50 Gb/s NRZ data transmission over OM5 fiber in the SWDM wavelength range

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ABSTRACT

The development of advanced OM5 wideband multimode fiber (WBMMF) allowing high modal bandwidth in the spectral range 840-950 nm motivates research in vertical-cavity-surface-emitting-lasers (VCSELs) at wavelengths beyond the previously accepted for short reach communications. Thus, short wavelength division multiplexing (SWDM) solutions can be implemented as a strategy to satisfy the increasing demand of data rate in datacenter environments. As an alternative solution to 850 nm parallel links, four wavelengths with 30 nm separation between 850 nm and 940 nm can be multiplexed on a single OM5-MMF, so the number of fibers deployed is reduced by a factor of four.

In this paper high speed transmission is studied for VCSELs in the 850 nm – 950 nm range. The devices had a modulating bandwidth of ~26-28 GHz. 50 Gb/s non-return-to-zero (NRZ) operation is demonstrated at each wavelength without pre-emphasis and equalization, with bit-error-rate (BER) below 7% forward error correction (FEC) threshold. Furthermore, the use of single-mode VCSELs (SM-VCSELs) as a way to mitigate the effects of chromatic dispersions in order to extend the maximum transmission distance over OM5 is explored.

Analysis of loss as a function of wavelength in OM5 fiber is also performed. Significant decrease is observed, from 2.5 dB/km to less than 1.8 dB/km at 910 nm wavelength of the VCSEL.

Keywords: vertical cavity surface–emitting laser, fiber, data transmission.

1. INTRODUCTION

Datacenters are constantly driven toward faster data transmission speeds due to explosive growth of the internet, cloud and mobile applications, internet of things and autonomous driving. Current mainstream technology for short reach data transmission consists of Multi-Mode Vertical-Cavity-Surface-Emitting-Lasers (MM VCSELs) coupled into OM3 and OM4 multimode fibers (MMFs) specified for transmission of 850 nm light.

Next generation Ethernet standard includes a new wideband multimode fiber OM5 that has high Effective Modal Bandwidth (EMB) characteristics specified for wavelengths from 850 nm to 953 nm. The specified minimum EBM of OM5 spans from 4700 MHz·km for 850 nm to 2470 MHz·km for 953 nm light. [1],[2] Wideband MMFs show even higher bandwidths because they are optimized to have peak EMB at 875 nm, drastically improving the performance for longer wavelengths. [3]

This kind of fiber makes use of Short Wavelength Division Multiplexing (SWDM) applications possible, allowing quadrupling of the data transmitted through single MM fiber link.

This development creates a demand for fast and energy efficient light sources in this wavelengths range, specifically, to reduce crosstalk and enable independent detection of four channels - 850 nm, 880 nm, 910 nm and 940 nm.

850 nm VCSEL technology is up to date the most developed one due to its long history of commercialization in datacom applications. State of the art 850 nm VCSELs operated with On-Off Keying (OOK) Non-Return-to-Zero (NRZ) modulation are reported to reach 71 Gb/s transmission.[4] Data rates at about and beyond 100 Gb/s can be reached applying

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high order modulation formats such as pulse–amplitude modulation (PAM), discrete–multitone modulation (DMT) or carrierless amplitude/phase modulation (CAP). Record speed of 160 Gb/s per single VCSEL has been demonstrated using DMT modulation, while 148Gb/s, 112.5 Gb/s, 112 Gb/s and 90 Gb/s have been reported using duobinary 4-PAM, multi-CAP, 4-PAM and 8-PAM respectively. [5],[6],[7],[8]

940 nm VCSELs are shown to be capable of 50 Gb/s NRZ transmission recently, while 880 nm and 910 nm VCSELs are discussed mostly in SWDM content. [9]

High speed SWDM operation reported up to date is achieved in combination with electronic signal processing. First link with use of VCSELs of four wavelengths with aggregated speed above 200 Gb/s was demonstrated with 4-PAM signals 25.78125 Gbaud each using strong equalization techniques. [10] At the same time a SWDM link with NRZ transmission was reported to reach 100 Gb/s with 4x25 Gb/s VCSELs packaged into SFP+ modules including clock data recovery (CDR). [11] Shortly thereafter 200 Gb/s data rate was reached with 4x50 Gb/s NRZ modulation, with equalization on both TX and RX. [12]

Developments in VCSEL technology discussed in this paper allow reaching back-to-back transmission of 50 Gb/s for all four wavelengths of the SWDM range without electronic signal processing. Use of Single-Mode (SM) VCSELs with very narrow spectral widths allows to increase the link length to several kilometers of MMF.

