Performance analysis of communication links based on VCSEL and silicon photonics technology for high-capacity data-intensive scenario

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Abstract: To face the increased demand for bandwidth, cost-effectiveness and simplicity of future Ethernet data communications, a comparison between two different solutions based on directly-modulated VCSEL sources and Silicon Photonics technologies is carried out. Also by exploiting 4-PAM modulation, the transmission of 50-Gb/s and beyond capacity per channel is analyzed by means of BER performance. Applications for optical backplane, very short reach and in case of client-optics networks and intra and inter massive data centers communications (up to 10 km) are taken into account. A comparative analysis based on the power consumption is also proposed.

OCIS codes: (060.2330) Fiber optics communications; (140.7260) Vertical cavity surface emitting laser; (130.3120) Integrated optics devices.

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1. Introduction

The IEEE 802.3ba standard in definition by Ethernet Technology Summit defines and regulates data communication links for short-reach applications. At the physical level, the adoption of electro-optic (EO) transceivers is expected for high capacity links. In particular, the 100-Gb Ethernet is a standard both for very short-reach (less than 100 m) based on vertical-cavity surface-emitting laser (VCSEL) sources in case of multi-mode fiber (MMF) propagation and for reach up to 10 km in case of single-mode fiber (SMF) propagation [1]. The higher and higher capacity required in future data-intensive scenario pushes the research toward solutions guaranteeing Ethernet evolution to 400G and 1T Ethernet [2] exploiting VCSEL-based or Silicon Photonics (SP)-based transceivers. In order to increase the bandwidth of the data link, different possible solutions can be exploited: increase the transmission bit rate, increase the number of parallel fiber lanes, increase the number of fiber propagation modes (Mode Division Multiplexing - MDM), increase the number of wavelengths per fiber (Wavelength Division Multiplexing - WDM) and increase the number of bits per symbol by exploiting complex modulation formats. Obviously, the increase of the transmission bit rate per channel requires the employment of very high-speed electro-optical devices used at the transmitter and the receiver. Enhancing the number of parallel fiber lanes

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exploiting space-division multiplexing appears an easy solution. However, the overall costs grows owing to the increase of the optical interconnecting media: in fact, more complex ribbon connectors and layout are requested and no further evolution is expected due to the need of space density scaling. In WDM spatial links, different data channels can propagate on a single optical fiber using multiple wavelengths. Commercial WDM mux/demuxs are currently deployed for long-reach applications and now are used also in metro optical networks [3]. The implementation of WDM technique requires dedicated components and design that can increase the cost of the EO transceiver. Mode division multiplexing (MDM) could be a suitable technique for multimode links. Choosing a suitable subset of propagation constants, independent signals can travel on different propagation modes [4,5]. In the last years, some mode multiplexing and demultiplexing techniques have been experimentally validated [6]. However, MDM technique is still far from integration into commercial products.

The introduction of multi-level modulation format could represent an interesting tradeoff. Avoiding coherent detection at the receiver, for limiting cost and complexity, simple amplitude modulation formats, such as M-Pulse Amplitude Modulation (M-PAM) can be considered. In particular 4-PAM allows transmission of an equivalent amount of data in half the bandwidth. Real-time 4-PAM experimentation has been demonstrated using VCSELs [7–12] and some recent progress with efficient Silicon Photonics devices has been made [13–18].

The aim of this paper is to compare the performance achievable with the best VCSEL sources available today with the ones provided by means of SP technology in order to achieve 50-Gb/s and beyond transmission per channel, taking into account also the energy-saving point of view. The performance is analyzed by suitable simulations taking into account OOK and 4-PAM non-return-to-zero (NRZ) modulation. The VCSEL-based solution, exploiting direct modulation, is simpler and cost-effective with respect to the SP-based proposal, where the laser source is integrated with a separate segmented Mach-Zehnder electro-optic modulator. Different behavior in terms of frequency chirp and extinction ratio of the modulated signal is expected by employing the two different technological solutions. The most performing VCSELs proposed in literature operating at 850 nm, 1310 nm and 1550 nm are taken into account for our comparison. A comparative analysis in terms of BER performance is proposed both in back-to-back (BTB) case and after fiber propagation, demonstrating the capabilities of the two technological solutions to achieve transmission per channel of 50-Gb/s and beyond. The study is realized in case of data-intensive scenario, both for short reach and for client-optics networks used for communications intra and inter massive data centers up to 10-km. Moreover, we analyzed the components and the devices employed in the implementation of the transmitter and receiver blocks in order to quantify their power consumption and achieve a comparison considering the energy-saving impact. A final discussion is present in the conclusions.

