Long-wavelength VCSEL-based system exploiting direct DMT modulation and coherent detection for multi-Tb/s metro link

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***Abstract*— Direct DMT modulation using long-wavelength VCSEL combined with simplified coherent detection assures beyond 50-Gb/s per polarization over 200 km, in presence of WSS filters, for a cost-effective and energy-efficient solution in multi-Tb/s metro networks.**

Keywords—VCSEL, DMT, S-BVT, metro optical networks

I. Introduction

Short-wavelength multi-mode vertical-cavity surface-emitting lasers (VCSELs) dominate short-reach data communications, with very powerful performance in terms of transported capacity in multi-mode fiber (MMF) connections. Long-wavelength (LW) single-mode VCSELs realized in InP and emitting in the C-band have been also proposed to exploit the advantages of this type of sources in terms of low cost, energy efficiency, and small footprint. By using discrete multi-tone (DMT) modulation and direct detection (DD), 4-km links were bridged at 115-Gb/s using a directly modulated 1550-nm single-mode VCSEL [1], while longer reach (40 km) can be achieved at lower rates beyond 25 Gb/s [2, 3]. Thanks to bit and power loading optimized to the frequency-dependent transmission characteristics of the channel, DMT allows to maximize the transmitted capacity with respect to the available link bandwidth. LW VCSELs combined with DMT can thus guarantee very high capacities in networks sensitive to cost, footprint, and power consumption, such as the metropolitan area networks (MANs).

DMT appears ideal for direct modulation (DM) of the VCSEL due to the Hermitian symmetry property of the signal, but, in combination with DD, transmission reaches are limited below the typical distances covered by MANs, around hundreds of kms. In order to achieve extended reach, multicarrier modulation (either DMT or OFDM) can be combined with single-sideband (SSB); particularly, adopting SSB/OFDM beyond 20 Gb/s connection has been demonstrated over a multi-hop path of 185 km [4]. On the other hand, an effective solution to reach MAN distances, compensating the SSMF chromatic dispersion (CD), is to exploit digital coherent detection (COHD). DM VCSELs and coherent detection have been considered in [5] to generate and transmit 100-Gb/s signal based on 4-level pulse-amplitude-modulation (4PAM) and polarization division multiplexing (PDM), enabling 400-km SSMF propagation, with 100-GHz spaced channels, achieving a spectral efficiency of 1 bit/s/Hz.

In this paper, we experimentally assess the promising results obtained in our previous works [6, 7], on LW DM-VCSELs in combination with COHD, exploiting DMT with SSB modulation to increase the spectral efficiency and target MAN applications. Propagation up to 200-km SSMF is experimentally demonstrated together with the analysis of the impact of the cascade of wavelength selective switching (WSS) filters, in order to evaluate the number of network nodes crossed in the MAN path. We achieved a capacity per polarization higher than 50 Gb/s with 25-GHz occupation, showing that, thanks to DM-VCSELs and reduced-complexity COHD [5], we can provide a cost-effective and energy-efficient solution for MANs. According to the demonstrated performance and adopting a modular approach, a VCSEL-based low-cost sliceable bandwidth/bitrate variable transceiver

This work has been supported by the H2020 PASSION Project (GA 780326).

978-3-903176-21-8

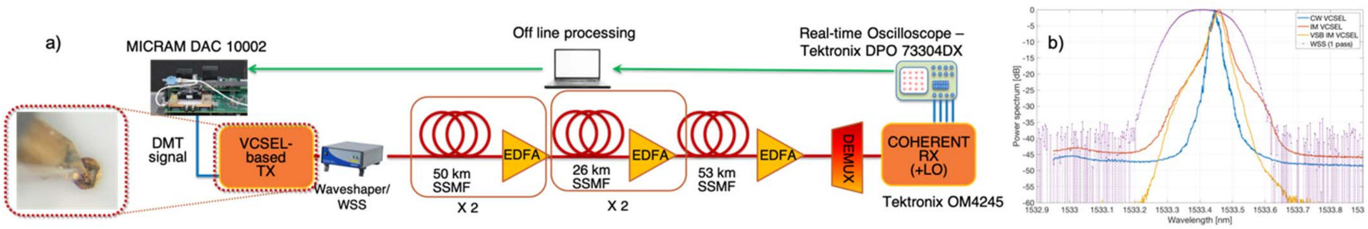

Fig. 1: a) Experimental setup. b) Measured optical spectra (CW spectrum – blue, DSB spectrum – red, SSB spectrum – orange, single-pass WSS transfer function – purple).

