Flexible Transmitters Based on Directly-Modulated VCSELs for Next Generation 50G Passive Optical Networks

PAOLA PAROLARI,[1] * ALBERTO GATTO,[1] CHRISTIAN NEUMEYR[2], PIERPAOLO BOFFI,[1]

[1] *Dip. Elettronica Informazione e Bioingegneria, Politecnico di Milano, P.zza Leonardo da Vinci 32, 20133 Milano, Italy*
[2] *Vertilas GmbH, Garching, Germany*
**Corresponding author: paola.parolari@polimi.it*

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Discrete multitone (DMT) modulation, thanks to its water-filling nature, is proposed to enable flexibility in passive optical networks (PON) optimizing the PON resource usage. The exploitation of DMT signals to directly modulate long-wavelength vertical cavity surface emitting lasers (VCSELs) can provide energy-efficient transmitters for 50G PONs. At first, we present preliminary experimental measures employing both single sideband and dual sideband DMT modulation with already available short-cavity VCSELs operating in the third window to study the PON performance as a function of the accumulated chromatic dispersion and of the received power. The experimental results are further compared with simulations, demonstrating the effectiveness of the developed simulation tool. Then we study the performance of DMT-modulated transmitters based on next-generation short cavity VCSELs with higher bandwidth (up to 20 GHz), operating in the O band evaluating their chromatic dispersion resilience. Finally, considering the statistics of a commercially deployed PON, we demonstrate that DMT modulation, providing link adaptation, offers a significant increase of the total aggregated capacity with respect to single-carrier based fixed-rate PON, optimizing the PON resource usage with respect to the available power budget and the dispersion impairments. © 2020 Optical Society of America

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1. Introduction

Passive optical networks (PONs), deployed in 2019 to serve more than 500 million homes [1], pretty represent the only optical access networks type. The time division multiplexed passive optical networks (TDM-PON) based on outside distribution networks (ODN) including point-to-multipoint passive optical power splitters are the most commonly optical access network architectures deployed so far. In order to satisfy the continuous growth of bandwidth demand coming from the core network, next generation (NG)-PON2 standard tried to upgrade this topology introducing the wavelength dimension, obtaining a time and wavelength multiplexed (TWDM) -PON. The 8-wavelength topology can provide 80 Gb/s capacity, while if 16 point-to-point WDM channels are added, up to 240 Gb/s can be obtained [2]. However, the costs and technological challenges of burst-mode, tunable optical network units (ONUs) have not slacked off in these years and thus it will be unlikely that TWDM-PON would ever become the preferred fiber to the home (FTTH) solution [1].

To satisfy the bandwidth (BW) demand pushed by new "hungry" applications, the line rate increase beyond the 10 Gb/s seems the preferred solution. Actually, after the work on the standardization of 25G TDM-PON, IEEE and ITU are looking for the candidate modulation formats and technologies for the next 50-Gbit/s PON (50G-PON) [3]. As the success of previous generations of TDM-PONs has relied on the pre-existence of mature high-volume technologies, a natural choice would be to follow the IEEE 802.3bs 50-Gb/s lane standardization for data center intra-connect (DCI). However, PON links need to address much higher power budget and longer reaches (up to 20-40 km) with respect to point-to-point DCI optical links, thus alternative solutions should be evaluated [3].

Moreover, to satisfy the operators' request of more flexible networks, link adaptation could be adopted. In current standardized PONs, where bit-rates are fixed, all transceivers are designed for the maximum rate under worst case channel conditions, incurring in actual resource waste. A network employing link adaptation could instead offer several advantages such as a significant gain in the network capacity, the

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flexibility to adapt to high peak user rates and a more efficient usage of the network resources including energy consumption [4]. This can be accomplished by flexible modulation schemes: recent works in PONs mainly focus on pulse amplitude modulations (PAMs) [4, 5] and a few works on adaptive modulation either based on direct detection (DD) or coherent detection [6, 7].

On the other hand, discrete multi-tone (DMT) has been used for years for digital subscriber line (DSL) applications over copper cables. As for fiber optic communications, the DSL channel is time invariant with stationary noise. These characteristics enable DMT bit loading to optimally adapt the transmission capacity to the communication medium features. In particular, DMT can be employed to allow the use of low-bandwidth optical components to achieve high capacity, even maintaining the cost-effective intensity modulation/ direct detection (IM/DD) approach [8]. Recently, we have proposed to use a DMT directly modulated (DM) tunable vertical-cavity surface-emitting laser (VCSEL), to achieve a colorless ONU transmitter and we bridged up to 40-km standard single-mode fiber (SSMF) with a transported upstream (US) capacity greater than 25 Gb/s [9].