2. Simulation setting

As explained in the previous section the objective of the paper is to achieve an aggregate bit rate per channel of at least 50 Gb/s by exploiting the frequency increase or multilevel modulation format, in order to allow Ethernet evolution forward 400 G and 1 T Ethernet. The OptSim simulation tool has been used to simulate the behavior of the EO transceiver in both the technological solutions [19] taking from the literature the operation parameters of the today available most performing VCSELs and SP-based implementations. In the paragraphs of the next Section 3 and in Section 4, we describe in details the simulative conditions adopted in our analysis for each technological solution. A simulative optical link for OOK and 4-PAM signal transmission has been designed. Moreover, the optical signal obtained by OptSim at the receiver is processed by means of a Matlab script, implementing a semi-analytical method for the estimation of BER performance both for OOK and 4-PAM modulation. In particular, according to [20], we consider the receiver noise independent by

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the signal and described by Gaussian statistics. We take into account just shot noise and electrical noise as in case of direct detection without optical amplification. The noise is added to the signal converted in the electrical domain by the photoreceiver, achieving the probability density functions corresponding to each symbol. With respect to Monte-Carlo method, this method does not have to take into account a very large number of noise realizations, taking advantage of the complete knowledge of the statistics. Therefore the semi-analytical method allows for obtaining an accurate estimation of BER with limited computational complexity. In case of 4-PAM modulation, the total symbol error rate was derived from error rate simulated on each of the 4-PAM threshold levels [7].

3. VCSEL-based link: performance evaluation

3.1 Analysis at 850 nm for very short MMF links

The VCSEL-based technological solution exploits a directly-modulated VCSEL as transmission optical source. At first, we analyze the performance of a multimode VCSEL source operating at 850 nm, such as the source usually employed for very short MMF data links. To make the simulation realistic and close to the edge research, we simulated one of the most performing 850-nm VCSEL shown in literature [21], referring to its experimental parameters such as spatial hole burning, lateral carrier diffusion, thermally dependent gain and thermal carrier leakage. At room temperature, this VCSEL reaches the maximum bandwidth of about 25 GHz with an output power of about 7 mW for a bias current of 12 mA (where the threshold current is about 0.99 mA).

The voltage amplitude and the rise time of the electrical driving signal have been optimized in order to obtain the optimum extinction ratio and to minimize the pulse overshoots of the modulated signal at the VCSEL output. The peak-to-peak driving amplitude voltage of the VCSEL (V_{pp}) of each on-off ramped signal was 0.9 V. In the simulation we used a 2^7-bit de Bruijn sequence to generate the transmitted OOK and 4-PAM signals. In such a sequence all the possible 7-bit patterns occur exactly once [22]. Therefore we account for the intersymbol interference on a reference bit due to any subsequence of three bits both preceding and succeeding the reference bit.

Also timing jitter was introduced in the simulation (0.5 ps and 3.3 ps of jitter for 25 Gsymbol/s and 50 Gsymbol/s modulation rate, respectively). At the receiver we considered direct detection by a standard photoreceiver consisting in a photodiode followed by a transimpedance amplifier with −3-dB bandwidth of 22 GHz, NEP of 38 pW/√Hz and responsivity of 0.45 A/W at 850 nm.

In order to highlight the main limitations of the VCSEL-based solution, the system performance has been evaluated for different transported bit rates, from 50 Gb/s to 80 Gb/s, in case of OOK and 4-PAM modulations. Simulative analysis has been performed directly in back-to-back (BTB) conditions taking into account that few-m propagation over standard MMF (typical of very short reach links in datacom applications) does not induce any significant power penalty at the receiver.

Figure 1 shows BER as a function of the received optical power in case of OOK transmitted signal in back-to-back (BTB). The considered VCSEL, characterized by 25-GHz bandwidth, allows anyway to achieve 50-Gb/s OOK modulation with error-free behavior. 60-Gb/s OOK modulation appears instead dramatically degraded owing to the bandwidth limitations of the employed VCSEL, pushed up to its limits, and of the employed receiver. Pre-emphasis pulse shaping [23] can be exploited to achieve better performance. In our simulative analysis, the pre-emphasis was implemented including in the model a two-tap Feed-Forward Filter (FFE) block in order to realize a simple, low-cost and low-consumption solution. Taking into account the network applications considered in our simulative analysis (very short reach and client-optics links) the use of equalization at the receiver side implies a more complex, expensive and dissipative implementation. For 60-Gb/s OOK modulation,

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even with the use of pre-emphasis, a BER less than 10^{-12} is not achieved, due to a large amount of jitter and distortion caused by the VCSEL limitations.