(S-BVT) can be realized [7]. Multiple DMT directly modulated VCSELs are integrated in SOI chips to provide 25-GHz spaced wavelength division multiplexed (WDM) channels and to generate up to 16-Tb/s capacity in case of PDM, matching the requested MAN traffic.

II. Experimental Setup

For the transmission performance evaluation, we employed the experimental setup shown in Fig. 1. An 18-GHz Vertilas VCSEL [5] is directly modulated by a DMT signal generated by a MICRAM 100-GS/s digital-to-analog converter (DAC10002) with 35-GHz electrical bandwidth and 6 bits vertical resolution. The DMT signal is calculated by Matlab® and is composed by 256 sub-carriers in 20-GHz range, i.e. the sub-carrier spacing is 78.125 MHz. A cyclic prefix (CP) of about 2.1% of the symbol length is added. The VCSEL emitting wavelength is 1533.5 nm, while its measured linewidth is about 5 MHz. The bias current is set at 9 mA, while the modulation depth is fixed at 450 mV in order to limit the frequency chirp insurgence and reduce the penalty due to SSB filtering. A Finisar Waveshaper 4000S, which mimics the transfer function of 25-GHz standard WSSs [8], further performs the single sideband filtering operation thanks to 8-GHz detuning with respect to the VCSEL modulated spectrum. The generated single-polarization SSB optical signal is amplified by an Erbium-doped fiber amplifier (EDFA) and propagates on different SSMF spools with launch powers of +1 dBm and a total reach of about 200 km (implemented by fiber spans with different lengths). The signal is detected by a Tektronix coherent receiver OM4245 with 45-GHz bandwidth. The local oscillator (LO) is a tunable 100-kHz laser with +15.5 dBm optical power. The inphase/quadrature signals are acquired by a Tektronix real-time oscilloscope with 8-bits vertical resolution, 100-GS/s and 33-GHz electrical bandwidth respectively. As direct modulation is exploited, the transmitted signal is just intensity modulated and a simplified coherent receiver can be used [5]: after I and Q components recovery and CD compensation, the I and Q square moduli are performed and summed up in order to obtain the originally transmitted intensity signal. This avoids the use of phase and frequency recovery, reducing the complexity of the receiver DSP and also relaxing the constraints on VCSEL and LO linewidths. As a drawback, this operation cancels the advantages in terms of bit error rate (BER) as a function of signal to noise ratio (SNR) of coherent detection, so that the same performance as DD is obtained when the received optical power is enough to neglect the photoreceiver electrical noise. The following off-line processing provides channel deskew, digital symbol synchronization, CP removal, sub-carriers phase recovery and demodulation. An example of the optical spectrum before and after single-pass WSS filtering is shown in the inset of Fig. 1. In particular, the standard dual sideband spectrum (continuous red curve) visible after VCSEL direct modulation is filtered by the 25-GHz WSS transfer function (dotted purple curve) detuned of about 8 GHz, achieving the desired SSB condition (continuous orange curve), with a good extinction of the spectrum right side. The estimation of the channel characteristics is performed by transmitting a probe DMT signal mapped with uniform QPSK loading, providing the SNR of each sub-carrier. The measured SNRs are then exploited for performing Chow's algorithm, which is the standard bit- and power-loading procedure for obtaining a good approximation of the highest bit rate achievable by the transmission system [9]; the target bit error rate (BER) was set at $4.6 \cdot 10^{-3}$ accordingly with the exploitation of an advanced hard-decision forward error correction code with 7% overhead [4].

