Transmitter and receiver solutions for VCSEL exploitation in access and metro networks

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ABSTRACT

The high capacity demand, to support broadband services and everything-to-internet connectivity is pushing the limits of both access and metro networks, requiring the adoption of novel strategies for the optical transceiver modules. This represents an opportunity for the adoption in these network scenarios of novel photonic technologies based on single-mode vertical cavity surface emitting lasers (VCSELs) at long wavelengths. On one hand, the access network evolution requires a line rate increase beyond 10 Gb/s, targeting 50 Gb/s propagation in passive optical networks (PONs) over a few tens of kms in standard single mode fiber (SSMF) with simple, cost effective and energy efficient transceivers. On the other hand, the future metropolitan area network (MAN) will need to handle multi-Tb/s traffic in a very dynamic scenario, over variable distances up to hundreds of kms while promoting sustainability, reducing the CapEx and OpEx costs and power consumption. Both needs can be fulfilled by adopting VCSEL direct modulation with multicarrier modulation formats such as discrete multitone (DMT), in combination with distinct transmitter architectures and receiver solutions to support different aggregate capacity requirements and transmission reaches. In any case DMT with bit/power loading enables flexible rate and adaptive distance for metro network applications and link adaptation and PON resource usage optimization for future access networks. In this work, we report our recent results on the adoption of VCSEL technology in both scenarios, with special focus on the receiver and transmitter adopted architectures.

Keywords: metropolitan area network, passive optical networks, discrete multitone modulation, vertical cavity surface emitting lasers, multi-Tb/s capacty

1. INTRODUCTION

Nowadays, most of the total data traffic is concentrated in less of the 5% of the geographical area, this situation particularly impacts the operation of access networks, e.g. passive optical networks (PONs), and metropolitan area networks (MANs). The continuous increase of “hungry” applications and services such as 5G, Mobile Edge Computing, UHD TV, etc.. is generating a huge IP traffic which pushes the operational limits of PONs and MANs. To support this continuous growth of bandwidth demand coming from the core network both network segments need to adopt novel strategies.

After the not very successful experience of next generation (NG)-PON2 standard which tried to evolve the access topology introducing the wavelength dimension, obtaining a time and wavelength multiplexed (TWDM) -PON, it seems that access standardization is moving towards the line rate increase beyond the 10 Gb/s of TDM-PONs. IEEE and ITU are looking for the candidate modulation formats and technologies for the next 50-Gbit/s PON (50G-PON)[1]: although it would be beneficial to rely on the pre-existence of mature high-volume technologies for data center intra-connect (DCI), PON links need to address much higher power budget and longer reaches with respect to point-to-point DCI optical links; thus, it is mandatory to adopt alternative solutions[1]. Moreover, network flexibility and link adaptation are becoming operators' requests because they offer several advantages such as a significant gain in the network capacity, the flexibility to adapt to high peak user rates and a more efficient usage of the network resources including energy consumption[2].

As MANs are concerned, beside the capacity increase, optical transport technologies should enable the development of agile solutions, different from the model of long-haul transmission, that can flexibly adapt to the path/traffic conditions,

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associated with software defined networking (SDN), supporting a "pay-as-you-grow" evolution, to target cost reduction and possibly energy efficiency[3].

In both segments, the answer to the above requirements can be given by the adoption of novel strategies for the optical transceiver modules, employing advanced photonic technologies based on single-mode (SM) vertical cavity surface emitting lasers (VCSELs) at long wavelengths (LW) and direct modulation (DM) with multicarrier modulation formats such as discrete multitone (DMT). Of course, the two network applications require distinct transmitter architectures and receiver solutions to support different aggregate capacity requirements and transmission reaches.

In the case of the access network, simplicity and low costs are required while targeting single wavelength 50 Gb/s transceivers, thus direct detection (DD) is mandatory. Hence, as chromatic dispersion (CD) is a main impairment for 50G-PON propagation, to target such rates over typical link distances of the order of 20 km, the use of long wavelengths VCSELs in the O-band is necessary to take advantage of standard single mode fiber (SSMF) almost null CD.

In the case of MANs instead, the next generation transceivers should target multi-Tb/s capacities[3], thus we propose to use massive photonic integration to develop a photonic integrated circuit (PIC) transmitter including multiple InP LW C-band high-bandwidth VCSEL sources and Silicon-photonic (SiPh) multiplexers[4] to aggregate a multi-Tb/s capacity[5]. The exploitation of DM with DMT modulation[6] at the transmitter is combined with coherent detection (COHD) at the receiver side to allow propagation in hundreds of kilometers links.

