] and 164 Gbit/s with 4 level Pulse Amplitude Modulation (PAM-4) [4]. Previous studies of VCSEL transmission in this wavelength range showed the feasibility of 100 Gbit/s 4-PAM transmission for each individual wavelength [5]. Through the use of VCSELs with increased bandwidth data rates above 100 Gbit/s could be demonstrated [6].

In this work we study simultaneous data transmission of 4xλ high bandwidth VCSELs over a single OM5 fiber.

2. Performance of transmitters based on 28 GHz VCSELs

During the tests performed in this work, compact VCSEL modules were used. These modules consisted of a VCSEL wire-bonded to a high-frequency connector with very short wires, coupled into 1m long OM3 MMF capable. The modules are capable of high-speed operation without additional electronics. In the initial test these modules were directly attached to an SHF bit pattern generator, while the high-speed receiver integrated in a Tektronix sampling oscilloscope with was used at the receiver side. (Figure 1)

The VCSELs studied have high bandwidth >28 GHz and are capable of 50 Gbit/s NRZ modulation without equalization or signal processing (Figure 1). As can be seen from the eye-diagrams, the 940nm VCSEL has the slowest rise time and lower bandwidth compared to other devices, which does not influence the NRZ data transmission too much but will play a larger role in the PAM experiments.

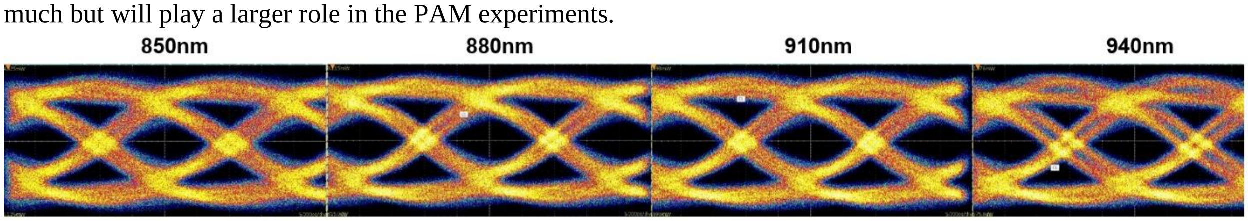

Figure 1. Unequalized 50Gb/s NRZ eye-diagrams acquired individually on 850 nm – 940 nm VCSELs operated at 5 mA.

3. Experimental setup

During the PAM and DMT transmission experiments, each VCSEL was directly driven by individual channel of the Keysight M9502A AWG. The electrical signal in the AWG was pre-equalized to compensate for the electrical channel response of the channel, additional equalization to compensate for the optical components was applied consistent with previous publications [4]. Signal generation for the DMT modulation is described in Ref. [3].

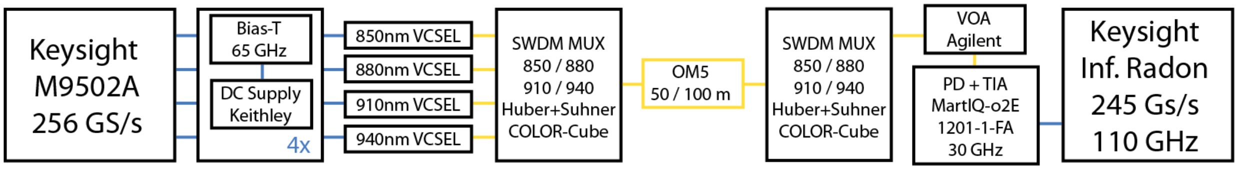

Figure 2. Experimental setup

Fiber outputs of the VCSEL modules were connected through an optical isolator to a SWDM multiplexer (Huber+Suhner COLOR-Cube). The output of the combiner was connected to a OM4 fiber of up to 100 m length. At the receiver side, a SWDM de-multiplexer with ~30 dB separation between the channels was used. Each output of the demultiplexer was connected to a variable optical attenuator (VOA) and a high-speed receiver (MatrIQ-O2E 1201-1-FA, 30 GHz) with low noise amplifier (SHF 804 TL, 55 GHz). The signal was acquired with a Keysight Real Time Oscilloscope (Infinium Radon, 245 Gs/s 110 GHz). Figure 2 shows the experimental setup. Due to the availability of the components on the receiver side, while all channels were active during the measurements, only one individual channel was measured at a single time. Another deficiency of the setup is a peak at 30 GHz in the electrical characteristic of the system (Fig. 6) that influenced the BER especially at the DMT modulation.