In case of 4-PAM, which requires a half modulation bandwidth with respect to OOK, it is possible to achieve very good 50-Gb/s and 60-Gb/s signals, exploiting 25-Gbaud and 30-Gbaud symbols respectively, without use of pre-emphasis. Figure 2 shows BER as a function of the received optical power in case of 4-PAM in BTB for bit rates of 50 Gb/s, 60 Gb/s and 80 Gb/s. Comparing Fig. 1 and Fig. 2 performance at the same equivalent bit rate 50 Gb/s, the power penalty introduced by the exploitation of 4-PAM with respect to OOK are lower compared to the expected theoretical one [8]. This behavior is due to the VCSEL bandwidth limitations, that affect the OOK performance. Increasing the total bit rate even up to 80 Gb/s, error free performance is achieved, only using pre-emphasis, with 4-dB power penalty at receiver with respect to the 60-Gb/s case. The eye diagrams at the output of the receiver at 80-Gb/s with and without pre-emphasis are also shown in the insets of Fig. 2, where the effect of the FFF-based pre-emphasis is visible in the opening of the inner eye. The results of our simulations in case of 50-Gb/s 4-PAM agree with the experimentation reported in literature based on this type of VCSEL [10]. Just some power misalignment is obtained for the different operation conditions. Our simulative analysis allows for confirming the capabilities of the already developed 850-nm VCSELs to generate even 80-Gb/s transmission by means of directly-modulated 4-PAM. Thanks of this kind of solution, the highest bit rate never reached up to date can be achieved for very short reach applications, where the MMF impairments in terms of attenuation and dispersion are not relevant.

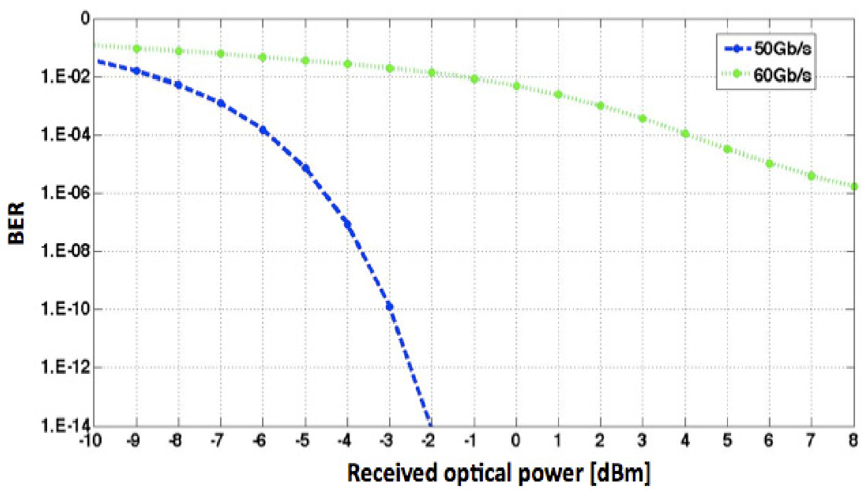

Fig. 1. BER vs received optical power in BTB for OOK modulation in case of 850-nm VCSEL-based solution.

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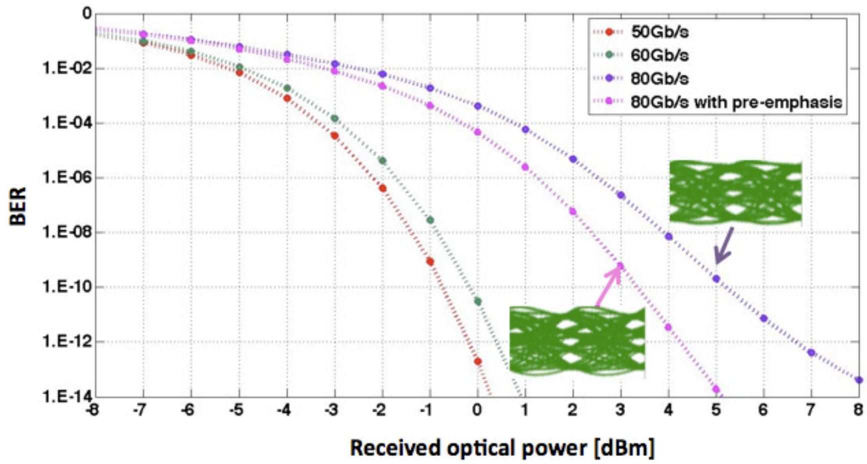

