Dual modulation VCSEL-based sustainable transceiver for SSB DMT signals transmission

Stefano Gaiani
Dept. Electronics, Information and Bioengineering
POLITECNICO DI MILANO
Milan, Italy
stefano.gaiani@polimi.it

Paola Parolari
Dept. Electronics, Information and Bioengineering
POLITECNICO DI MILANO
Milan, Italy
paola.parolari@polimi.it

Alberto Gatto
Dept. Electronics, Information and Bioengineering
POLITECNICO DI MILANO
Milan, Italy
alberto.gatto@polimi.it

Pierpaolo Boffi
Dept. Electronics, Information and Bioengineering
POLITECNICO DI MILANO
Milan, Italy
pierpaolo.boffi@polimi.it

***Abstract*—Single sideband DMT signal performance is analyzed in order to achieve high capacity and high spectral efficiency over 50-km uncompensated SMF. A sustainable implementation of the SSB DMT-based transceiver is proposed by means of a VCSEL source and a dual-modulator scheme, providing SSB without optical filtering and Hilbert transform implementation. Moreover, Kramers-Kronig detection, made possible by SSB, is studied at the receiver to effectively compensate the chromatic dispersion with direct detection.**

Keywords—SSB, DMT, VCSEL, Kramer-Kronig receiver.

I. INTRODUCTION

Nowadays, high-capacity optical transceivers are required to meet the increasing traffic demand in metro, access and inter-datacenter networks. Sustainability in terms of cost and power efficiency is mandatory, combined to high spectral efficiency and tolerance to propagation fiber impairments, such as the chromatic dispersion (CD), considering that standard coherent detection appears not convenient for such applications. The use of single sideband (SSB) modulation [1] is a promising approach to compact the wavelength-division multiplexed (WDM) channels, and to make the modulated signal more robust to CD in uncompensated links, in case of intensity modulation – direct detection (IM-DD) sustainable systems. With respect to dual sideband (DSB) signals, SSB allows to double the spectral efficiency and to halve the WDM spacing, or to relax the requirements in terms of stability of the laser emitted wavelength. Moreover, SSB is more resilient to the power fading induced by the CD when DD is applied.

To achieve a sustainable transceiver, also sustainable laser sources, such as vertical cavity surface emitting lasers (VCSELs), can be used. This kind of optical source is already massively employed for datacom interconnections. Today, InP long-wavelength (LW) VCSELs emitting in the C band are available on the market and can be used for telecom applications. In order to target high rate per channel by exploiting VCSEL direct modulation, multicarrier modulation formats, such as discrete multitone (DMT) appear very attractive. DMT permits to tailor the transmission to the system condition thanks to bit and power loading, matching the limited modulation bandwidth of the VCSEL and the nonuniform response of the whole communication system [2]. Starting from LW VCSEL with electrical modulation spectrum below 20 GHz, almost 70-Gb/s rate has been demonstrated in the back-to-back condition thanks to DMT [3].

On the other side, Kramers-Kronig (KK) detection [4] can be exploited at the receiver as a sustainable solution, avoiding coherent detection: KK allows the optical field reconstruction after DD, and hence the CD compensation. The SSB spectrum with a strong carrier component is a mandatory requirement for applying KK processing.

In this paper, we analyze the performance of a SSB DMT-modulated signal generated by a LW VCSEL in a medium-reach IM-DD system, up to 50 km of standard single-mode fiber (SSMF). To preserve the sustainability of the system, the SSB modulation is not achieved by means of a complex in-phase and quadrature (IQ) modulator driven by the Hilbert transform, nor thanks to an optical filter, precisely aligned to the laser emission wavelength. On the contrary, we exploit the dual modulation (DM) scheme [4]: the combination of digital filtering, phase variations induced by the direct modulation of a VCSEL and IM provided by a single Mach-Zehnder Modulator (MZM) is used to suppress a lateral sideband and to generate a SSB signal. The employment of an electro-absorption modulator (EAM) is also considered to provide DM scheme [5], [6].

The performance of the SSB DMT signal generated by the DM cascade, also supported by KK detection, is compared with the behavior achieved by the employment of coherent detection, used to get the target performance. The analyzed approach, based on DM and KK, maintains the system sustainability, while allowing digital CD compensation. We demonstrate that thanks to the developed KK-based SSB DMT system, almost 70-Gb/s capacity per wavelength is transported over 50 km SSMF, providing the possibility of high compactness in WDM aggregation.

