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Effective 100 Gb/s IM/DD 850 nm multi- and single-mode VCSEL transmission through OM4 MMF

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***Abstract*—To cope with the ever increasing data traffic demands in modern data centers, new approaches and technologies must be explored. Short range optical data links play a key role in this scenario, enabling very-high speed data rate links. Recently, great research efforts are being made to improve the performance of vertical-cavity surface-emitting lasers (VCSELs) based transmission links, which constitute a cost-effective solution desirable for massive deployments. In this paper, we experimentally demonstrate intensity-modulation direct-detection transmissions with a data rate of 107.5 Gb/s over 10 m of OM4 multi-mode fiber (MMF) using a multi-mode VCSEL at 850 nm, and up to 100 m of OM4 MMF using a single-mode VCSEL at 850 nm. Measured bit error rates were below 7% overhead forward error correction limit of 3.8e-03, thus achieving an effective bit rate of 100.5 Gb/s. These successful transmissions were achieved by means of the multi-band approach of carrierless amplitude phase modulation.**

***Index Terms*—Multi-band carrierless amplitude phase modulation, Optical fiber communication, Vertical cavity surface emitting lasers.**

I. INTRODUCTION

THE ever increasing amount of transmitted data does not only increase the data rates of the transmission in the access, metro and core networks but also in the short connections, e.g. the optical data interconnects. The optical interconnects are applied to transmit data within information technology (IT) infrastructure, starting from in-rack communication to intra-data center connections. The key features requires for such applications are high throughput, limited footprint, reduced power consumption and reduced cost of the solution [1], [2].

An appealing transmission solution for optical interconnects is based on vertical-cavity surface-emitting lasers (VCSELs) and multi-mode fiber (MMF). VCSELs have key advantages of wide bandwidth, low energy consumption and low-cost manufacturing, while MMF can be easily coupled to VCSELs [3]. However, as optical link length increases, the modal and chromatic dispersion in MMFs deteriorate the transmission quality of traditional multi-mode (MM) VCSELs. The impairments imposed by both dispersions can be mitigated by reducing the number of modes of these VCSELs, ideally to achieve single-mode (SM) operation [4], [5]. VCSEL technology constitute a low-cost transmission solution, desirable for massive deployments, e.g. data center interconnects, which decreases costs by less than half compared with standard single-mode fiber (SSMF) solutions in data centers [6]. The VCSEL data interconnect cost advantage originates from low capital as well as operational, e.g. limited energy consumption, cost [7].

Optical communication systems are evolving from classic spectral inefficient non-return to zero (NRZ) schemes to more advanced and flexible modulation schemes such as quadrature phase shift keying (QPSK) [8], [9], pulse amplitude modulation (PAM) [10], [11], discrete multi-tone (DMT) [12]–[14], multi-band approach of carrierless amplitude phase (MultiCAP) [15], [16], polybinary modulation [17], [18], among others. By combining VCSEL technology with these advanced modulation schemes, spectral efficiency can be boosted up, enabling low-cost 100G links at single wavelength, single polarization, and direct detection.

A significant research effort is devoted to increase the transmission data rates and performance of VCSEL interconnects. The highest bit rates reported by some of these works including both the bit rates before and after forward error correction (FEC) decoding are: 115 Gb/s pre-FEC and 95.8 Gb/s post-FEC for back-to-back (B2B) transmissions by

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means of DMT modulation at 1550 nm [12]; 71.88 Gb/s pre-FEC and 67.18 Gb/s post-FEC for B2B transmission using DMT modulation at 850 nm [13]; 84 Gb/s pre-FEC and 78.51 Gb/s post-FEC for B2B transmissions with DMT modulation at 850 nm [14]; 54 Gb/s pre-FEC and 50.47 Gb/s post-FEC on-off keying (OOK) transmission up to 2.2 km of OM4 MMF at 850 nm [5], [19]; and 71 Gb/s NRZ modulation with no FEC codes with a BER <1e-12 over 7 m of OM3 MMF at 850 nm [20].