Fig. 2. BER vs received optical power in BTB for 4-PAM modulation in case of 850-nm VCSEL-based solution. Simulated received eye diagrams at 80 Gb/s with and without pre-emphasis are reported in the insets.

3.2 Analysis at 1310/1550 nm for client-optics SMF links

The same simulative analysis, both for 4-PAM and OOK modulation, was carried out considering also SMF propagation, in order to take into account also applications related to client optics networks for few-km communications intra and inter massive data centers. For this analysis, simulations based on the exploitation of single-mode VCSEL sources at 1310 nm and 1550 nm were realized. The interest for the so-called second window of the transmission spectrum of the fiber (1310 nm) is connected to the null chromatic dispersion demonstrated around this wavelength in the SSF. Hence, this transmission wavelength is chosen for attenuation-limited scenario, where the maximum propagation reach is limited just by the link length through the fiber attenuation. The third spectral window around 1550 nm shows minimum attenuation and in this case the reach is limited by the chromatic dispersion accumulated during the propagation. In this last case, not only the link length, but also the transmission symbol rate affects the best performance. For the VCSELs emitting at long wavelengths in the second and the third windows the current technology based on InP shows maior limitations in the achievable modulation bandwidth with respect to the GaAs-based VCSELs described in the previous paragraph 3.1. In our simulation, the VCSEL model was designed referring to the most recent high-speed VCSEL at 1310 and 1550 nm reported in literature [24]. Considering the characteristics of these sources, the new operating bias current is 4.53 mA.

The largest 3-dB bandwidth of the VCSEL taken into account for our simulations is around 15 GHz. The maximum output power at 4.53 mA is about 2 mW at room temperature. The electrical swing voltage to drive the VCSEL is 0.5 V, lower than for 850-nm VCSEL case.

Owing to the VCSEL bandwidth limitation, it is not possible to achieve error-free generation of a 50-Gb/s signal by exploiting OOK modulation. Regarding 4-PAM modulation, the results at 1550 nm are represented in Fig. 3. In BTB condition 50-Gb/s performance at BER = 10^{-12} is similar to the simulated one in the case of 850-nm source. A sensitivity improvement of 1 dB is achieved thanks to the better responsivity of the photodiode (about 0.8 A/W) at such wavelengths. The used bandwidth of the receiver is 22 GHz, the same considered in the previous case at 850 nm. The optical propagation was implemented considering a standard SMF with attenuation of 0.2 dB/km and chromatic dispersion of 17 ps/nm/km at 1550 nm. The effect of the signal frequency chirp induced during VCSEL modulation, combined with fiber chromatic dispersion, affects the propagation

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of the 50-Gb/s 4-PAM signal. A power penalty of 1.5 dB is obtained at BER = 10^{-6} after 1-km SMF propagation due to the high value of the frequency chirp (linewidth enhancement factor $\alpha > 3$). No error-free transmission is reached after 2-km SMF propagation.

Concerning 1310-nm transmission, the modeled single-mode VCSEL presents characteristics very similar to the 1550-nm case. With 50-Gb/s OOK modulation it is not possible to achieve error free propagation owing to the VCSEL bandwidth limitation (also at 1310 nm maximum bandwidth is 15 GHz). If 4-PAM modulation is implemented, (see Fig. 3) then the transmission performances are limited only by the SMF attenuation (0.35 dB/km at 1310 nm) and not by the chromatic dispersion, that is about zero at 1310 nm. Negligible power penalties (less than 0.5 dB) are visible with respect to BTB, although the high symbol rate, as explained in [25]. In this case, the maximum reach is attenuation-limited: considering a VCSEL power of 2 mW, about 10-km propagation distance is achievable.