To realize PON transmitters for the line rate of 50 Gb/s in this paper we propose to exploit DMT direct modulation of fixed wavelength short cavity (SC) VCSELs, which are reliable both in O and C bands and provide high modulation bandwidths [10, 11]. Section 2 discusses the proposed solution including considerations on the energy efficiency of a VCSEL-based transmitter.

It is well known that chromatic dispersion (CD) is a main impairment for 50G-PON downstream (DS) signals which are then hosted in the O-band around 1342±2nm [12]; yet for a typical reach of 20-km SSMF the accumulated CD is around 74 ps/nm. In Section 3 we experimentally evaluate the performance of the DMT-flexible transmitter exploiting currently available C-band VCSELs using direct DMT modulation both in dual sideband (DSB) and single sideband (SSB) configurations. We analyze the performance as a function of the cumulated CD and up to 160 ps/nm.

In Section 4 we compare the obtained results with simulations achieved by developing a transmission model including the electro/optical and chirp transfer functions of the VCSELs. We then evaluate the performance of a 50G PON transmitters based on next-generation SC VCSELs under development.

In Section 5 we show the capabilities of direct DMT modulation to increase the data rate in IM/DD PONs with the use of standard hard-decision (HD) forward error correction (FEC). Statistics regarding a commercially deployed PON is considered to evaluate the impact of the proposed transmitter on the flexible PON aggregated capacity.

2. 50G PON VCSEL based flexible transmitters

VCSEL sources are characterized by a light emission normal to the semiconductor layer structure, with respect to traditional edge-emitting semiconductor lasers, such as distributed feedback (DFB) lasers, that allows simple and cost-effective on-wafer test of VCSEL chips.

In the short wavelength region of up to ~1-μm, GaAs VCSELs are massively employed in high-speed data communications as well as for computer and datacom applications. Most of these VCSELs are multi-transverse mode (MM) sources and are compatible with inexpensive optical coupling into multi-mode fibers (MMFs). On the other hand, MM VCSEL lack of specific control on mode forming dynamics and mode polarization prevents their use in km-reach connections for which single-mode (SM) emission has been adopted, targeting on-off keying (OOK) operation up to 60 Gb/s on few hundred meters of MMF [13].

In order to design low-cost and energy-efficient transmitters for flexible 50G PON, devices with emission in the O- and C-band are needed; this is assured by long-wavelength (LW) InP VCSELs. In particular, the proposed LW VCSEL 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 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 [14]. Just the dielectric distributed Bragg reflectors differ between O and C band SC devices while both 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, 11, 15].

Although long-wavelength VCSELs do not show commercial mass production, they appear very promising for applications in medium-reach connections employing SSMFs. In particular high data rate transmission can be achieved combining VCSEL use and direct DMT modulation. DMT is an effective modulation technique for stationary media, employed for decades in copper links, but also appropriate for fiber-based PON connections [16]. Thanks to its water-filling nature, DMT can distribute the power and the modulation according to the spectral transfer function of the transmission link. The signal-to-noise ratio (SNR) of each subcarrier is estimated during the training phase, and a suitable bit loading is performed to maximize the whole transported capacity with respect to single-carrier modulation performance. DMT modulation shows advantages not only in terms of performance, but also in terms of flexibility and compatibility. In case of optical networks, this flexibility allows to optimize the transmitted capacity as a function of losses or dispersion impairments, enabling to boost the performance of very short links [17].

The adopted InP LW SC VCSEL sources are optimized to emit either in the O-band or in the C-band providing output optical powers up to 7 dBm at bias currents in the range of 5-10 mA. In the experimentation we employed already available 17-GHz bandwidth VCSELs, but in the frame of the European H2020 project PASSION VCSELs with a higher bandwidth (up to 25 GHz) are being developed [18]. The use of 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 actually constituted by the VCSEL itself and by the laser driver circuit. Its power consumption can be calculated taking into account that the VCSEL bias current is quite low, around 9 mA, and that the needed modulation current can be provided by commercially available linear drivers for PAM4 applications [19]. Considering the target capacity of 50 Gb/s, the VCSEL energy consumption per bit is about 0.7 pJ, while the power consumption of the drivers supporting signal rates up to 56Gb/s is 230 mW. Hence, the total energy consumption per bit is about 5.3 pJ, that is pretty low with respect to the consumption of optical modules including standard DFB lasers and silicon photonics chips for external modulation [20]. On the other hand, it is worth noting that in case it is mandatory to stabilize the laser wavelength as to obtain SSB DMT modulation the power consumption of the transmitter nearly quadruplicates [21]. Finally, advanced modulation formats such as DMT or PAM use digital signal processing (DSP) blocks (including the digital-to-analog converters (DACs) and analog-to-digital converters (ADCs)) present in the application specific integrated circuit (ASIC) to actually send the high-bandwidth input/output signals to the optical module. Due to the higher number of operations required to generate DMT signals, the power consumption of the CMOS-based electrical interface and relevant signal processing components for DMT is nearly three times higher than for PAM4 modulation, around 50 pJ/bit [22]. Nevertheless, advances in CMOS technology will bring about energy saving in the RF components, including ADCs and DSP blocks [23] and DSP-efficient FFT and simplified algorithms [24] can further reduce ASIC power consumption. InP VCSEL technology combined with DMT direct modulation thus have the capability to implement alternative sustainable transmitters for 50G PON applications.