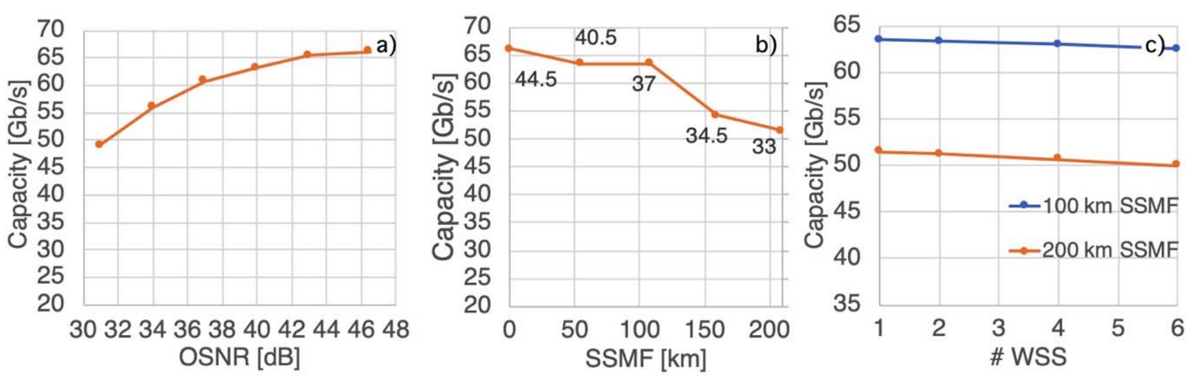

Fig.2. a) Total transported capacity vs OSNR in BTB condition. b) Total transported capacity vs SSMF propagation length for single-channel single-polarization transmission. The relative OSNR values measured at each SSMF reach are shown along the curve. c) Total transported capacity vs number of crossed WSSs for 100-km and 200-km SSMF propagation.

Fig. 3. Multi-Tb/s S-BVT transmitter based on VCSEL integration with modular approach.

III. Experimental Results

At first, the performance of the optical channel has been evaluated in terms of total transported capacity in back-to-back (BTB) condition varying its optical SNR (OSNR) between 46 dB to 31 dB thanks to a variable optical noise loader. As shown in Fig. 2(a), the capacity monotonically increases with OSNR, as expected, ranging from about 50 Gb/s for 31 dB OSNR to more than 66 Gb/s for 46 dB OSNR. A strong increase in the capacity can be noticed for low OSNR values, while after 42 dB no significative change is visible, i.e. at high OSNR levels the signal performance is determined only by electrical noise. Then, the capacities obtained after SSMF propagation for a single-channel single-polarization condition are reported in Fig. 2(b). The measured OSNR related to each SSMF reach for launch powers of +1 dBm are reported below the curve. A capacity around 65 Gb/s is maintained up to 100-km SSMF propagation thanks to high OSNR levels, while it decreases for 150 km and 200 km. However, a total transported capacity per polarization higher than the target 50 Gb/s can still be achieved even after 200-km propagation.

Finally, the impact of the cascade of WSS filters, which can be detrimental due to the filter narrowing effect [10], on the directly-modulated DMT signal performance, has been experimentally evaluated for 100-km and 200-km SSMF lengths. The cascade of WSS filters has been emulated by the Finisar Waveshaper filter. As shown in Fig. 2(c) the capacity barely reduces increasing the number of crossed WSSs, allowing capacities higher than 50 Gb/s even after 200-km SSMF propagation and 6 crossed WSS-like network nodes.

IV. Multi-Tb/s VCSEL Based S-BVT

Multiple InP single-mode VCSELs, covering the whole C-band, can be massively integrated on a SOI chip obtaining a modular S-BVT transmitter, as depicted in Fig. 3. The single module is constituted by 40 VCSELs integrated with a 100-GHz wavelength multiplexer providing up to 2 Tb/s capacity; more details on the S-BVT architecture can be found in [7, 11]. The experimentation reported above demonstrates beyond 50-Gb/s capacity per VCSEL per polarization with 25-GHz occupancy, hence up to 4 identical modules can be interleaved in a supermodule by temperature tuning to cover the C-band (about 4 THz) with 25-GHz wavelength granularity [7]. Up to 8 Tb/s capacity can therefore be supported in 25-GHz spacing multi-channel transmission over reaches of the order of 200 km [12]. PDM can be also exploited to double the total capacity obtaining up to 16 Tb/s capacity per fiber [7].

V. Conclusions

C-band single-mode VCSELs have been exploited to achieve beyond 50-Gb/s capacity per polarization by means of SSB DMT direct modulation and simplified coherent detection. 200-km SSMF reach is demonstrated also in presence of 25-GHz WSS filters. Based on this performance, 4-b/s/Hz spectral efficiency can be achieved with PDM and S-BVT design based on multiple modules can be adopted for targeting future MAN requirements in terms of very high capacity, low footprint, cost and power consumption.

Acknowledgment

This work has been supported by the H2020 PASSION Project (GA 780326). The authors thank Tektronix, Micram and Opsys Technologies sponsorship.

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