II. SIMULATION SETUP

A. SSB generation by DM scheme

The DM scheme has been implemented by the cascade of a directly modulated VCSEL and an intensity modulator, driven with different signals. The former induces a suitable phase modulation needed for SSB generation, while the latter permits to generate the required DMT signal. As intensity modulator, we considered a single MZM, biased at the quadrature point, providing high-quality IM, not introducing

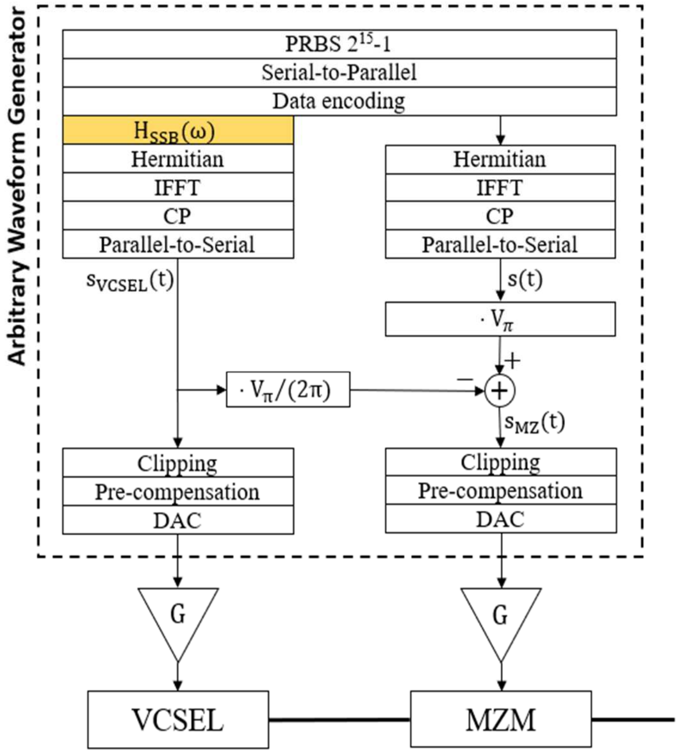

Fig. 1. Optical SSB DMT signal generation algorithm for the VCSEL-MZ dual modulator architecture.

undesired chirp contributions when used in the push-pull configuration. An alternative to the MZM is the employment of an EAM, biased in the linear region, adding a further phase modulation due to the chirp.

Fig. 1 shows the block diagram related to the DM-based generation of the optical SSB DMT signal. First, the transmitted symbols are encoded starting from a pseudo-random bit sequence (PRBS) having a 2^{15}-1 length. This encoding is based on the system SNR curve (estimated a priori) and exploits the bit and power loading approach. After the encoding, two copies of the obtained spectrum are realized. For what concerns the MZM replica, the Hermitian spectrum is added (since a real-valued driving signal is wanted) and then the IFFT, the cyclic prefix (CP) addition and the parallel-to-serial operation are performed. The resulting signal is named s(t). The VCSEL copy goes through the same steps, but first a digital filter having the frequency response:

$$H_{SSB}(\omega) = \frac{2\pi}{\alpha_{VCSEL}\sqrt{1+\Omega^2}} \cdot e^{-i\left\{\frac{\pi}{2} - \arctan(\Omega)\right\}} \tag{1}$$

is applied to the spectrum, where α_{VCSEL} is the VCSEL linewidth enhancement factor, κ is the VCSEL adiabatic chirp parameter, P_0 is the VCSEL average output power and $\Omega = \kappa P_0/\omega$. This filter derives from the SSB signal generation conditions, which were retrieved in a single-sinusoid context and then extended to a DMT signal as it is a superposition of harmonics. The resulting waveform is named $s_{VCSEL}(t)$. The next step is the subtraction between the two signals, so that the MZM can cancel the undesired VCSEL IM but maintaining the induced phase modulation, which is required to fulfill the SSB conditions. Therefore, the driving signals for the VCSEL and the MZM are respectively:

$$s_{VCSEL}(t) = s(t) * h_{SSB}(t) \tag{2}$$

$$s_{MZ}(t) = V_\pi s(t) - \frac{V_\pi}{2\pi} s_{VCSEL}(t) \tag{3}$$

where $h_{SSB}(t)$ is the impulse response of the SSB digital filter, V_π is the MZM π-voltage and * is the convolution product. The coefficients in Eq. (3) are needed for the cancellation of the VCSEL IM and to make the amplitudes of the first order terms equal. Then, the two waveforms undergo a clipping process to limit their peak-to-average power ratio (PAPR). Finally, the two signals are pre-compensated to mitigate the impact of the devices frequency responses and quantized with a digital-to-analog converter (DAC). Assuming to be in a small signal regime and limiting to a first order analysis, the output optical field is:

$$E_{out}(t) = \sqrt{P_0 \cdot \left[1 + G_{VCSEL} s_{VCSEL}(t)\right]} \cdot e^{i \cdot s_H(t)} \cdot e^{i \cdot \phi_N(t)} \cdot \\ \cdot \cos\left\{\frac{\pi}{2} \cdot \frac{2 G_{MZ} s_{MZ}(t) - V_B}{V_\pi}\right\} \tag{4}$$

where $s_H(t)$ is the Hilbert transform of the signal s(t), $\phi_N(t)$ is the VCSEL phase noise, G_{VCSEL} and G_{MZ} are the driving signals amplifications for the VCSEL and the MZM respectively and $V_B = V_\pi/2$ is the bias voltage of the MZM.