3. Experimentation

The performance of the transmitter based on DM-SC VCSELs is evaluated by the experimental setup of Fig. 1, emulating a splitter-based PON. Both DSB DMT and SSB DMT modulations are performed in order to study their resilience towards CD. The available VCSEL emits at 1533.5 nm, but it shows the same characteristics in terms of chirp and E/O bandwidth of 1.3 µm devices. Thus, ¼ of SSMF length is needed to accumulate in the C band a dispersion equivalent to the O band one, e.g. a spool of less than 6 km SSMF is needed to accumulate more than 74 ps/nm corresponding to 20-km SSMF transmission at 1342 nm [12]. The obtained experimental results are also used as benchmarks for the development of a suitable simulation tool as further described in Section 4.

A. 3 Experimental set up

At the optical line terminal (OLT), the transmitter hosts a 17-GHz LW SC VCSEL, which is directly modulated by a DMT signal generated by a Micram 100-GS/s digital to analog converter (DAC) with 35-GHz electrical bandwidth and 6-bit vertical resolution, through a 25GHz electrical driver. 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 bias current is set to 9 mA, with an optimized modulation amplitude of 10 mA and 8 mA for DSB DMT and SSB DMT modulations respectively. SSB modulation is performed by exploiting a programmable optical filter (Finisar WaveShaper 4000S) featuring a super-gaussian transfer function [25], which is detuned by 8 GHz with respect to the signal carrier, removing the low-frequency signal sideband.

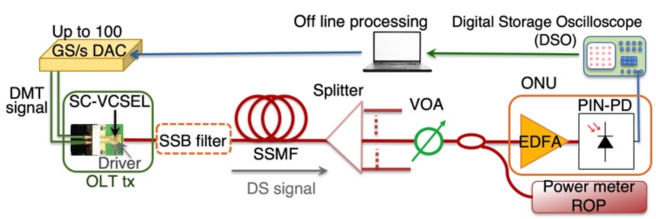

Fig. 1. Experimental setup.

The back to back (BTB) performance is compared with the results obtained after propagation in different spools of SSMF to cumulate up to 160 ps/nm CD; a variable optical attenuator takes into account further ODN losses and varies the received optical power (ROP). At the ONU end, we used a preamplified receiver, composed by an Erbium-doped fiber amplifier (EDFA) followed by a 25-GHz PIN photodiode; anyhow this configuration can be easily replaced by a 25G avalanche photo diode (APD).

The received signal is acquired by a Tektronix real-time oscilloscope (DPO 73304DX) with 8 bits vertical resolution, 100 GS/s sampling rate 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.

B. 3 Experimental results

The DMT modulation allows to adapt the modulation of each subcarrier to the channel characteristics, which are at first estimated by transmitting a probe DMT signal with uniform QPSK loading, providing the SNR of each sub-carrier. Then the measured SNRs are exploited for performing Chow's algorithm, i.e. a suitable bit- and power-loading procedure for obtaining a good approximation of the highest bit rate achievable by the transmission system [26]. We set the target BER at $4.62 \cdot 10^{-3}$, corresponding to the pre FEC BER of advanced HD FEC codes with 7% overhead [11].

Fig. 2 shows the measured transmitted capacities as a function of the ROP for BTB and 100 ps/nm cumulated CD. In BTB condition SSB modulation outperforms DSB modulation: although for high received powers DSB capacity is slightly higher than the SSB one, SSB modulation shows a better sensitivity, permitting to achieve 50 Gb/s capacity even for -24 dBm ROP. As expected, due to SSB resilience towards CD, for 100 ps/nm cumulated dispersion conditions, SSB modulation shows again better performance and achieves a sensitivity to target 50 Gb/s transmission around -23 dBm, while DSB modulation requires -18 dBm.