2. EXPERIMENT

The transmission experiments were performed on the chip level with a VCSEL probe station (Figure 1).

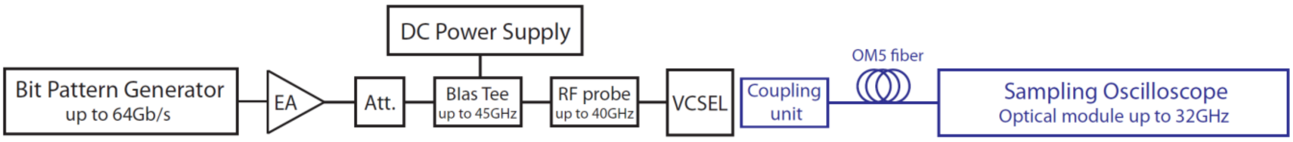

Figure 1. Experimental setup.

The electrical 50 Gbit/s Pseudo-Random non-return to zero Binary Sequence (PRBS) is generated by an SHF 12104A Bit Pattern Generator (BPG). DC current is provided to the VCSEL and combined with AC signal by the bias tee with the bandwidth of 45 GHz. The emitted light signal was coupled into a multi-mode wide-band OM5 Prysmian Group fiber with a lensed coupling unit.

The received optical is analysed with a Tektronix sampling oscilloscope DSA 8300 with optical module with bandwidth of up to 32 GHz. No temperature control, digital signal processing or pre-emphasis were applied in these measurements. The quality of eye diagrams was analysed through software of the oscilloscope due to lack of MMF photo-receiver with high enough responsivity and bandwidth for such measurements at 910 nm – 945 nm.

Because it was previously reported that wavelength-related crosstalk can be significantly reduced by a proper wavelength division on the receiver side, [12] each wavelength channel is tested separately due to simplify the experiment. In a real environment with four channels operated simultaneously it is expected that the wavelength division can introduce additional losses in the received optical power.

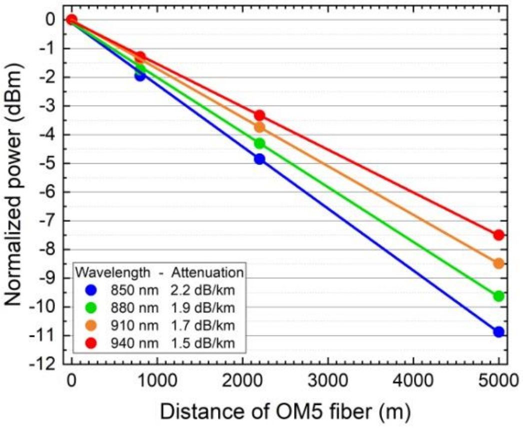

Figure 2. Attenuation of signals with different wavelengths through various lengths of OM5 wideband fiber.

High frequency data transmission measurements strongly depend on the received optical power of the signal. By passing through fiber the signal is attenuated by absorption and scattering losses. To estimate the influence of these effects attenuation measurements were performed for different lengths of fiber spools. (Fig. 2) The results reflect that attenuation of the OM5 fiber is the highest for 850 nm signals with -2.2 dB/km and lowest for 940 nm signals with -1.5 dB/km

3. SHORT-REACH DATA TRANSMISSION WITH MULTI-MODE VCSELS

MM VCSELs of four wavelengths were used for data transmission experiments. (Fig. 3) 850 nm, 880 nm and 910 nm VCSELs were fabricated in basic oxide-confined technology (Fig. 3.a.). 940 nm VCSELs studied in this work additionally had Zn-diffusion region surrounding the aperture.[13,]9All VCSELs have very low threshold current of ~0.4 mA and optical power levels above 1 mW as shown in their Light-Intensity (L-I) curves. Spectral characteristics of the VCSELs vary due to different types of investigated VCSELs. (Fig. 3.b.)