B. *Simulation parameters*

The DMT signal is composed by 255 subcarriers with a 78.23 MHz spacing to cover a 20 GHz-bandwidth without any gap at low frequencies. The CP length is equal to the 2.1% of the frame length.

The transmitter employs a 17 GHz-bandwidth VCSEL (with 5 MHz linewidth [8]) and a MZM with a 20 GHz-bandwidth and a π-voltage equal to 5 V ([7]). The VCSEL main parameters for the chirp are: $\alpha_{VCSEL} = 3.7$, $\kappa = 15.2$ GHz/mW ([8]) and $P_0 = 2.6$ mW. For a comparison, it is considered also the transmitter constituted by the cascade of the VCSEL and an EAM with linewidth enhancement factor equal to 0.5 ([6]) and a 20 GHz-bandwidth. The corresponding SSB signal generation algorithm is reported in [5].

The optical signal is launched into a standard single-mode fiber (SSMF) with a power equal to 3 dBm. This fiber is characterized by a CD coefficient equal to 16 ps/(nm·km) and an attenuation of 0.25 dB/km.

At the receiver, after a 25 GHz HWHM optical filter useful to suppress the out-of-band noise, the SSB DMT signal power is set at -3 dBm; the signal is then detected with a photodiode (PD) having 0.7 A/W-responsivity, 25 GHz-bandwidth and 100 pA/√Hz Noise Equivalent Current (NEC).

Regarding the KK receiver, the applied algorithm is the approximation reported in [9], that allows to avoid up- and down-sampling, simplifying the digital signal processing (DSP) and saving power.

III. SIMULATION RESULTS AND DISCUSSION

The simulations aim is to maximize the transmitted capacity with a target bit error rate (BER) of $4.6 \cdot 10^{-3}$ [3]. The results are shown in Fig. 2, where the capacity curves are reported for: DM achieved by the cascade of the VCSEL and the MZM (blue lines); DM achieved by the cascade of the

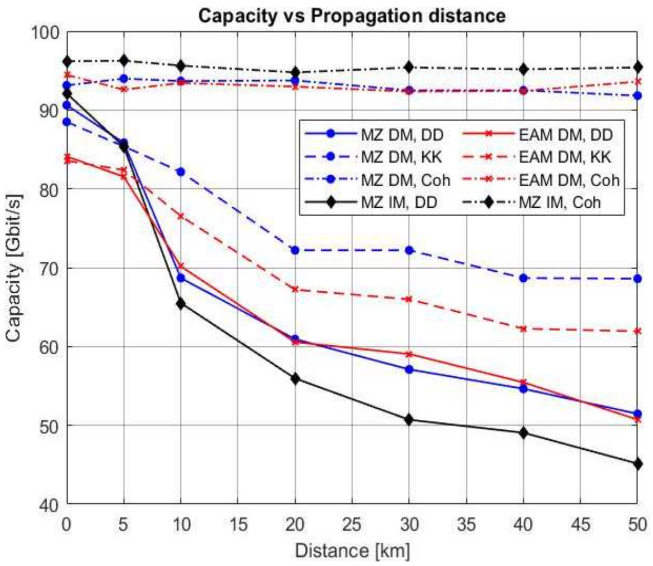

Fig. 2. Transmitted capacity as a function of the propagation distance.

VCSEL and the EAM (red lines); VCSEL operating in continuous wave (CW) followed by a MZM providing the external IM for the generation of a DSB signal. At the receiver side, DD (solid lines) and KK receiver (dashed lines) are analysed, compared also with the case of coherent (Coh) detection (dashed dotted lines) constituting the reference for the CD compensation, guaranteeing the best performance and allowing to transmit basically a constant capacity independently on the propagation distance.

DD-based performance deteriorates as the distance increases. As expected, the DSB signal performs worse than the SSB signal, owing to the frequency-selective power fading. Considering the SSB signals, the VCSEL-MZM DM shows an advantage with respect to the VCSEL-EAM DM for very short distances, while the trend is identical as distance increases. This is due to the better IM provided by the MZM with respect to the EAM.