4. Crosstalk

Figure 3 shows BER measured on an individual channel in cases where a) only one laser was active and b) all lasers were modulated simultaneously. On all channels, the presence of the signals from other lasers has no influence on the measured BER on the selected channel. It can be concluded that crosstalk does not impair the system, which is also expected due to the relative high DEMUX isolation.

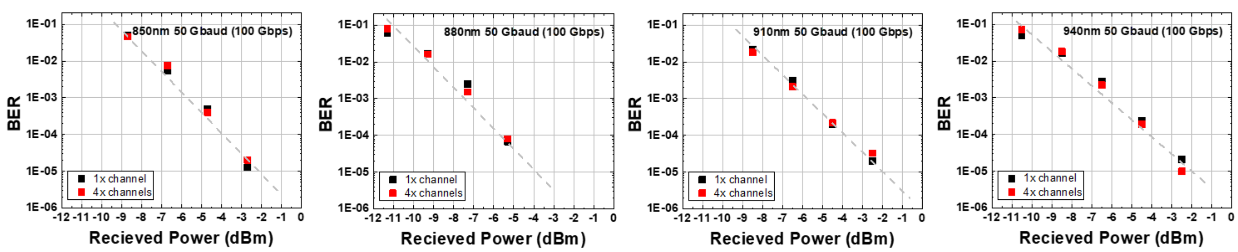

Figure 3.BER measured on individual channels with other VCSELs turned on and off.

4. Data transmission

Figure 4 shows PAM-4 eye-diagrams at 50 Gbaud (100 Gbit/s) data transmission through 50m of OM5 fiber realized in the setup. The eye diagrams are open consistent with reference eye diagrams acquired under 50 Gbaud NRZ modulation (Fig. 1).

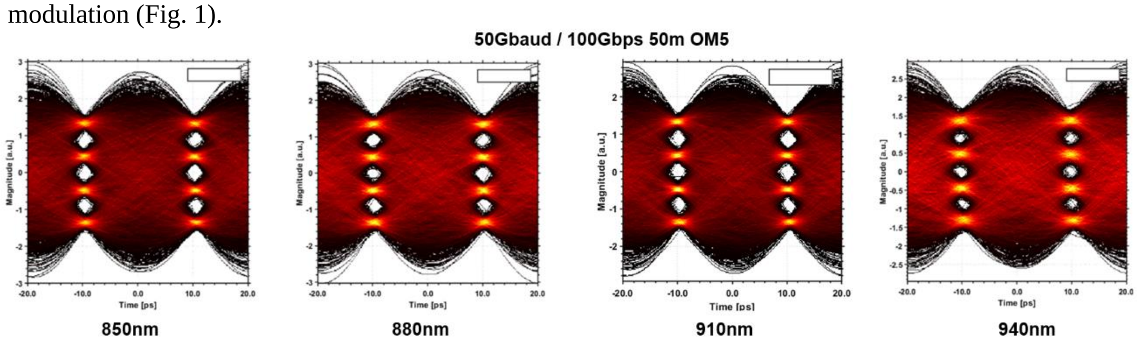

Figure 4. 50 Gbaud (100 Gbit/S) PAM4 eye diagrams acquired on directly modulated VCSEL modules in the 850nm – 940 nm range after transmission to 50 m of OM5 MMF.

At 50 Gbaud (100 Gbit/s) and 60 Gbaud (120 Gbit/s), 100 m data transmission could be achieved for all channels with BERs below 3.8E-3 HD-FEC level [7]. Data transmission up to 64 Gbaud (128 Gbit/s) could be realized with transmission distance up to 50m with BER below 7% HD FEC level. Due to reduced bandwidth of the 940 nm VCSEL, 100 m transmission at 64 Gbaud could be achieved for this VCSEL with BERs compatible with 20% SD-FEC [8], while other channels showed BER below HD-FEC level. (Figure 5)