In both cases DMT with bit/power loading enables a flexible rate, achieving a sliceable bandwidth and bitrate variable transceiver (S-BVT) able to adapt to metro network applications[7] and link adaptation and PON resource usage optimization for future access networks.

In Section 2 we present the features characterizing the transceivers for the two scenarios, with particular regard to transmitter and receiver sides. In Section 3 we present results on 50 Gb/s IM/DD downstream (DS) PON transmission and compare results with some simulations to achieve evaluations on the flexible PON aggregated capacity. Moreover, we experimentally assess the performance of DM-VCSELs in combination with COHD, exploiting DMT with single sideband (SSB) modulation to increase the spectral efficiency and target MAN distances and applications. Finally, Section 4 draws the conclusions.

2. TRANSMITTERS AND RECEIVERS SOLUTIONS FOR PON AND MAN SCENARIOS

As said previously, the common characteristics of our proposals for access and MAN scenarios is the exploitation of VCSELs directly modulated by multicarrier signals and in particular by DMT[8, 9].

VCSEL sources are characterized by a light emission normal to the semiconductor layer structure, that allows simple and cost-effective on-wafer test of VCSEL chips. The adopted LW InP VCSELs can show an emission wavelength up to 2 µm; their design features a dielectric bottom mirror, a buried tunnel junction (BTJ) for the current confinement, a gold substrate acting as a heat sink, a multi quantum well (MQW) active region and an optimized waveguide design. SM operation is guaranteed by a transverse waveguide structure, with high sidemode suppression ratio and polarization stable output. A short cavity (SC) structure, displaying a very short resonator length and an optimized active region, reduces the effective photon lifetime while high relaxation-resonance frequencies and low parasitic effects guarantee high-speed modulations. SC devices present a current aperture of about 5 µm and an effective cavity length of 2.5 µm leading to modulation bandwidths up to 20 GHz with relative intensity noise below -140 dB/Hz[10]. The use of VCSELs with DM and advanced modulation format can facilitate their exploitation for high speed transmission.

DMT with bit and power loading allows to adapt the transmitted signal to the link characteristics providing a great flexibility at the DSP level. In case of optical networks, this flexibility allows to optimize the transmitted capacity as a function of losses, transmission impairments (e.g. dispersion, nonlinearities etc.), and traffic patterns. At the transmitter digital-to-analog converters (DACs) are used to generate the DMT signal, which is fed to a laser linear driver; high-rate laser linear driver circuits are already commercially available for PAM4 applications[11]. At the receiver analog-to-digital converters (ADCs) are needed for further signal decoding. Due to the fast Fourier transform (FFT) and inverse FFT (IFFT) operations required to manage DMT signals, the needed relevant signal processing components are quite complex, but DSP-efficient FFT and simplified algorithms[12] are being studied to simplify DMT use. We will analyze two DMT variants. The first one is dual side-band (DSB) DMT, in which the transmitted signal instantaneous power is modulated by a positive and real-valued DMT signal. The resulting optical spectrum is double-sided and requires a total bandwidth that is twice the bandwidth of the real DMT signal. The second DMT variant is single side-band (SSB) DMT, in which one of the two optical sidebands is removed by optical filtering achieving a better spectral efficiency. As subcarriers are loaded with multilevel QAM signals, 50 Gb/s capacity can be easily obtained with a DMT modulating signal occupying a bandwidth of around 16 GHz[13]. Although the same optical DMT signal is employed, different characteristics are necessary for both the transmitters and the receivers in the two scenarios.

2.1 Access transmitter

Transmitters for 50G PONs need to fit small form factors. Since the use of VCSEL simple direct DMT modulation avoids the need of an external modulator, the transmitter optical module, which is responsible for electro/ optical (E/O) conversion, is only constituted by the VCSEL itself and by the laser driver circuit. Considering that the main impairment in PON 50G transmission is CD, high-capacity downstream (DS) signals should be hosted in the O-band around 1342±2nm[14]; yet, for a typical reach of 20-km SSMF, the accumulated CD is around 74 ps/nm. As said before, SC high-bandwidth VCSEL technology is already reliable both in O and C bands; in fact, just the dielectric distributed Bragg reflectors differ between the two bands. Low-cost and energy-efficient transmitters for flexible 50G PON can be thus designed, considering that the VCSEL energy consumption per bit is about 0.7 pJ, while including the driver power consumption the total energy is about 5.3 pJ/bit, that is pretty low with respect to the consumption of optical modules including standard DFB lasers and silicon photonics chips for external modulation[15]. In case of SSB DMT modulation obtained with optical filtering it is mandatory to stabilize the laser wavelength and, therefore, the power consumption of the transmitter nearly quadruplicates. On the other hand, application specific integrated circuit (ASIC) for DMT high-bandwidth signals show an energy consumption around 50 pJ/bit[16].