In this paper, we demonstrate two record experiments utilizing 850 nm VCSEL and OM4 MMF with a post-FEC bit rate of 100.5 Gb/s (i.e. pre-FEC bit rate of 107.5 Gb/s with 7% overhead FEC) over the distances of 10 m for MM-VCSEL transmission and of 100 m for SM-VCSEL transmission [21]. Furthermore, for B2B transmissions with the SM-VCSEL, a pre-FEC and post-FEC bit rates up to 112.5 Gb/s and 105.14 Gb/s were achieved, respectively. MultiCAP modulation, with advantages of adaptivity as well as feasible implementation and direct detection was applied. Bit error rate (BER) measurements were below 7% forward error correction (FEC) limit of 3.8e-03. Additionally, SM-VCSEL transmission experiments showed excellent performance up to 1000 m MMF at data rates of 85 Gb/s.

This paper is organized as follows: Section II gives a brief description of MultiCAP modulation scheme. In section III the experimental setup is described in detail and in section IV the experimental results are given. Finally, in section V conclusions are presented.

II. MULTI-BAND CARRIERLESS AMPLITUDE PHASE MODULATION

Carrierless amplitude phase modulation (CAP), similarly to quadrature amplitude (QAM) and high order phase shift keying (PSK) modulations, is a multilevel and multidimensional modulation scheme capable of transmitting two channels of data simultaneously [22], namely the in-phase (I) and quadrature (Q) channels. These two channels are generated by means of two orthogonal pass-band filters obtained from the time-domain multiplication between the root raised cosine (RRC) pulse shape function and a pure cosine and sine tones for I and Q components, respectively:

$$p_i(t) = g(t)cos(2\pi f_c t) \quad (1)$$

$$p_q(t) = g(t)sin(2\pi f_c t) \quad (2)$$

where $g(t)$ is a pulse shaping function that has a RRC spectral characteristic. CAP filters have three main parameters: i. the cosine and sine frequency determining the central frequency of the transmitted band; ii. the roll off factor α of the RRC, which determines the excess bandwidth required, i.e. with an RRC pulse shape the total pass-band bandwidth of a CAP band is 1+α times the baud rate; iii. the filter length in the number of samples which affects both performance and complexity of the system. For short lengths the overall system is simpler, but performance decreases significantly [16].

To generate a CAP signal, the original binary sequence is first mapped using an M-ary QAM or PSK encoder, and then the mapped symbols are up-sampled to perform a time-domain convolution with the orthogonal filters. After filtering, the signals from the two channels are added and transmitted. At the receiver first two matched filters separate the I and Q channels. The optimum filters are the ones matched to the passband filters described in (1) and (2), respectively [23]. Finally, the retrieved I and Q signals are down-sampled and the data is decoded. The overall CAP architecture has been demonstrated to be less complex and with better performance than DMT architecture [24].

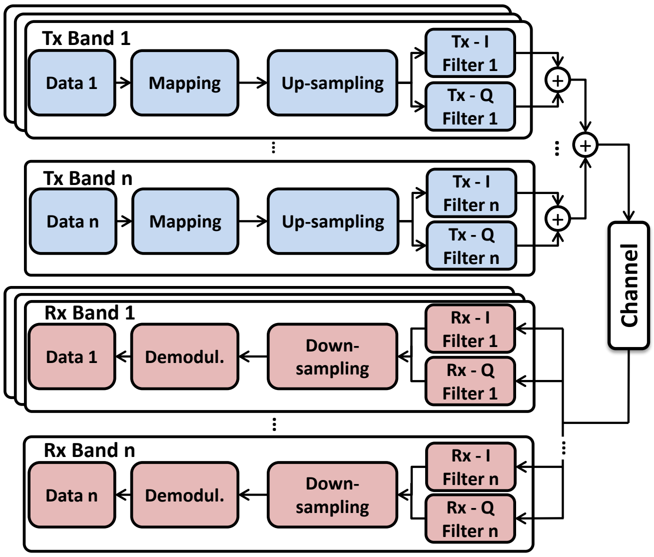

Fig. 1. The block diagram of MultiCAP transmitter and receiver.