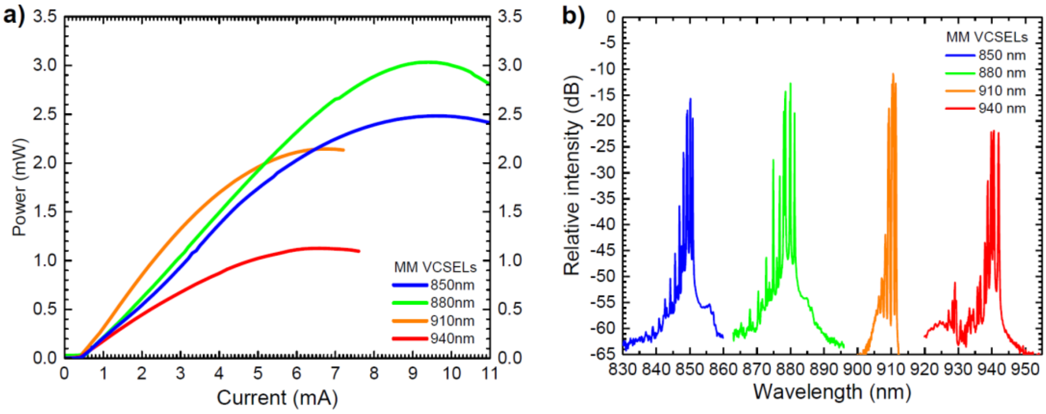

Figure 3. LI (a) and spectral (b) characteristics of VCSELs used for the tests.

910 nm and 940 nm VCSELs suffered from overheating with the rollover current limited to 6-7 mA, which impaired their high-frequency performance. (Fig. 4)

For large signal measurements PRBS9 was used, bias current was individually adjusted for each chip and driving voltage was fixed to 0.55 Vpp.

All chips are capable of 50 Gb/s back-to-back (B2B) and 100 m transmission through wideband OM5 fiber at room temperatures. Further analysis of eye diagram reveals that 940 nm VCSEL has the fastest rise time among all tested VCSELs, resulting on a larger vertical opening of the eye. However, the horizontal opening is smaller compared to that of 850 nm and 880 nm VCSELs, which do not suffer from additional noise

During the transmission experiments, no digital signal processing, pre-emphasis or equalization were used. The corresponding bathtub curves for each wavelength and fiber length were extrapolated from jitter and noise analysis of the eye pattern. [14]

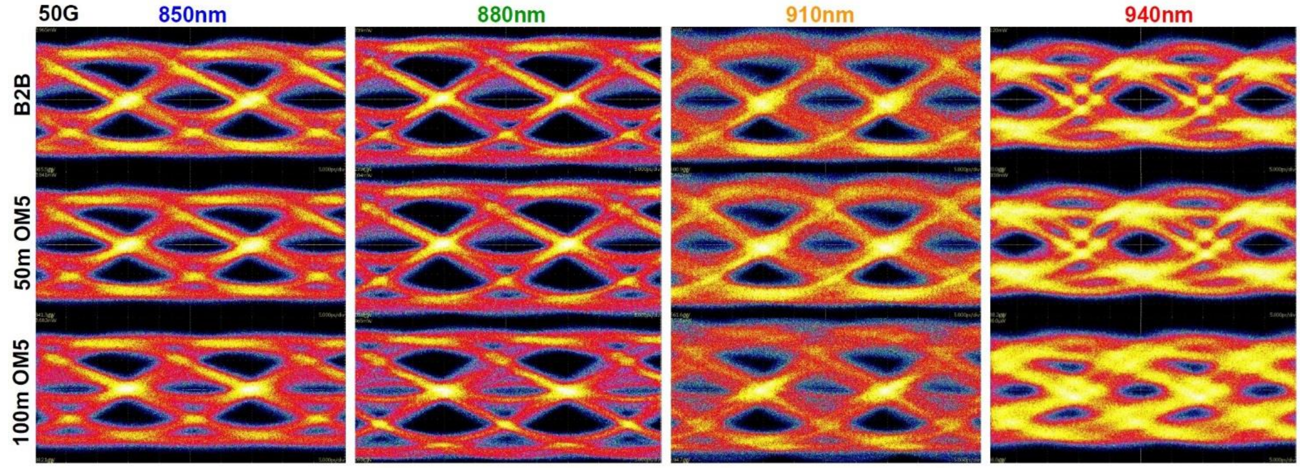

Figure 4. 50 Gb/s NRZ eye diagrams after different distances of OM5-MMF with 850 nm, 880 nm, 910 nm and 940 nm VCSELs (horizontal scale: 5ps/div, total frame length 50ps).