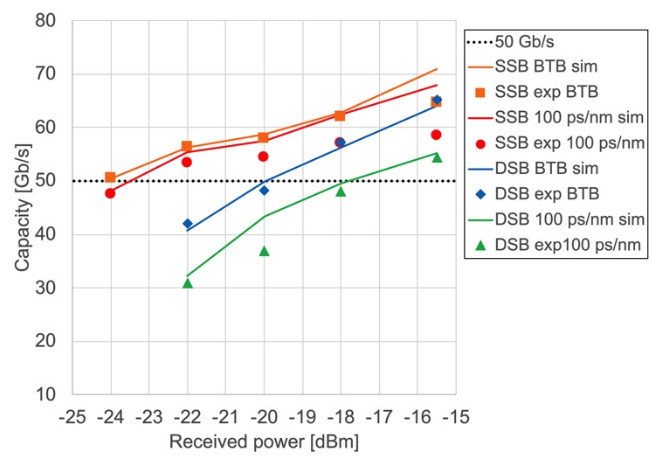

Fig. 2. Transmission capacities as a function of ROP for SSB DMT (orange and red) and DSB DMT (blue and green), in BTB (squares and diamonds) and after 100ps/nm cumulated CD (circles and triangles). Experimental results are represented by full markers and simulations by lines.

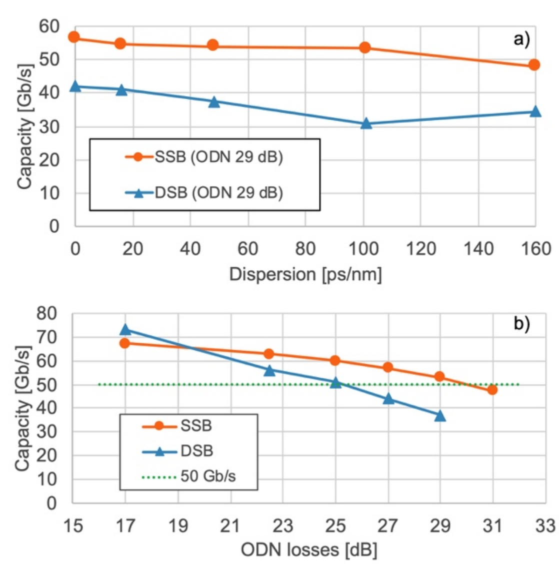

Fig. 3. Measured transmission capacities for SSB (circles, orange line) and DSB (triangles, blue line) modulation as a function of a) cumulated CD for 29-dB ODN losses; b) ODN losses for 100-ps/nm cumulated CD.

Fig. 3 a) shows the measured transmission capacities as a function of cumulated CD dispersion for 29 dB ODN losses, considering that the VCSEL output power ranges around 7 dBm. The PR30 class can be successfully supported for SSB modulation (circles, orange line) up to 140 ps/nm corresponding to more than 35 km propagation in the O band. Conversely, in case of 29-dB ODN losses DSB modulation (triangles, blue line) reaches capacities between 30 and 41 Gb/s, the swinging trend is due to the frequency location and depth of the dip present in the SNR transfer function due to the interplay between the chirp and CD, which prevents the loading of a few central subcarriers with high signal constellations [27]. Finally, if we focus on the CD of 100 ps/nm, in Fig. 3 b) it can be seen that DSB modulation is able to target the transmission capacity of 50 Gb/s up to 25-dB ODN losses, while SSB modulation bears 5-dB more losses, outperforming DSB modulation. The SSB modulation behavior is consistent with its higher resilience towards CD impairments.

4. Study of performance of next generation VCSEL based 50G PON transmitter

In order to study the performance of transmitters based on new generation LW SC VCSELs, currently under development [18], we conceive a simulation tool whose accuracy has been verified by comparison with Section 3 measurements.

A. 4 Simulation tool development and validation

The modeling tool based on Matlab™ includes all the transmitter, propagation, and receiver blocks. The DM VCSEL is modeled considering both the intrinsic modulation properties and the extrinsic device parasitic components. The overall electrical modulation frequency response is described by the relaxation resonance frequency, the intrinsic damping factor and the parasitic cut-off frequency [27]. The setting of these parameters allows to model the VCSEL frequency response. The VCSEL is also characterized by its linewidth, which is set to 5 MHz, as actually measured in current SC devices. DM is performed by varying the applied current, setting a bias current and adding a variable modulation. This influences the chirp amount associated with DM which is accounted for by the linewidth enhancement factor, α, and by the laser-specific adiabatic constant related to thermal effects, κ. The α factor impacts on both the chirp transient and adiabatic components, while the κ factor influences only the adiabatic chirp. In the following simulations the α and κ factor are 3.7 and 1.52×10^{13}; these values were measured for the SC VCSELs under test in Section 3 [27]. For the modelling of Section 3 measurements, the receiver block is constituted by a pre-amplified linear 25-GHz PIN PD, characterized by a noise equivalent current (NEC) of 40 pA/√Hz and a responsivity of 0.7 A/W; moreover, due to the presence of the EDFA, the optical signal to noise ratio (OSNR) is varied accordingly to the input (i.e. received) optical power.