MultiCAP modulation relies on the simultaneous transmission of several CAP signals assigned to different frequency bands, ensuring that these bands do not overlap. This is achieved by using not only one pair of orthogonal filters, but several pairs with different cosine and sine frequencies assigned to each frequency band [16], [25]. Fig. 1 shows the block diagrams of a MultiCAP transmitter and receiver.

The flexibility offered by MultiCAP allows to independently choose the modulation scheme, order, and signal power, i.e. allows bit loading and power loading in each band [12], [13], [16]. Thanks to these extra degrees of freedom, is possible to overcome the need of a flat frequency response of the channel which is required for reliable transmission of conventional CAP signals. The combination of bit loading and power loading for each band makes MultiCAP an appealing candidate for optical fiber links, where frequency selectivity and uneven gain of the channel cause significant degradations of the transmitted signal. However, it is to be noted that the advantages of this multi-band approach requires higher digital signal processing (DSP) resources. Some studies [26], [27] demonstrate that CAP and DMT have similar DSP complexity (i.e. number of basic real-valued arithmetic operations), therefore when the number of bands used in MultiCAP modulation increases, the DSP complexity increases proportionally as well.

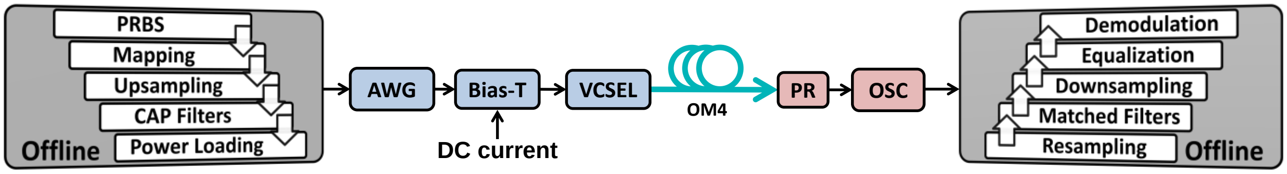

Fig 2. The block diagram of experimental setup. PRBS: pseudo-random binary sequence, AWG: arbitrary waveform generator, VCSEL: vertical cavity surface emitting laser, PR: photoreceiver, OSC: real time oscilloscope.

III. EXPERIMENTAL SETUP

Figure 2 shows the block diagram of the experimental setup. The transmitter consisted of a 65 GSa/s arbitrary waveform generator (AWG), a bias-T, a current source and a VCSEL. Standard multiple oxide aperture VCSEL design was applied for MM-VCSEL [28], while the SM-VCSEL design allowed oxide aperture induced leakage effect to be applied for mode selection [29]. In order to achieve SM operation, thick multiple oxide apertures were used. For such design the optical field distribution of the tilted modes (in the oxidized area) becomes non-orthogonal to the VCSEL cavity mode enabling the optical leakage process. The VCSEL used in the experiments has 3 µm-diameter oxide apertures (total oxide thickness ~70 nm) with which SM operation was achieved.

The packaged and pigtailed MM-VCSEL was biased with 8 mA current and driven by a modulating signal of 0.7 V_{pp}. In Fig. 3 is shown the probe station with the SM-VCSEL wafer. The SM-VCSEL was biased with 2.8 mA and driven by a modulating signal of 1 V_{pp}. No thermal stabilization was applied to both VCSELs. After transmission over the MMF OM4 fiber, which has a bandwidth of 4700 MHz·km, the optical signal was converted to the electrical domain in a 22 GHz bandwidth photoreceiver (PR) with an optional electrical amplifier. The electrical signal was captured in a 100 GSa/s real time oscilloscope (OSC) for further offline DSP.