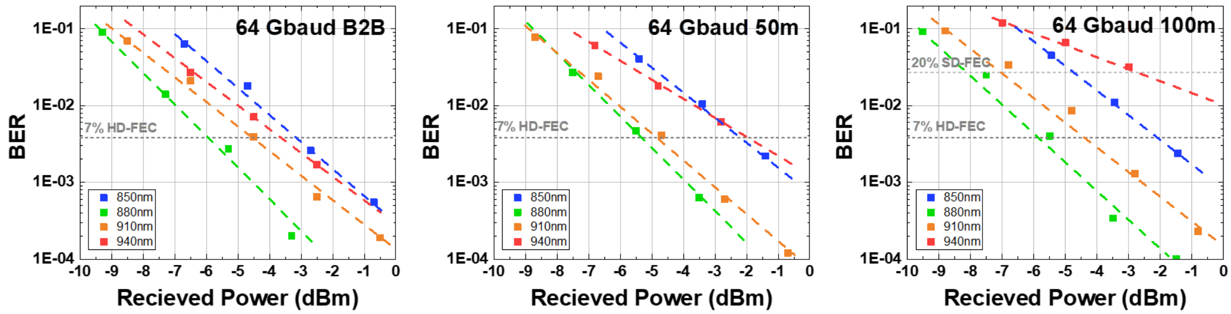

Figure 5. BER measurements for 64 Gbaud PAM-4 (128 Gbit/s) data transmission through ~2m, 50m and 100m of OM4 fiber.

Figure 6.a shows back-to-back signal to noise (SNR) ratio of the electrical path of the system and SNR on each individual optical channel. Among effects limiting the data throughput are the optical bandwidth of the VCSELs, increased noise due to optical reflections at low frequencies and a 30 GHz peak originating in the electrical path.

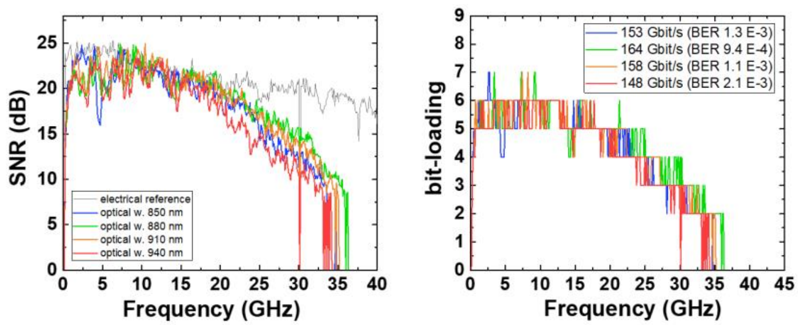

Figure 6. a) Signal to noise (SNR) ratio b) bit loading and BER measured for DMT signals with gross data rate around 150 Gbit/s.

Figure 6.b. shows bit-loading for each individual channel applied for the DMT data transmission experiment. Around 150 Gbit/s signals could be generated on each channel. A combined throughput of 600 Gbit/s can be thus achieved with BER < HD-FEC level and potentially above that with SD-FEC.

4. Conclusion

We have demonstrated a parallel 4×λ VCSELs link in the 850-940 nm spectral range modulated with PAM-4 at 60-64 Gbaud through a100 m-long single MMF resulting in a total throughput of ~500 Gbit/s. With DMT modulation a gross throughput of 600 Gbit/s could be achieved with BER below HD-FEC level.

5. References

[1] C. A. Brackett, "Dense wavelength division multiplexing networks: Principles and applications." IEEE Journal on Selected areas in Communications, vol. 8, no. 6, pp. 948-964 (1990).
[2] D. Molin et al., "WideBand OM4 multi-mode fiber for next-generation 400Gbps data communications", ECOC 2014, Cannes (2014).
[3] N. Ledentsov Jr, et al. "Serial data transmission at 224Gbit/s applying directly modulated 850 and 910nm VCSELs." Electronics Letters, vol. 57, no 19, pp. 735-737 (2021).
[4] J. Lavrencik, et al., "168Gbps PAM-4 multimode fiber transmission through 50m using 28GHz 850nm multimode VCSELs." In 2020 Optical Fiber Communications Conference and Exhibition (OFC) (2020).
[5] J. Lavrencik, et al., "Scaling VCSEL-MMF links to 1 Tb/s using short wavelength division multiplexing." Journal of Lightwave Technology, vol. 36, no. 18, pp. 4138-4145 (2018).
[6] N. N. Ledentsov, et al., 'Anti–waveguiding vertical–cavity surface–emitting laser at 850 nm: From concept to advances in high–speed data transmission', Opt. Express, vol. 26, no. (1), pp. 445-453 (2018).
[7] M. N. Sakib, et al., 'Study of Error Correction Codes for PAM Signals in Data Center Applications', IEEE Photon. Technol. Lett., vol. 25, no. 23, pp. 2274-2277 (2013).
[8] D. Chang, et al., 'LDPC convolutional codes using layered decoding algorithm for high speed coherent optical transmission', Optical Fiber Communication Conference, USA, p. OW1H4 (2012).