To validate the simulation tool the experimental conditions are reproduced: the DMT signal is composed by 256 sub-carriers in 20 GHz range, with a 2.1% CP; the bias current is set to 9 mA, with a modulation amplitude of 10 mA and 8 mA for DSB DMT and SSB DMT modulations respectively. The SSB signal is obtained by detuning of 8 GHz a 21-GHz full-width half-maximum (FWHM) super-gaussian filter in order to select half of the 20-GHz DMT DSB spectrum, while preserving the optical carrier. Both the ROP and the OSNR are varied during simulations according to the performed measurements. The obtained results are shown in Fig. 2 as continuous lines matching the color of the measured capacities, represented by the markers, for BTB and 100 ps/nm CD. In both transmission conditions there is a good agreement between simulations and experimental results, although for high ROP values (e.g. -15.5 dBm) the simulations for SSB DMT modulation slightly overestimates the obtained capacities. The overestimation is due to the fact that for high ROP the EDFA pre-amplified PIN PD presents for SSB (which at equal optical power has a double effective signal amplitude with respect to DSB) a saturated behavior which is not accounted for in simulations.

Indeed, when we simulate the performance of next generation VCSEL-based transmitters, we employ in the receiver-block a stand-alone 25 GHz APD that is actually going to be hosted in the ONU transceivers [3]. 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 [28, 29]. These values are used to obtain next sections results.

B. 4 Performance evaluation with next generation VCSEL

After validating the simulation tool, we employ it in order to evaluate the performance of transmitters based on next generation O-band SC VCSEL in case of advanced HD FEC with 7% overhead, providing a pre-FEC BER of $4.62 \cdot 10^{-3}$. The VCSEL parameters modeling the frequency response are set in order to achieve a modulation bandwidth of 20 GHz; the bias current is 9 mA, while the modulation amplitudes are separately optimized for DSB and SSB modulations in the case of 105 ps/nm accumulated dispersion and are set respectively to 14 mA and 12 mA. Moreover, in the case of SSB modulation the filter detuning was optimized to 10 GHz. In both cases the optimization aims at the provision of the highest capacity.

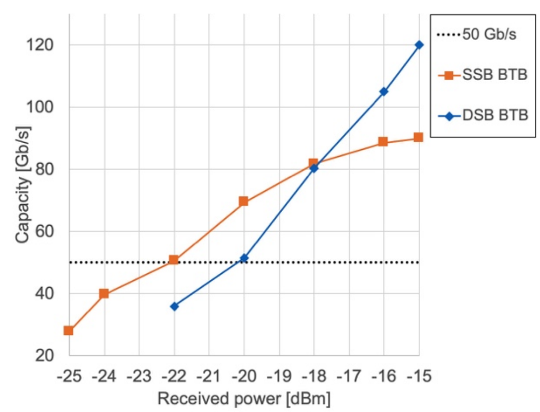

Fig. 4. BTB capacity as a function of the ROP for SSB DMT (orange squares) and DSB DMT (blue circles).

Fig. 4 shows the results for the obtained capacity as a function of the ROP in BTB: SSB-DMT outperforms DSB modulation for lower ROP, while for ROP higher than -18 dBm a limitation to the performance of SSB-DMT appears, leading to a saturation of the achievable capacity at high optical powers. The reduction of the SSB capacity is due to the signal-signal beat interference (SSBI), a self-interfering term originated by the direct detection operation [30]. The sensitivities for 50 Gb/s capacity are -22 dBm and -20 dBm for SSB and DSB DMT transmitters respectively. This performance is comparable with recent results obtained with a single rate 50-Gb/s PAM-4 transmitter using an O-band directly modulated laser (DML) and 20-GHz optics which achieved a 50 Gb/s sensitivity of -18.5 dBm at 10^{-3} BER [31,]. The PR 30 link budget can thus be supported as at bias current around 10 mA the VCSEL output power is around 7 dBm. When we include the impact of CD on the transmission of the DM signals the better performance of SSB DMT are even more evident. As expected, in fact, SSB DMT presents a higher resilience towards CD; the study is summarized in Fig. 5. The contour plot demonstrates that for ROP higher than -22 dBm and for CD up to 140 ps/nm (corresponding to the dispersion of 40 km SSMF) SSB DMT modulation allows a transmission capacity higher than 50 Gb/s (turquoise-green- yellow sectors), while between -25 dBm and -22 dBm (blue sectors) the capacity ranges between 28 Gb/s and 50 Gb/s.