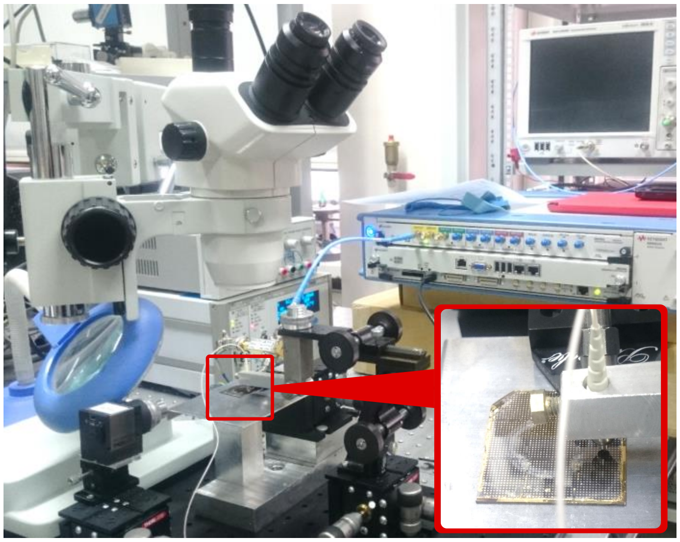

Fig. 3. The precision alignment probe station with SM-VCSEL chip wafer (inset).

IV. EXPERIMENTS

A. MultiCAP Signal Generation and Signal Processing

A MultiCAP signal with 10 frequency bands with a baud rate of 2.5 Gbaud each was utilized. For each band, decorrelated pseudo random binary sequences (PRBSs) of 2^{11}-1 bit length were independently generated (i.e. a PRBS with a different time shift for each band). Then, the PRBS of each band was repeated several times accordingly to the symbol constellation in which the sequences of each band were mapped, thus the resulting number of symbols of each band was the same. The obtained symbol sequences for each band were up-sampled and then filtered by the pair of orthogonal CAP filters corresponding to each band. Next, power loading was employed by assigning weights to each band in order to mitigate the channel gain unevenness. For all bands its corresponding pair of CAP filters were implemented as finite impulse response (FIR) filters with a length of 45 symbols each and an α of 0.03. The separation between the central frequencies of the bands was 2.55 GHz, starting in 1.3125 GHz as central frequency of the first band. The total bandwidth of all 10 bands was 25.5 GHz achieving a spectral efficiency of 4.21 bit/s/Hz.

At the receiver, to have a sampling rate multiple integer of the baud rates of the signal at the transmitter, the signal stored by the OSC with a sampling rate of 100 GSa/s was resampled to 130 GSa/s. Subsequently, I and Q channels of each band were retrieved by filtering with the filters matched to the CAP filters at the transmitter. After filtering, each channel was down-sampled to construct the corresponding symbol constellations, from which the symbols were demodulated employing a decision-feedback equalizer (DFE) and the k-means algorithm. The equalizer employed used the recursive least squares (RLS) adaptive algorithm, 30 feed-forward and feed-back taps, a forget-factor of 0.9999, and a value of 0.1 to initialize the diagonal elements of the inverse correlation matrix for Kalman gain computation. BERs and error vector magnitudes (EVMs) were computed offline, for each band separately, from the actual received data stored with the OSC.