The SSB signal performance in case of DD remains in any case limited by the combination of chromatic dispersion and the non-linear terms coming from the small-signal approximation of Eq. (4). In fact, being the sideband suppression limited just to the first order, the unwanted contributions, having a DSB nature, interplay with the CD affecting the system SNR, thus reducing the achievable capacity. The CD compensation achieved by the KK algorithm improves the performance. Indeed, this leads to a relevant capacity improvement for lengths above 10 km. While the achieved capacity exploiting MZM and EAM devices with pure DD is similar, the VCSEL-MZM DM behaves better with respect to the VCSEL-EAM DM when KK detection is applied. This capacity reduction is caused by the residual EAM-phase modulation, which lowers the quality of the SSB signal by limiting the sideband suppression. With respect to the DSB signal, the capacity gain at 50 km is around 15-Gbit/s for the VCSEL-EAM DM, and more than 20-Gb/s for the VCSEL-MZM DM, leading to almost 70-Gb/s of transported capacity for a single wavelength.

From a performance perspective, the VCSEL-MZM DM seems preferable with respect to the VCSEL-EAM DM, especially with KK detection. On the other hand, the latter has an advantage from a photonic integration point of view owing to the low EAM dimensions, easing the integration process [10]. Nevertheless, innovative MZMs realized in semiconductor technology with reduced footprint and good $V_{\pi}L$ figure of merit (L being the MZM phase shifters length) are starting to be available ([7]), so they can be possibly integrated with a VCSEL to implement the discussed transceiver architecture in a compact and sustainable way.

IV. CONCLUSIONS

A sustainable approach for a transceiver based on SSB DMT signal is proposed. SSB is achieved by means of the dual modulation scheme, avoiding the use of an optical filter nor the Hilbert transform implementation. A low-cost C-band VCSEL source with 17 GHz-bandwidth is exploited at the transmitter, while at the receiver KK detection preserves the simplicity of the architecture, allowing digital CD compensation. Almost 70-Gb/s capacity per wavelength is transported over 50 km SSMF, with a high spectral efficiency guaranteed by the SSB DMT modulation.

ACKNOWLEDGMENT

This work was supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGeneration EU, partnership on “Telecommunications of the Future” (PE00000001 - program “RESTART”).

REFERENCES

[1] G. H. Smith, D. Novak and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fibre-radio systems", Electron. Lett., vol. 33, no. 1, pp. 74-75, Nov. 1997.

[2] A. Gatto, M. Rapisarda, P. Parolari and P. Boffi, "Discrete Multitone Modulation for Short-Reach Mode Division Multiplexing Transmission," Journal of Lightwave Technology, vol. 37, no. 20, pp. 5185-5192, 2019..

[3] P. Parolari, A. Gatto, C. Neumeyr and P. Boffi, "Flexible transmitters based on directly modulated VCSELs for next-generation 50G passive optical networks," Journal of Optical Communications and Networking, vol. 12, no. 10, pp. D78-D85, 2020.

[4] H. Kim, "EML-based optical single sideband transmitter", IEEE Photon. Technol. Lett., vol. 20, no. 4, pp. 243-245, 2008.

[5] T. Bo, B. Kim, Y. Yu, D. Kim, and H. Kim, “Generation of broadband optical SSB signal using dual modulation of DML and EAM,” Journal of Lightwave Technology, vol. 39, no. 10, pp. 3064-3071, 2021.

[6] Tianwai Bo and Hoon Kim, "Generalized model of optical single sideband generation using dual modulation of DML and EAM," Opt. Express 28, 28491-28501 (2020)

[7] Tatsurou Hiraki, Takuma Aihara, Takuro Fujii, Koji Takeda, Yoshiho Maeda, Takaaki Kakitsuka, Tai Tsuchizawa, and Shinji Matsuo, "Integration of a high-efficiency Mach-Zehnder modulator with a DFB laser using membrane InP-based devices on a Si photonics platform," Opt. Express 29, 2431-2441 (2021)

[8] P. Parolari *et al.*, "Preliminary Assessment of Photonic Solutions Based on C-Band VCSELs for Multi-Tb/s Metro Networks," *2020 22nd International Conference on Transparent Optical Networks (ICTON)*, Bari, Italy, 2020, pp. 1-5, doi: 10.1109/ICTON51198.2020.9203396.

[9] Tianwai Bo and Hoon Kim, “Kramers-Kronig receiver operable without digital upsampling,” *Optics express* vol. 26,11 (2018): 13810-13818. doi:10.1364/OE.26.0

[10] L. Marigo-Lombart *et al.*, "29GHz-Bandwidth Monolithically Integrated EAM-VCSEL," *2019 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, Munich, Germany, 2019, pp. 1-1, doi: 10.1109/CLEOE-EQEC.2019.8872590.