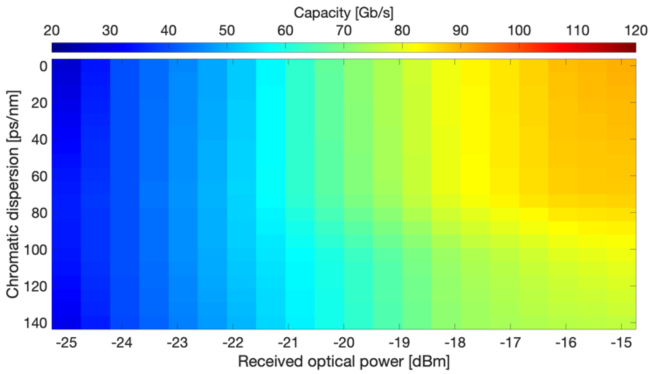

Fig. 5. Contour plot of the SSB DMT transmission capacity as a function of ROP and cumulated CD. Capacity higher than 50 Gb/s (turquoise-green- yellow sectors) capacity between 28 Gb/s and 50 Gb/s (blue sectors).

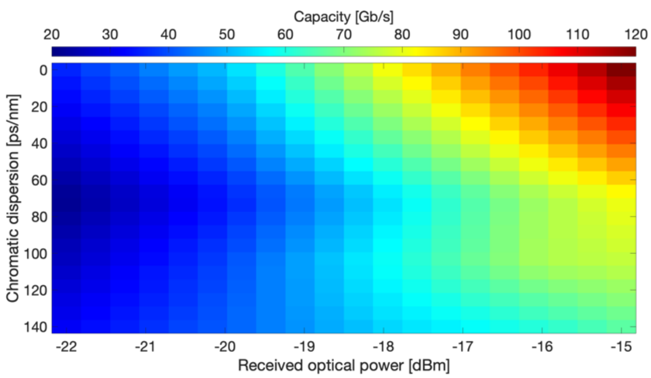

Fig. 6. Contour plot of the DSB DMT transmission capacity as a function of ROP and cumulated CD. Capacity between 20 Gb/s and 50 Gb/s (blue sectors) capacity higher than 50 Gb/s (turquoise-green-yellow-red sectors).

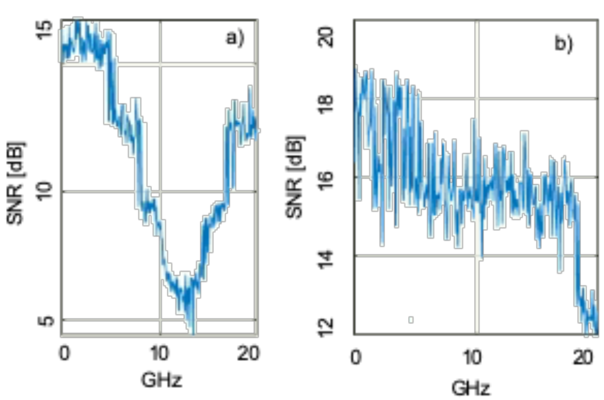

Fig. 7. Subcarrier SNR after bit-loading a) DSB DMT transmission with ROP of -18 dBm, 74 ps/nm CD, capacity of 53.7 Gb/s b) SSB DMT transmission with ROP of -22 dBm, 74 ps/nm CD, capacity of 52.7 Gb/s

Fig. 6 shows the results concerning DSB DMT, for which the CD impact on transmission performance is more significant. Capacities higher than 50 Gb/s and for CD up to 140 ps/nm are achieved only for ROP higher than -19 dBm (green-yellow-red sectors); however, for CD lower than 70 ps/nm (corresponding to 20 km SSMF) and ROP higher than -18 dBm more than 80 Gb/s capacity are supported.

The SSB DMT higher resilience to CD is confirmed by comparing Fig. 7 a) and b) where the actual SNR after bit loading is displayed after propagation in 20 km SSMF (74 ps/nm cumulated CD) for DSB and SSB DMT, respectively. The achieved capacity in both cases is slightly higher than 50 Gb/s but a 4dB higher ROP is necessary for the DSB DMT signal. Fig. 7 a) in fact shows a dip in the SNR around 10 GHz, this is consistent with the frequency dips present in the fiber channel transfer function due to the interplay between the specific chirp and CD. On the contrary (Fig.7 b)) the SSB SNR does not present any dip due to the interplay between chirp and CD, constantly decreasing for higher frequencies. The dip presence in DSB DMT highly reduces the allowed constellation level that can be supported by the subcarriers around the dip frequency, providing an overall performance worse than the SSB DMT one.