B. VCSEL characterization

Figure 4 shows the light-current-voltage (LIV) curves and the optical spectra of the utilized SM- and MM-VCSELs. For the SM/MM-VCSEL operating wavelengths were 853.1/860.5 nm, respectively. The MM-VCSEL had over 10 modes and the SM-VCSEL suppression ratio of the strongest mode was 39 dB. The maximum optical power for SM/MM-VCSEL was -1.4 dBm and 4.4 dBm, respectively. Fig. 5

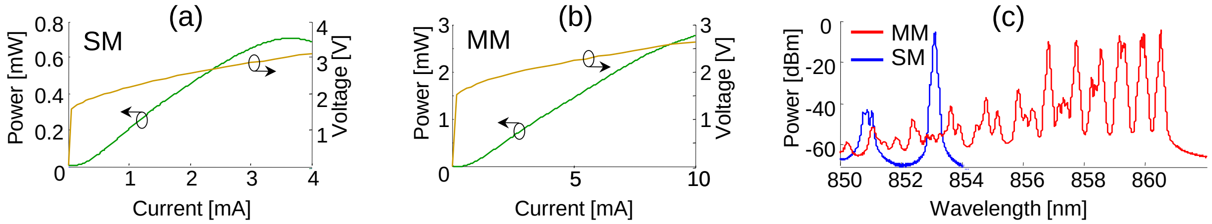

Fig 4. Light-current-voltage curves of (a) SM-VCSEL and (b) MM-VCSEL, and (c) optical spectra of SM and MM VCSELs.

shows the normalized (to the first trace measurement point) frequency response of the MM and SM-VCSELs based transmission link for various OM4 fiber lengths [5]. The frequency responses were measured with a 50 GHz network analyzer, which was connected to the VCSELs input and the PD output. The measurements were performed with the SM-VCSEL similar to the one used in the MultiCAP experiments. While the B2B curves are similar for both lasers (i.e. the 6 dB electrical bandwidth of about 26 GHz), a clear improvement of the SM laser is visible for lengths >100 m. For the MM-VCSEL the 6 dB electrical bandwidth does not exceed 5 GHz for the lengths >100 m, while for the SM-VCSEL it is over 15 GHz for the lengths up to 1600 m (excluding 1000 m) and over 8 GHz for all lengths.

It is to be noted that for all characterization tests and fiber optic transmissions in the experiments, the VCSELs did not have any kind of thermal stabilization and all tests were performed at ambient temperature within the laboratory.

C. *Transmission experiments*

First, transmission with MM-VCSEL was performed. A transmission of 107.5 Gb/s was achieved over 10 m of OM4 MMF with a received optical power of 3.9 dBm. For low frequencies, the link had a fairly flat frequency response which allowed to employ 64-QAM modulation scheme in the first two bands. Contrary, at high frequencies, the link frequency response was uneven and had a lower gain. Consequently, it was necessary to decrease the modulation order of the high frequency bands to maintain a low BER, e.g. binary phase shift keying (BPSK) modulation scheme for the last band. In Table I the BER and main parameters of each band are presented. The BER of all bands was below 7% FEC threshold of 3.8e-03, thus achieving a total effective bit rate of 100.5 Gb/s. Fig. 6 shows the received electrical spectrum of the MultiCAP signal together with the constellations and EVMs of all bands. Due the link frequency response, bands 9 and 10 had considerable lower power than the other bands, which not even with power loading could be compensated enough to increase its modulation order.

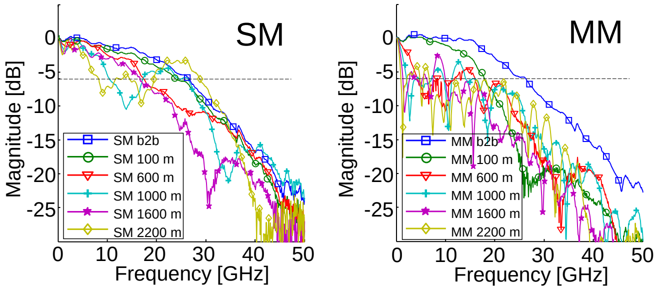

Fig. 5. Frequency response of the MM and SM-VCSELs based link.