2.2 MAN transmitter

The target for MAN transmitters is to offer multi-Tb/s capacity while allowing dynamic and flexible adaptation to traffic/channel conditions, achieving a multi-Tb/s sliceable bandwidth and bitrate variable transceiver (S-BVT)[17]. As said, flexibility is obtained through DMT modulation, while photonics technology can support the high-capacity target. In particular, 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. 1. 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[4, 18]. SSB modulation allows to interleave up to 4 identical SOI chip modules by temperature tuning to cover the C-band (about 4 THz) with 25-GHz wavelength granularity[19]. Expecting a 50-Gb/s capacity per VCSEL per polarization, this super-module can therefore support up to 8 Tb/s capacity. Polarization-division multiplexing (PDM) can be also exploited to double the total capacity obtaining up to 16 Tb/s capacity per fiber with 4-b/s/Hz spectral efficiency[20].

Fig. 1. Multi-Tb/s S-BVT transmitter based on VCSEL integration with modular approach.

2.3 Access receiver

In case of 50G PON, DD is the preferred receiver solution for its simplicity: the receiver block, in fact, is hosted in the ONU transceivers[1]. Indeed, thanks to DMT modulation the photodiode (PD) bandwidth can be around 25 GHz, allowing the exploitation of avalanche PD (APD) which are already commercially available[1]. The use of APD is fundamental to achieve the necessary power budget and support at least class N1, i.e. 29 dB, ODN loss. Si-Ge APDs can achieve a gain-bandwidth product of 300 GHz, which at 25 GHz allows a gain of 12, with NEC around 20 pA/√Hz and responsivities close to 0.7 A/W[21].

2.4 MAN receiver

In order to target transmission distances typical of MANs, i.e. hundreds of kilometers, it is necessary to employ digital COHD which allows easy CD DSP compensation, avoiding also the VCSEL chirp interplay with CD. Moreover, COHD enables the use of PDM to increase the transmitted spectral efficiency. VCSEL DM leads to a transmitted signal which is just intensity modulated, thus a simplified coherent receiver can be used[6]: 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 approach has the drawback to cancel the COHD advantages in terms of bit error rate (BER) as a function of signal to noise ratio (SNR) with respect to DD, but avoids the use of optical carrier phase and frequency recovery, reducing the complexity of the receiver DSP and also relaxing the constraints on VCSEL and local oscillator (LO) linewidths[22].

3. ACCESS AND MAN SCENARIO EXPERIMENTAL RESULTS

The above transmitters and receivers have been experimentally evaluated to demonstrate the effectiveness of the proposed architectures and photonic technologies. In both scenarios an 18-GHz Vertilas VCSEL 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 to 9 mA, with an optimized modulation amplitude of 10 mA and 8 mA for DSB DMT for SSB DMT modulations respectively. SSB modulation is performed by exploiting a programmable optical filter (Finisar WaveShaper 4000S) featuring a super-Gaussian transfer function in case of access scenario[23], and the transfer function of 25-GHz standard WSSs in case of the MAN scenario[24]. A detuning of 8 GHz with respect to the signal carrier, removing the low-frequency signal sideband, performs the single sideband filtering operation.

3.1 50G PON transmitters based on DM VCSELs

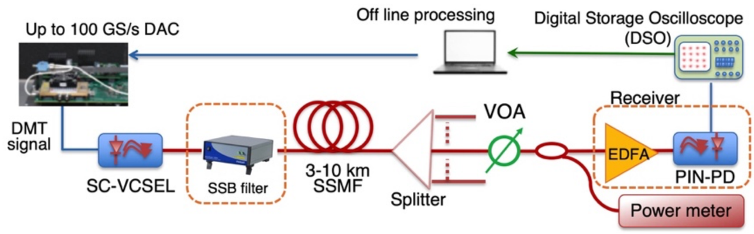

Fig.2 Experimental setup for 50G PON transceiver performance evaluation.