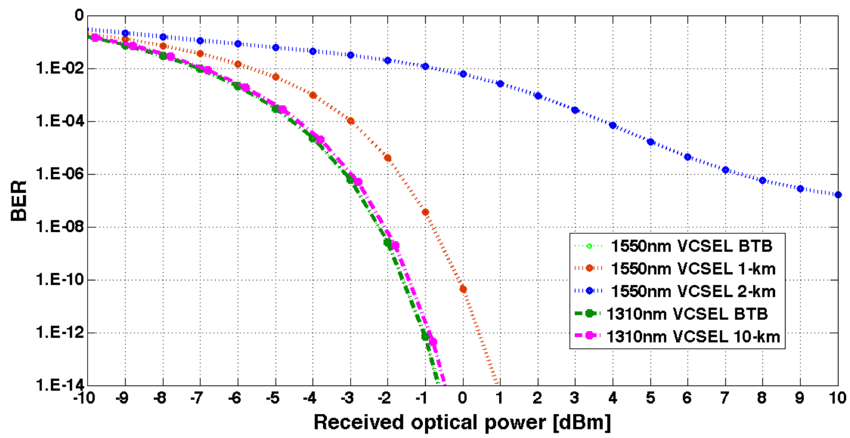

Fig. 3. BER vs received optical power at 50 Gb/s at different SMF propagation distances in case of 1550-nm and 1310-nm VCSEL-based solution with 4-PAM modulation.

4. Silicon Photonics-based link: performance evaluation

This solution exploits an optical integrated technology based on silicon. We simulated the integration of a laser source and of an external electro-optical modulator. In particular, in our simulations the radiation emitted by a Distributed FeedBack (DFB) laser is externally modulated by a Mach-Zehnder modulator. For the modeling, we took the parameters from recent literature, considering a maximum output power of single-mode 1550-nm DFB laser equal to 10 mW and a RIN value of −145 dB/Hz [18]. We adopted the Mach-Zehnder modulator suitable for 40-Gb/s operation, with insertion losses of 4.2 dB, modulator peak-to-peak driving signal of 0.9 V and modulated signal extinction ratio (ER) of 20 dB [18]. At the receiver side we considered a Ge-photodetector [17] with 3-dB bandwidth equal to 22 GHz, 1550-nm responsivity equal to 0.8 A/W and dark current less than 18 nA. In the simulations to compare the performance with respect to the VCSEL-based link, where possible all the parameters have been set to the same values, used in the VCSEL-based link. The DFB optical power is set to 2 mW and the amplitude of the electrical signal to drive the Mach-Zehnder modulator and the V_{bias} were set in order to achieve three equally spaced eyes at the output.

Figure 4 shows BER as a function of received optical power for 50-Gb/s OOK and 4-PAM signal, in case of BTB, 1-km, 2-km, 5-km and 10-km SMF propagation. In case of OOK modulation, the power penalties with respect to BTB are negligible for 1-km SMF propagation and about 1 dB at BER = 10^{-6} after 2 km. After 10-km propagation, owing to the chromatic dispersion, the transmitted OOK signal at 50 Gb/s is strongly distorted and error

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free conditions can be achieved only with a large amount of received optical power, making 50-Gb/s OOK modulation not reasonable for real applications targeting up to 10 km.

When 4-PAM signal is transmitted, in BTB condition we find a penalty of about 4 dB at BER = 10^{-10} with respect to OOK as expected. Considering also SMF propagation, after 1 km, 2 km and 5 km no power penalties are visible, while about 2-dB penalties are obtained at BER = 10^{-6} for 10-km SMF propagation due to the presence of not null chromatic dispersion at 1550 nm. With respect to the VCSEL-based solution at 1550 nm, where the propagation is highly limited by the destructive combination between the VCSEL chirp and the dispersion, the high quality of the signal generated by the external electro-optic modulator allows to transmit a total capacity of 50 Gb/s over 10-km reach with limited impairments. Also propagation distances longer than 10 km could be achievable by exploiting the SP-based technological solution.