Next, transmission with SM-VCSEL was performed. An additional 25 dB gain electrical amplifier was placed after the PD to compensate for the limited optical signal power. A transmission of 107.5 Gb/s was achieved over 100 m of OM4 MMF with a received optical power of -2.54 dBm. With a similar trend as in the MM-VCSEL transmission, the highest modulation order scheme used was 64-QAM for the bands at low frequencies and the lowest modulation order scheme used was quadrature phase shift keying (QPSK) for the last two bands. In Table II, the BER and main parameters of each band are presented, while Fig. 7 shows the received electrical spectrum of the MultiCAP signal together with the constellations and EVMs of all bands. The frequency response of the 10 m MM-VCSEL link and the 100 m SM-VCSEL link are quite similar to the extent that, with the proper power assignment of each band, only the modulation order scheme of bands 8 and 10 were changed. It is to be noted that, for both VCSELs, thanks to power loading technique bands with the same modulation order have practically the same EVM. Additionally, depending on the modulation order of each band (i.e. the spectral efficiency), the processed bits per band range from 362496 to 2174976 and from 483328 to 1449984, for the MM-VCSEL and SM-VCSEL transmissions, respectively, validating the reliability of the BER results presented.

Finally, with the SM-VCSEL, the experiments towards maximum bit rate transmission at a given distance with adjustable as well as fixed (107.5 Gb/s) bit rate were performed. Fig. 8(a) shows the maximum bit rates achieved below 7% FEC limit as a function of the MMF length. The maximum bit rate achieved was 112.5 Gb/s in the B2B test, and the maximum length tested was 1 km achieving a bit rate of 85 Gb/s. Fig. 8(b) shows the average BER of all bands for 107.5 Gb/s transmission in function of MMF length. For longer distances the higher order modulation schemes, such as 64-QAM, degrade considerably increasing the BER as can be noted. For the maximum bit rate transmission experiment, Table III presents a summary of all MMF links lengths and the modulations schemes of all bands. As the link length increases, the link bandwidth and the received optical power decrease. Therefore, the EVMs of all bands worsen and the modulation order of some bands must be decreased accordingly in order to ensure a BER below 7% FEC limit.

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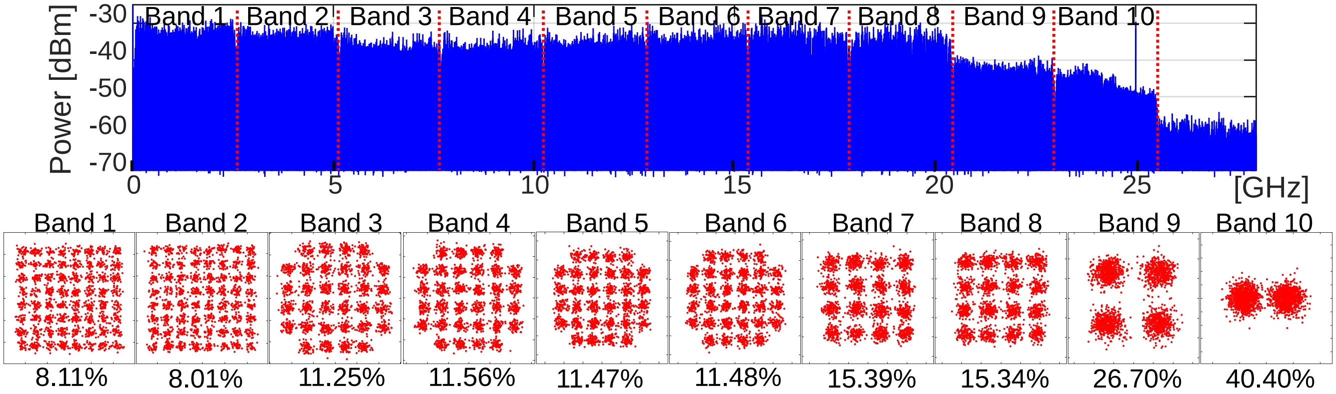

Fig 6. Received electrical spectrum and constellation diagrams after DFE for 107.5 Gb/s 10 m MM-VCSEL transmission.