5. Discussion

Flexibility is considered a major characteristic for the future efficient access optical networks. This feature can be obtained by link adaptation accomplished by flexible modulation schemes, offering a significant gain in the network capacity, the adaptation to high peak user rates and an efficient usage of the network resources including energy consumption. The proposed VCSEL transmitter, based on DM DMT modulation, providing bit and power loading, is a promising candidate to enable the link adaptation feature in 50G PON. The advantages with respect to current PONs, where all transceivers bit-rates are fixed, are estimated by evaluating the gained throughput improvement. In particular we consider the statistical distribution of the ROPs collected in one-operator GPON deployments [4]; as the ROP range presents a standard normal distribution [7, 32] we fitted the statistics of the data set of the GPON deployment with a normal distribution [4]. The obtained Gaussian curve is shown in Fig. 8, which displays the number of ONUs as a function of their corresponding ROP; each ROP slice corresponds to one standard deviation.

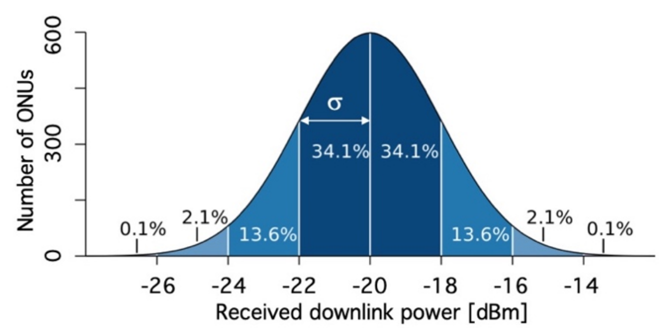

Fig. 8 Normal distribution fitting the ONU received optical power, according to the data set of the deployed GPON presented in [4].

Only a small portion of the ONUs is close to the prevalent received power sensitivity limit of −27 dBm, while more than 83% of the ONUs in the network has a ROP of at least -22 dBm. It is thus clear that the use of fixed rate transmitters designed for the maximum rate under worst case channel conditions incurrs in actual resource waste. Thanks to the ROP statistical distribution and to the results presented in Section 4 for 20-km SSMF (around 74 ps/nm CD), we calculate the cumulative sum of the aggregated data rates as a function of the percentage of users. As

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we included for all the ONUs (i.e. for all the ROPs) the CD penalty associated with 20-km SSMF transmission the results displayed in Fig 9 underestimate the actual overall throughput in particular for DSB DMT transmitters, while SSB DMT performance are almost not impacted by CD up to 100 ps/nm. Anyhow in case of SSB the flexible VCSEL-based PON exploiting DMT has a throughput of ~ 66 Gb/s, with a 30% increase with respect to the fixed-rate 50G PON. In case of DSB, the flexibility provides ~ 37 Gb/s, with a 48% increase with respect to fixed-rate 25G PON.

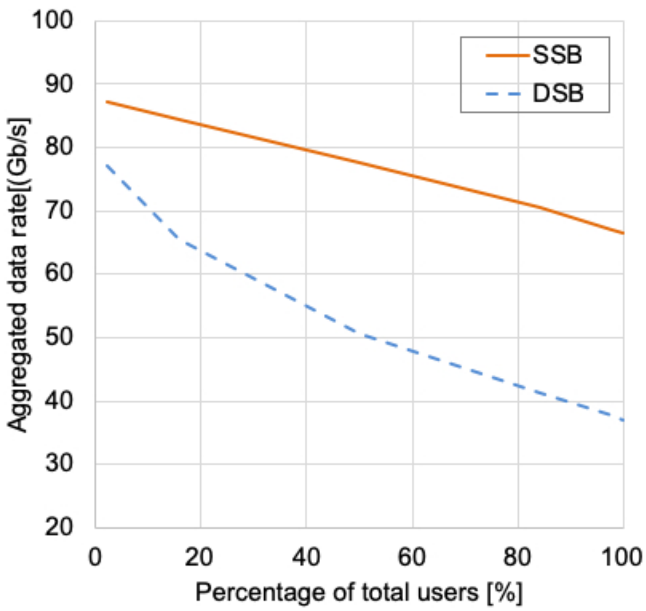

Fig. 9 Cumulative sum of the aggregated data rates as a function of the percentage of users who experience the aggregated data rate on the y-axis or higher (SSB DMT orange continuous, DSB DMT blue dashed line).