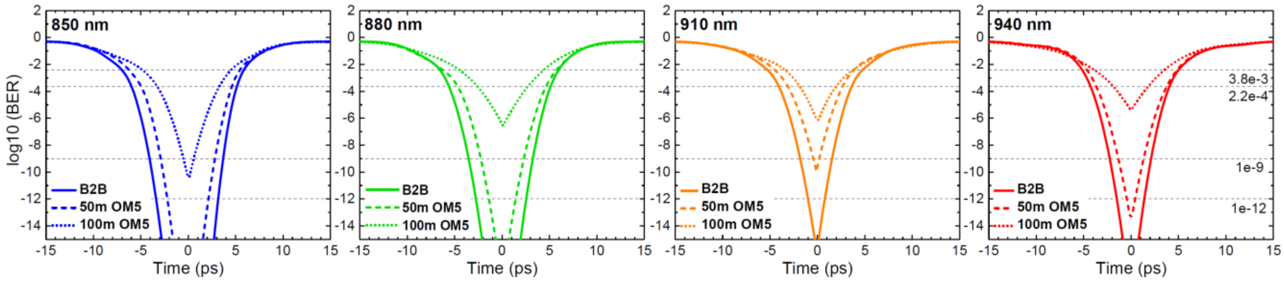

Figure 5. 50 Gb/s horizontal bathtub curves for 850 nm, 880 nm, 910 nm and 940 nm VCSELs after different transmission distances.

Horizontal opening of the eyes is extracted from bathtub curves. For B2B configuration at BER=1e-12 maximum opening of 6.5 ps is obtained for 850 nm VCSEL, while minimum opening of 1.8 ps is obtained for 910 nm VCSEL. These values represent a 32.5 % and 9.0% of the total bit period (Tb). 50 m transmission at BER=1e-12 is possible for 850 nm, 880 nm and 940 nm, but only possible at BER=1e-9 for 910 nm.

After 100 m OM5 maximum opening at BER=2.2e-4 of 6.4 ps (0.32*Tb) is again obtained for 850 nm VCSEL, while minimum opening of 3.6 ps (0.18*Tb) is now obtained for 940 nm VCSEL. Chromatic dispersion affects specially 880 nm and 940 nm VCSELs due to their larger root-mean-squared (RMS) spectral width, as it is visible on Fig. 3.b.[15]

4. LONG-REACH DATA TRANSMISSION WITH SINGLE-MODE VCSELS

Transmission of signals of large spectral width is limited by the chromatic dispersion. Chromatic dispersion of typical fibers for 850 nm signals is ~100 ps/nm·km and leads to delays between modes as large as 0.2 ps/m for typical MM VCSELs, order of magnitude higher than the influence of the modal dispersion. This delay caused by chromatic dispersion increases strongly with the spectral width and is especially critical for high speeds. [16]

For that reason, SM VCSELs with very low spectral width can be a promising solution for increasing the link length through reduction of the influence of chromatic dispersion.

SM VCSELs in 850 nm and 910 nm spectral range were designed and used for transmission experiment at 50 Gb/s data transmission through km-long wideband MMFs. Due to only recent expansion of VCSEL development to 880 nm and 940 nm, no SM chips were available for experiment at the moment, but will be added in future experiments.

Similar to the MM chips investigated above, 910 nm device is suffering from higher voltage, overheating and noise than the 850 nm VCSEL. (Fig. 7) Both chips are SM with more than 25 dB Side-mode Suppression Ratio (SMSR) at the operation point of ~2.8 mA and have above 1 mW power. For large signal measurements PRBS 9 was used and driving voltage was individually adjusted for each chip.

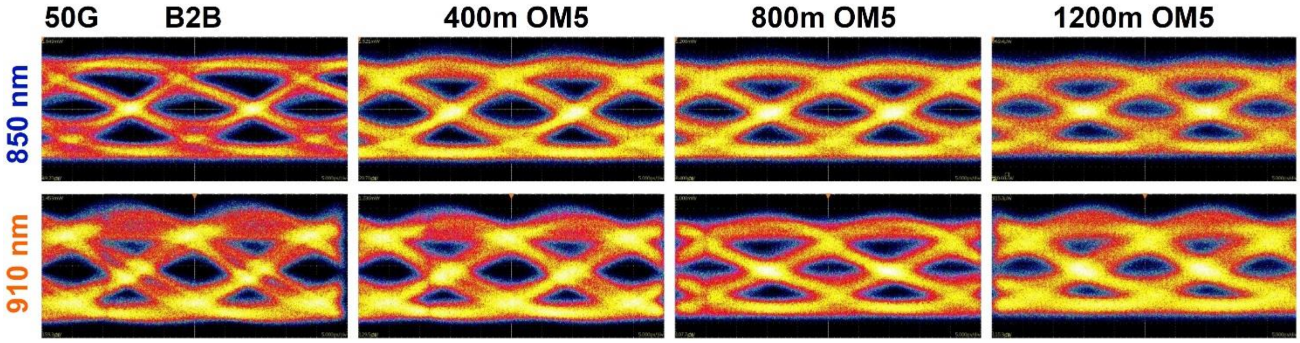

Figure 6. 50 Gb/s NRZ eye diagrams after different distances of OM5-MMF with 850 nm and 910 nm SM-VCSELs (horizontal scale: 5ps/div, total frame length 50ps).