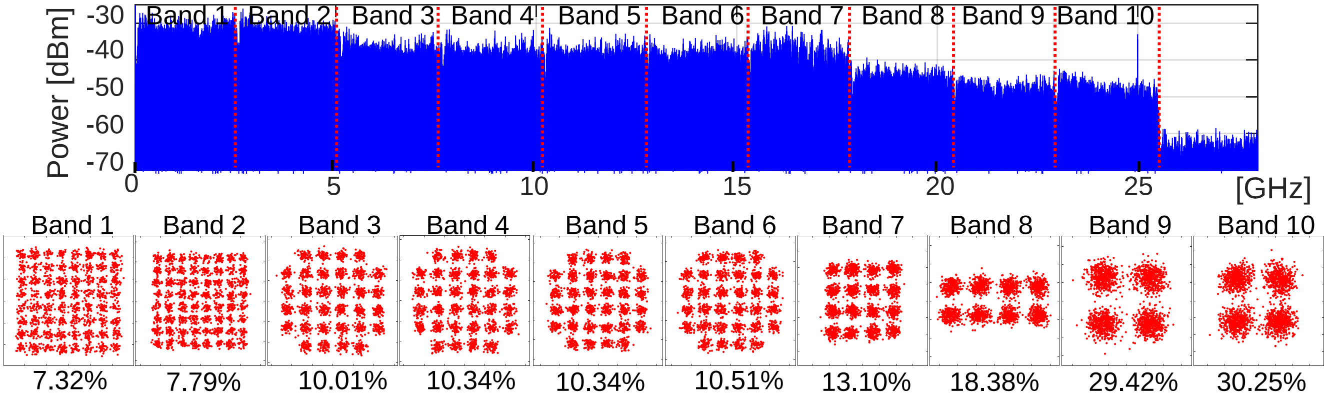

Fig 7. Received electrical spectrum and constellation diagrams after DFE for 107.5 Gb/s 100 m SM-VCSEL transmission.

TABLE I
BER AND MAIN PARAMETERS OF MM-VCSEL 107.5 GB/S TRANSMISSION OVER 10 M OF OM4

Band	1	2	3	4	5	6	7	8	9	10
Baud rate [Gbaud]	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Modulation	64-QAM	64-QAM	32-QAM	32-QAM	32-QAM	32-QAM	16-QAM	16-QAM	QPSK	BPSK
Bit rate [Gb/s]	15	15	12.5	12.5	12.5	12.5	10	10	5	2.5
Central Freq. [GHz]	1.3125	3.8625	6.4125	8.9625	11.5125	14.0625	16.6125	19.1625	21.7125	24.2625
Power Loading [dB]	2	1	0.3	0.6	1	2.1	1.2	2.6	0.4	2
Transmitted Bits	2174976	2174976	1812480	1812480	1812480	1812480	1449984	1449984	724992	362496
BER	**3.12e-03**	**2.58e-03**	**2.36e-03**	**2.53e-03**	**3.76e-03**	**3.33e-03**	**2.63e-03**	**2.77e-03**	**7.89e-04**	**3.56e-03**

TABLE II
BER AND MAIN PARAMETERS OF SM-VCSEL 107.5 GB/S TRANSMISSION OVER 100 M OF OM4

Band	1	2	3	4	5	6	7	8	9	10
Baud rate [Gbaud]	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Modulation	64-QAM	64-QAM	32-QAM	32-QAM	32-QAM	32-QAM	16-QAM	8-QAM	QPSK	QPSK
Bit rate [Gb/s]	15	15	12.5	12.5	12.5	12.5	10	7.5	5	5
Central Freq. [GHz]	1.3125	3.8625	6.4125	8.9625	11.5125	14.0625	16.6125	19.1625	21.7125	24.2625
Power Loading [dB]	2	2.1	-0.2	0.7	1.7	2.6	2	1.1	-1	2.1
Transmitted Bits	1449984	1449984	1208320	1208320	1208320	1208320	966656	724992	483328	483328
BER	**1.80e-03**	**2.94e-03**	**1.33e-03**	**1.58e-03**	**1.26e-03**	**1.89e-03**	**1.11e-03**	**1.66e-03**	**1.69e-03**	**2.08e-03**