As depicted in Fig.2, the originated DMT signal is transmitted over different SSMF fiber spools, to evaluate CD tolerance of transmitters based on DM VCSELs accumulating a CD up to 160 ps/nm. As the VCSEL under test emits at 1533.5 nm, the target dispersion of 74 ps, equivalent to the cumulated CD of 20-km SSMF at 1342 nm, is obtained with a spool of less than 6 km SSMF[25]. The effects of CD on the DM-DMT signal are evaluated up to 10-km SSMF propagation while a variable optical attenuator (VOA) takes into account further optical distribution network (ODN) losses. Both DSB and SSB DMT variants have been tested: in case of DSB DMT the programmable optical filter was removed after the VCSEL. At the receiver end, we used a preamplified receiver, composed by an Erbium-doped fiber amplifier (EDFA) followed by a 25-GHz PIN photodiode, which can be anyhow substituted by a 25G APD[1]. The received signal is acquired by a Tektronix real-time oscilloscope (DPO 73304DX) with 8 bits vertical resolution, 100 GS/s and 33-GHz electrical bandwidth. Off-line processing provides digital symbol synchronization, CP removal, sub-carriers phase recovery, equalization and demodulation. Finally, the bit error rate (BER) count is obtained.

The evaluation of the performance is obtained by estimating at first the channel characteristics by transmitting a probe DMT signal with uniform QPSK loading, providing the signal-to-noise ratio (SNR) of each sub-carrier. Then, the measured SNRs are exploited for performing Chow's algorithm[26], for a bit- and power-loading procedure by setting the target BER at $4.6 \cdot 10^{-3}$, as for advanced hard-decision forward error correction (FEC) code with 7% overhead[27].

Fig. 3 a) shows the measured transmitted capacities as a function of the received power for back to back (BTB), 50 ps/nm and 100 ps/nm cumulated CD. In BTB condition DSB modulation outperforms SSB modulation just for very high received optical powers (ROPs), while SSB modulation shows a better sensitivity to the ROP, permitting to achieve 50 Gb/s even for -24 dBm. For 50 ps/nm and 100 ps/nm cumulated dispersion conditions, SSB modulation has always better performance and achieves a sensitivity to target 50 Gb/s transmission around -23 dBm for both propagation conditions, while DSB modulation requires -18 dBm and -17 dBm, respectively. Considering that the VCSEL output power ranges around 7 dBm, the N1 class can be successfully supported for SSB modulation (circles, continuous line) up to 140 ps/nm as shown in Fig. 3 b), allowing more than 35-km propagation in O band. On the other hand, for DSB modulation (triangles, dashed line) the N1 class allows a capacity between 30 and 41 Gb/s. Finally, if we focus on the CD target of 74 ps/nm, in Fig. 3 c) it can be seen that DSB modulation is able to target the transmission capacity of 50 Gb/s up to 24 dB ODN losses, while

SSB modulation bears 6-dB more losses, outperforming DSB modulation. The SSB modulation behavior is consistent with its higher resilience towards CD impairments.

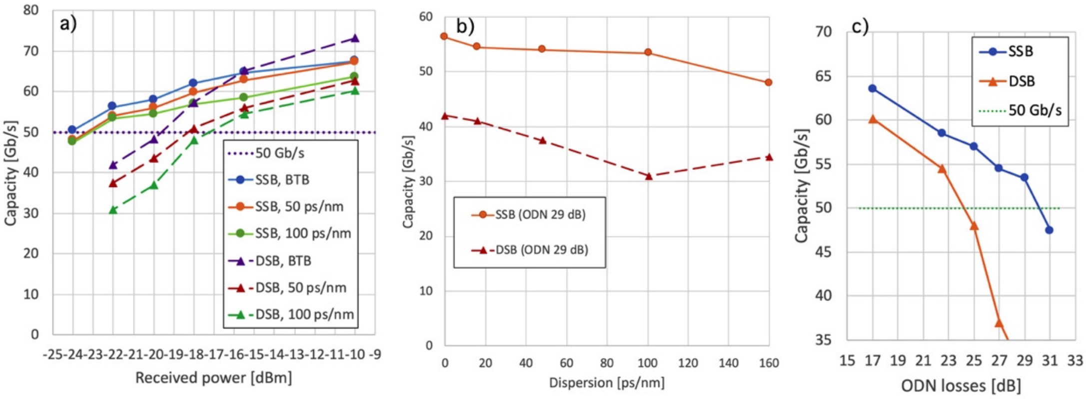

Fig. 3. a) Transmission capacities as a function of received power for SSB (circles) and DSB (triangles) DM-DMT VCSEL modulation for various accumulated CD. b) Transmission capacities for SSB (circles) and DSB (triangles) modulation as a function of cumulated CD for 23-dB and 29-dB ODN losses. c) Transmission capacities for SSB (circles) and DSB (triangles) modulation as a function of ODN losses for the target cumulated CD of 80-ps/nm.