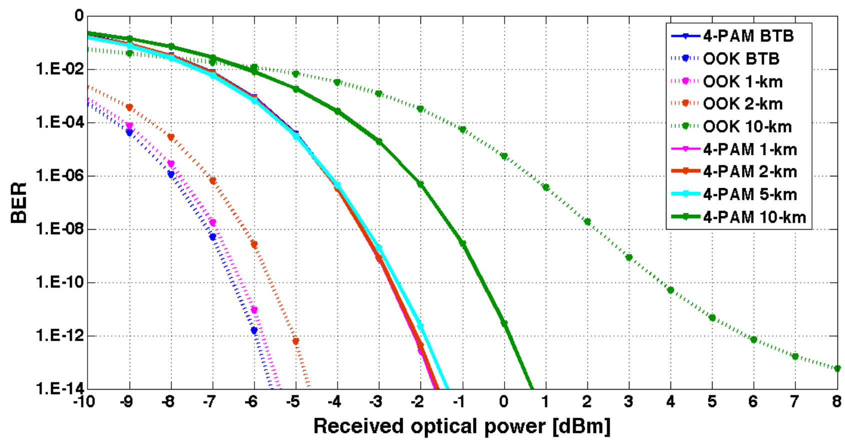

Fig. 4. BER vs received optical power at 50 Gb/s at different SMF propagation distances in case of SP-based solution with OOK and 4-PAM modulation.

5. Power consumption evaluation

In a realistic high-capacity data-intensive link the final choice for one of the two solutions analyzed in the previous section will depend also by the power consumption associated to each technology. A comparative analysis, taking into account both VCSEL-based and SP-based technologies, exploiting OOK and 4-PAM modulation formats, was carried out. For both the technologies, information taken from the experimental data presented in literature and from commercial sheets related to devices available on the market were found for operating bit rate of 25 Gb/s. In case of commercial devices, all the functionalities required at the transmitter and receiver side regarding signal generation, clock signaling and clock data recovery (CDR) are considered. For 4-PAM the employment of a 4-PAM encoder/decoder in addition to a standard OOK transceiver is required, as explained in [26]. Equalization functionality is usually implemented. The whole power consumption of the optical link is strictly dependent by the choice of the electronic technology. Generally, the electronic circuitry is implemented using complementary-metal-oxide semiconductor (CMOS) technology, exploited in the generation of the signal, in the clock, driver, pre-emphasis/equalization functions, in the TIA and eventually in the encoding/decoding functions.

In case of 4-PAM format, the encoder can be realized by an electrical circuit containing mainly delay elements, such as flip-flop, together with combiners in order to generate symbols with 4 levels [26]. The consumption of this kind of circuitry is very low (about 0.1 pJ/b). If the decoder is implemented using high resolution Analog to Digital Converter

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(ADC), the power consumption at receiver side is dominated by the ADC. Almost 40% of the total power consumption is spent in data circuits and about 56% in clock circuits, while the rest is in the digital logic circuitry [27].

Table 1 shows the results of our comparison for 25-Gb/s bit rate transmission.

Table 1. Energy efficiency of VCSEL and SP-based links at 25-Gb/s bit rate

Technology	OOK [pJ/b]			4-PAM [pJ/b]		
	TX	RX	TOTAL	TX	RX	TOTAL
VCSEL	8.5	1.77	10.28	5.3	~2	~7.3
Silicon Photonics	24	4.84	28.84	22.3	~5	~27.3

Regarding the VCSEL-based solution, thanks to the very low threshold current (< 1 mA), the VCSEL element at the operation conditions analyzed in our simulations (I_{bias} = 12mA; driving voltage = 2.8 V) shows at 25 Gb/s an energy consumption per bit of about 1.3 pJ/b. This contribution is very low compared to the consumption of the driving device. For example, considering the commercial-level OOK driver reported in [25], at 25 Gb/s we find energy per bit of 7.2 pJ/b (75 mW of consumption for data supply and 105 mW for clock supply). To give realistic consumption information also in case of 4-PAM format, since at the moment no commercial 4-PAM driver especially designed for VCSEL is available, we have taken into account the specifications of 4-PAM driver initially developed for electrical-based interconnections [28]. This assumption can be considered correct, because the output electrical amplitude and the voltage supply are compatible with the modulation requirements of the VCSEL source. About 4 pJ/b of energy dissipation is achieved (about 102 mW of power consumption). In Table 1, in the column related to the TX side, the values added to the VCSEL dissipation are reported. Regarding the RX side, we used experimental data coming from [29]. For 4-PAM format, a simple receiver constituted by three comparison devices, each one for the three necessary thresholds, is employed, avoiding the need of complex ADCs. This simple scheme helps to save power. Usually, each comparison device consumes about 0.1 pJ/b. Comparing the achieved results, it is interesting to notice that for VCSEL-based link at the same bit rate the total energy consumption for OOK and 4-PAM solutions is comparable. For the specific implementation taken into account in our analysis the consumption for OOK is even higher with respect to 4-PAM. From these results we can deduce that it is possible to achieve also 50-Gb/s bit rate transmission by exploiting 4-PAM-modulated VCSELs, not only guaranteeing good performances in terms of transmission as shown in the Section III, but also in terms of power consumption with respect to usual OOK modulation.