V. CONCLUSION

To the best of our knowledge, for the first time an effective bit rate over 100 Gb/s is transmitted, at single wavelength, single polarization, and direct detection, with an 850 nm MM-VCSEL over 10 m of OM4 MMF and with an 850 nm SM-VCSEL over 100 m of OM4 MMF. These two records, with comparable hardware constraints and resources as previous works [12]–[14], [20], were achieved through the use of MultiCAP modulation. BERs below 7% FEC limit were measured.

To be able to increase the length of optical links, work is dedicated to develop more advanced designs to increase the output power of VCSELs. Recently, with oxide apertures having a total thickness of 100 nm, the oxide apertures diameter for SM operation was increased to 5 μm at currents

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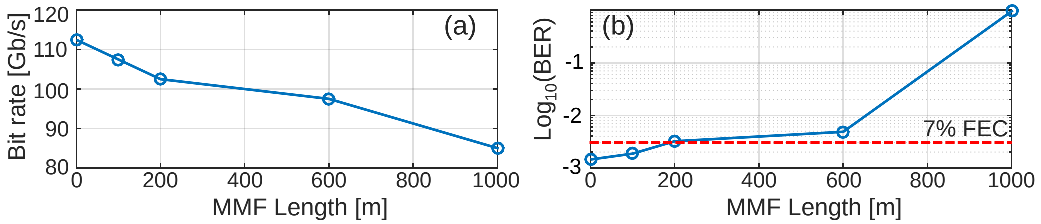

Fig 8. SM-VCSEL (a) maximum bit rate below 7% FEC limit versus MMF length and (b) 107.5 Gb/s transmission BER versus MMF length.

TABLE III
SM-VCSEL SET OF MODULATION SCHEMES FOR EACH MMF LENGTH

Distance [m]	**Band 1**	**Band 2**	**Band 3**	**Band 4**	**Band 5**	**Band 6**	**Band 7**	**Band 8**	**Band 9**	**Band 10**	**Bit Rate [Gb/s]**
0	64-QAM	64-QAM	64-QAM	64-QAM	32-QAM	32-QAM	16-QAM	8-QAM	QPSK	QPSK	112.5
100	64-QAM	64-QAM	32-QAM	32-QAM	32-QAM	32-QAM	16-QAM	8-QAM	QPSK	QPSK	107.5
200	64-QAM	64-QAM	32-QAM	32-QAM	32-QAM	16-QAM	16-QAM	8-QAM	QPSK	BPSK	102.5
600	32-QAM	32-QAM	32-QAM	32-QAM	32-QAM	16-QAM	16-QAM	8-QAM	QPSK	BPSK	97.5
1000	32-QAM	32-QAM	32-QAM	16-QAM	16-QAM	8-QAM	8-QAM	QPSK	QPSK	BPSK	85

exceeding 5 mA with >15dB Side-Mode Suppression Ratio (SMSR) [30].

Due the high data rates of optical interconnects, signal integrity requirements in data centers are getting more stringent (e.g. a BER of 1e-15 is considered error free). With alternative low-density parity-check (LDPC) code schemes [31] is possible to reduce the post-FEC BER floor, however, the overhead required is larger. With the BERs achieved, our results are suitable for applications with bit rates over 50 Gb/s compliant with recent IEEE 802.3 and Fibre Channel standards (i.e. BER<1e-13).

The presented results demonstrate that ultra-high speed links over 100 Gb/s with distances up to 100 m can be realized by using cost-effective MMF and 850 nm VCSELs, disruptingly opening a technology solution for the high capacity data interconnects that can be further increased by combination with short-WDM (SWDM).

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