Despite lower optical power budget available, in comparison with MM VCSELs, transmission below forward error correction (FEC) threshold of 3.8e-3 could be realized up to 1.2 km of OM5 fiber.

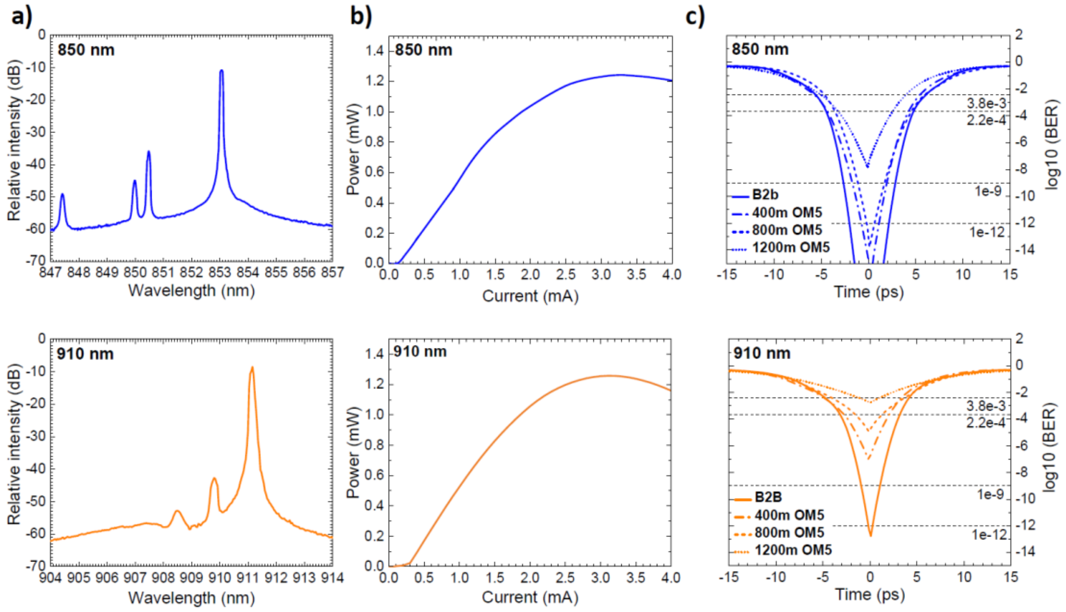

Figure 7. LI (a), optical spectra (b) and 50 Gb/s horizontal bathtub curves after different transmission distances (c), for 850 nm and 910 nm SM-VCSELs used for the tests.

B2B eye diagrams show that 910 nm VCSEL has a faster rise time to that of 850 nm VCSEL. However, 910 nm bathtub curves are worse due to additional noise.. Since both chips are single mode, transmission distance affects the eye quality in a very similar way.

For B2B configuration at BER=1e-12 openings of 4.2 ps (0.21*Tb) and 0.5 ps (0.025*Tb) are obtained for 850 nm and 910 nm VCSELs respectively. After 1200 m transmission the eye openings are 9.1 ps (0.455*Tb) and 2.9 ps (0.145*Tb).

7. CONCLUSIONS

In this paper we demonstrate short reach NRZ data transmission at 50 Gbit/s data rate at four different wavelengths in the SWDM range with multi-mode VCSELs without digital signal processing (DSP) or pre-emphasis.

50 Gbit/s data rate transmission over km long distances with bit-error-rate (BER) below 7% forward error correction (FEC) threshold is demonstrated for the first time without DSP or pre-emphasis with both 850 nm and 910 nm VCSELs. Use of signal processing and shaping techniques like DSP, CDR or pre-emphasis can further improve the performance of the link described in this paper.

With the technology described in this paper 200 Gbit/s link through single multi-mode fiber channel can be realized with four VCSELs in SWDM range operated with On-Off Keying (OOK) NRZ modulation. If single-mode VCSELs are used, such link can extend to km-long distances.

Current state of the art high order modulation formats enable bit rates of up to 160 Gb/s per single VCSEL.5 Use of high order modulation formats like PAM[17] DMT[18,19], or multi-CAP[20] in combination with SWDM can create a potential for achieving 1 Tbit/s transmission through single fiber channel with VCSELs.

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