Regarding the SP-based solution, taking into account the characteristics of the devices reported in literature for 25 Gb/s operation, we deduce that 4-PAM implementation consumes as much as the OOK one [16,18]. At the TX side, the consumption depends by the encoder implementation [18]. At the RX side, the same scheme analyzed in case of VCSEL solution and above described is considered. If no ADC are employed [16], the consumption is actually comparable between OOK and 4PAM modulation.

Finally, a comparison between the VCSEL-based and the SP-based solutions in terms of power consumption can be deduced. In Table 1 the considered power consumption of the VCSEL is about 30 mW, while from [18] the power consumption of the DFB is deduced higher than 100 mW. Then, from the analysis results reported in Table 1, by considering clock, digital control and drivers implemented with the same CMOS technology, a significant difference in terms of power consumption between the two solutions is obtained, due to the different encoding design and above all due to the employed laser source.

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6. Discussion and conclusion

In the near future, in order to provide the Ethernet evolution to 400G and 1T Ethernet in the data-intensive scenario, the choice of the technology and of the transmission technique is fundamental to fulfill the requirements like simplicity, scalability and bandwidth enhancement. In our analysis we have taken into account VCSEL-based and SP-based technology. In particular, the attention has been focused on 4-PAM as a simple multilevel modulation format, representing a good trade-off able to increase the transmission rate without the need of complex demultiplexers and of coherent detection with high-speed digital signal processing. A comparison between OOK and 4-PAM formats has been presented, in terms of BER performances. The simulative analysis has considered and modeled the most performing VCSELs and SP-based devices proposed in literature in order to predict the behavior of the most updated and advanced links and connections realizable today.

The VCSEL-based solution, exploiting direct modulation, is simpler and cost-effective. We demonstrated the capability for multi-mode 850-nm VCSEL-based solution to transport a capacity up to 80 Gb/s per channel by exploiting 4-PAM modulation with pre-emphasis. This solution appears ideal in case of very short reach applications over MMF interconnections, but also in case of backplane-based applications, to facilitate very high capacity throughput.

When the propagation distance is getting longer (for example for intra-chassis connections, local area networks, client optics networks), we have to move to long-wavelength operation, taking into account the impact of the propagation impairments introduced by the fiber for high transmission rate. In case of 10-km SMF target, to maintain the simplicity and the cost-effectiveness inherent of the VCSEL-based solution transmitting up to 50 Gb/s, the only possibility is to operate at 1310 nm, i.e. in the region of null chromatic dispersion of the fiber. In this range, 50-Gb/s transmission over 10 km is achievable by exploiting 4-PAM modulation, even by using VCSEL sources. Otherwise, at 1550 nm, the frequency chirp introduced by the direct modulation of the VCSEL combined with fiber chromatic dispersion limits the propagation reach.

On the other hand, SP appears a very attractive technology to develop integrated EO transceivers. High performances in terms of signal generation are guaranteed by the use of external modulation, but paying the price in terms of cost and complexity. Not introducing any kind of frequency chirp and providing high extinction ratio in the modulated signal, SP-based solution allows for reaching 10-km SMF propagation with moderate penalties in case of 50-Gb/s transmission by exploiting 4-PAM modulation.

From the point of view of power consumption, for each considered technology the power consumption of OOK and 4-PAM transceiver is comparable, depending on the circuit design. The main difference between VCSEL-based and SP-based solution is in the power consumption of the employed light sources and drivers.

Moreover, in order to achieve more spectral efficiency, a future increment of number of levels in M-PAM modulation (i.e. from 4 to 8 or 16) is desirable. VCSEL technology is clearly limited due to characteristic of the laser itself, while the SP solution allows to achieve higher multi-level amplitude coding with simple implementation and limited consumption. For short-reach applications (hence including backplanes) SP is scalable, but as demonstrated less power efficient with respect to the VCSEL-based technology. For medium reach applications SP appears instead very promising, also to monolithically integrate further functionalities in the same device.

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