Furthermore it is possible to evaluate the performance of the proposed transmitters referring to a generic typical PON in which we can assume that the ROP has a standard normal distribution in a 9-dB range, accounting for transmitter output power variations, fibre drop and splices loss ranges, as specified in ITU-T PON standards [32].

Table 1 Throughput for a generic typical PON

	SSB DMT	**DSB DMT**
25 Gb/s sensitivity @ -3σ	63.6 Gb/s (84% >50Gb/s)	73.1 Gb/s (84% >50Gb/s)
25 Gb/s sensitivity @ -3σ and 20-km CD impairment	63.8 Gb/s (84% >50Gb/s)	49.5 Gb/s (50% >50Gb/s
N1 (-3σ ROP @ 29 dB ODN)	81.5 Gb/s (99.9% >50Gb/s)	84.8 Gb/s (95.1%> 50Gb/s)
N2 (-3σ ROP @ 31 dB ODN)	71 Gb/s (95.1%> 50Gb/s)	61.8 Gb/s (63%> 50 Gb/s)
E1 (-3σ ROP @ 33dB ODN)	56.1 Gb/s (63%> 50 Gb/s)	-

Table I shows the throughputs for both SSB and DSB DMT transmitters according to the results of Section 4 and taking into account that, as already discussed, the transmitter output power could range around 7 dBm. Moreover, for each case, in the parenthesis the percentage of ONUs supporting at least 50Gb/s capacity is displayed. If we suppose to guarantee at least 25 Gb/s capacity to all the PON ONUs, i.e. we align the -3σ point of the ROP standard normal distribution with the 25 Gb/s receiver sensitivity respectively for SSB DMT and DSB DMT, we can calculate the overall PON throughput [32]. In both cases the guaranteed throughput is higher than 60 Gb/s (second row of Table I), otherwise, if we include the CD impairment associated with 20-km transmission, the capacity provided by SSB DMT modulation is unchanged, thanks to SSB CD resilience, whereas the DSB DMT throughput drops slightly below 50 Gb/s (third row of Table I). Nevertheless, these results are very encouraging with respect to other proposed multi-rate transmitters and confirm DMT advantages due to the provided fine line-rate granularity [32].

On the other hand, if we consider the different PON power budget classes we need to align the -3σ point of the ROP standard normal distribution with the respective class ODN losses by taking into account the transmitter output power. Looking at the last three rows of Table I it can be seen that SSB DMT allows more than 50 Gb/s throughput up to class E1 (33 dB ODN), moreover the SSB 50 Gb/s sensitivity coincides with N1, i.e. 29 dB, ODN loss. DSB DMT supports only N1 and N2 classes, although with more than 60 Gb/s throughput. Finally, in both cases not all the PON transceivers can allow data transmission for E2 (35 dB) class.

6. Conclusion

We proposed the use of DMT in PONs as a flexible modulation to maximize the network aggregated capacity according to the available power budget. In particular, we analyzed the performance of flexible PON transmitters based on novel LW SC VCSELs exploiting DMT DM both in SSB and DSB configurations. InP VCSEL technology is a cost-effective solution for PON sources and in combination with DMT DM and DD guarantees the PON sustainability in terms of power consumption (5.3 pJ/bit for the 50G optical module transmitter).

Preliminary experimental measures with already available SC VCSELs operating in the third window allowed to evaluate the PON performance as a function of the accumulated CD and of the received power, demonstrating the possibility to support PR30-class 50G PON in case of SSB DMT modulation even up to 100-ps/nm CD.

The experimental results validated also the effectiveness of the developed simulation tool used to study the behavior of transmitters based on next-generation SC VCSELs with higher bandwidth operating in the O band. The SSB and DSB DMT modulated transmitter performance have been analyzed as a function of ROP and accumulated CD. These results together with the statistics of a commercially deployed GPON allowed to evaluate the total aggregated network capacity increase, granted by the flexible transmitters with respect to single-carrier based fixed-rate PON. Optimizing the PON resource usage according to the available power budget allows a 30% increase with respect to the fixed-rate 50G PON when employing SSB DMT and a 48% increase with respect to fixed-rate 25G PON in case of DSB DMT. The analysis of the proposed transmitters in a generic typical PON confirms the results of the deployed GPON, evidencing DMT advantages due to the provided fine line-rate granularity with respect to other proposed multi-rate transmitters e.g. based on PAM [32], although at the expense of a higher power consumption of the CMOS DSP blocks [22]. Moreover, both transmitters support N1 and N2 PON classes with a throughput higher than 60 Gb/s and only SSB DMT the E1 PON class with a throughput higher than 50 Gb/s.

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