The demonstrated performance, when considering the statistical distribution of the ROP within one typical PON deployment[2, 28], allows an increase in the throughput of a flexible PON employing the proposed DM-DMT VCSEL transmitter. For SSB DMT modulation the flexible VCSEL-based DS transmitter allows an aggregate rate of ~ 58 Gb/s, ~ 56 Gb/s and ~ 54 Gb/s respectively for BTB, 50 ps/nm and 100 ps/nm cumulated CD. On the other hand, for DSB DMT modulation we obtain an aggregate rate of ~ 46 Gb/s, ~ 41 Gb/s and ~ 37 Gb/s respectively for BTB, 50 ps/nm and 100 ps/nm cumulated CD. In case of a 20-km SSMF equivalent CD (around 70 ps/nm), the flexibility allows a 10% and 50% increase for SSB and DSB DMT with respect to the fixed-rate 50G PON and 25G PON respectively[29].

3.2 VCSEL-based system exploiting DMT DM and COHD for multi-Tb/s metro link

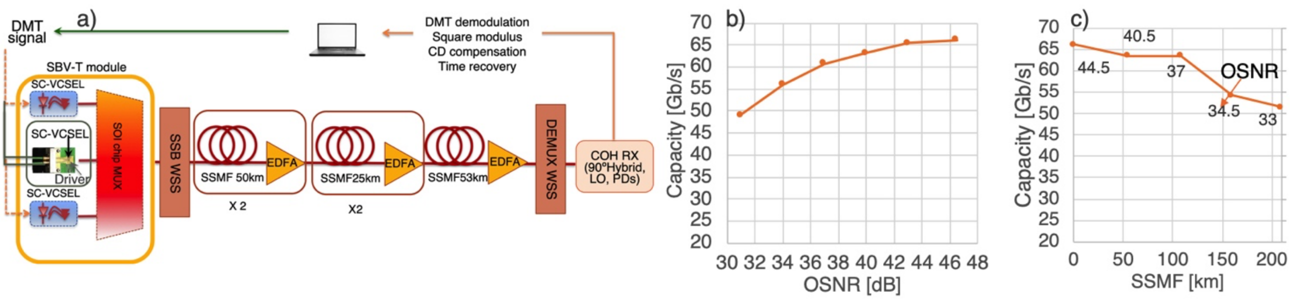

Fig.4 a) Experimental setup for MAN SBV-T performance evaluation. b) Total transported capacity vs OSNR in BTB condition. c) Total transported capacity vs SSMF propagation length for single-channel single-polarization transmission. The relative OSNR values measured at each SSMF reach are shown along the curve.

For the transmission performance evaluation in a MAN scenario we employ the experimental setup shown in Fig. 4a). Just the central 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 amplified 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. The DSP functions described in paragraph 2.4 are performed off-line. The same performance as DD is obtained when the received optical power is enough to neglect the photoreceiver electrical noise. Furthermore, channel deskew, digital symbol synchronization, CP removal, sub-carriers phase recovery and demodulation are performed. The same procedure described in paragraph 3.1 is used for channel estimation, bit and power loading and error count. Fig. 4(b) shows the BTB performance in terms of total transported capacity as a function of the optical SNR (OSNR). As expected, the capacity increases with OSNR, ranging from about 50 Gb/s for 31 dB OSNR to more than 66 Gb/s for

46 dB OSNR. Fig. 4(c) presents the capacities obtained after SSMF propagation for a single-channel single-polarization condition, while the measured OSNRs related to each SSMF reach for launch powers of +1 dBm are displayed 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 cascade of WSS filters has been emulated by the programmable optical filter: the impact of the cascade of WSS filters, which can be detrimental due to the filter narrowing effect[30], is not significant. 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[31].

4. CONCLUSIONS

As demonstrated by our recent results, the VCSEL technology adopted in specific transmitter and receiver architectures for PON and MAN scenarios can support the demanding requirements of future networks. In particular, DMT DM VCSELs achieving a per laser capacity beyond 50 Gb/s are the building blocks for 50G PON cost effective and energy efficient transceivers supporting link adaptation and PON resource usage optimization. In combination with massive photonic integration they can otherwise support S-BVT handling multi-Tb/s traffic in a very dynamic scenario, with flexible rate and distance adaptation up to hundreds of kms.

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