Optical PAM-4 Generation through Polarization Multiplexing in Single-Polarization Single-Mode VCSELs

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***Abstract*-PAM-4 modulation is considered a key enabler for scaling capacity in datacenter networks, due to its bandwidth efficiency and implementation simplicity. We propose a novel technique for optical generation of four-level signals by means of polarization multiplexing, leveraging the single-polarization operation of a double-mesa single-mode VCSEL with 20.5 GHz 3-dB bandwidth. The scheme obviates the need for linear electronic drivers and circumvents the requirement for driving the VCSEL in its linear regime. Experimental results verify the scheme, exhibiting BER within FEC standards at 28 Gb/s. Comparison with an electrical PAM-4 modulated VCSEL demonstrates superior performance of the proposed concept.**

Keywords—vertical cavity surface emitting lasers; polarization division multiplexing; optical interconnects; quaternary pulse-amplitude modulation (PAM-4);

I. Introduction

The relentless expansion of cloud applications, the never-ending demand for high bit rate video services and the flourish of the Internet of Things, are impelling data center traffic to grow vigorously. By the end of 2019, annual global data center IP traffic will reach 10.4 zettabytes with a compound annual growth rate (CAGR) of 25% [1]. Moreover, during 2018 the IoT is expected to surpass mobile phones as the largest category of connected devices [2]. Within this volatile environment, the need for an innovative solution that will address the proliferating and widely differing bandwidth demands in the datacenter in a cost-effective and straightforward way is more than urgent.

Optical interconnects are in the spotlight by virtue of their high-speed capabilities and unique bandwidth-distance product. Migration to optical interconnect systems with aggregate bandwidth of 100 Gb/s and, in the longer-run, 400 Gb/s seems the only viable solution in order to cope with these emerging trends, and to this purpose several approaches have been employed. Scaling the number of parallel optical links (lanes) can facilitate straightforward commercialization (a prominent example being CDFP active optical cables). However, this approach doesn't meet the vision of reducing module size and power consumption [3]. On the other hand, scaling the bitrate of serial optical systems necessitates specialized state-of-the-art photonics and electronics technologies [4]; however, to reach the cost and energy consumption targets of future interconnect systems, it is necessary to rely on currently-available CMOS nodes. With the speeds of both CMOS electronics and commodity optics unable to keep pace with surging interconnect lane speeds, there is growing consensus among academia and industry towards migration to higher-order modulation providing more bits-per-symbol [5]. Quaternary pulse-amplitude modulation (PAM-4) is attracting increasing attention due to its simple implementation that is compatible with intensity-modulation with direct-detection (IM/DD) and can potentially avoid the use of a sophisticated digital to analogue converter (DAC) at the transmitter [6]. Despite the implementation penalty in comparison with the NRZ modulation format, PAM-4 is suitable for short reach interconnects in application scenarios with sufficient margin. Along this path, high-speed PAM-4 systems have been demonstrated using state-of-the-art optoelectronic components, achieving over 100 Gb/s on a single wavelength [7]. A common challenge with such approaches arises from the non-linear response of typical components employed in these links (most notably VCSELs, due to their low cost, along with their electronic drivers). This requires operating them in the linear regime, thus restricting their dynamic range as compared to binary (NRZ) operation. Pre-distortion is possible to partially mitigate this effect, yet at the expense of higher complexity.

To further scale link capacity, more advanced concepts have been proposed leveraging polarization division multiplexing (PDM) in order to double bandwidth efficiency. However, PDM necessitates compensation of polarization drifts in the fiber, either using active polarization tracking or through coherent detection in an optical receiver with polarization diversity, assisted with digital signal processing. The latter approach is well-established in optical transport networks and has also been proposed for inter-datacenter links [8]. However, the complexity, cost and power consumption of the polarization-diverse coherent receiver strive to meet the stringent cost requirements of intra-datacenter networks, where direct-detection receivers are the norm.

In this paper, we present a novel method for optical generation of PAM-4 signals by means of polarization multiplexing of their binary optical tributaries, leveraging the single-polarization operation of a double-mesa single-mode VCSEL with 20.5 GHz 3-dB bandwidth. The proposed technique obviates the need for linear electronic drivers and circumvents the requirement for driving the VCSEL in its linear regime. Furthermore, although the concept involves the generation and transmission of a polarization-multiplexed signal, direct detection is employed at the receiver, similar to a conventional PAM-4 system, thus reducing the scheme's overall complexity. A low complexity implementation of the scheme can be achieved by combining the VCSELs with silicon photonics, leveraging recent efforts towards increasing the functionality of VCSEL-based integration engines [11]. This approach offers polarization stability with no back-reflections and can be implemented with only a few excess integrated components and small overhead in cost. In order to verify the validity of the concept, a data transmission experiment was held at 28 Gb/s exhibiting BER within FEC limits even after transmission within 500 m of standard single-mode fiber. Moreover, comparison of the polarization division multiplexed signal with an electrical PAM-4 modulated signal from the VCSEL at the same bit rate proved superior performance in both the back-to-back and the 500-m cases.

II. Double-Mesa Single-polarization VCSELs

The VCSELs presented in this work rely on a double-mesa short-cavity design [9] where the semiconductor cavity length is three times the laser´s emission wavelength. In order to reduce chip parasitic, we have designed and fabricated a double-mesa VCSEL structure fully encapsulated in benzocyclobutene (BCB). The smallest mesa defines the mesa capacitance and has a diameter d_{bm}. The presented double-mesa structure allows the fabrication of bottom mesas with a diameter up to 14 µm, reducing the capacitance by a factor of two compared to traditional designs [10].

To enhance the intrinsic dynamic performance, we have implemented a highly strained active region with six 5.0-nm thick AlGaInAs quantum wells grown with 1.7-% compressive strain. In Fig. 1, the active region is embedded between an *n*-doped InP layer and a highly-doped AlInAs cladding. Current confinement is achieved by a p^+-AlGaInAs/n^+-GaInAs buried tunnel junction (BTJ), which is highly conducting in a circularly-shaped area of diameter d_{btj} = 5 µm. Outside this area, current blocking is obtained by a reverse-biased p^+n-junction which extends over the bottom mesa area. The tunnel junction is overgrown by n-doped InP to match the cavity length. The abrupt change in the reverse-biased junction impurities concentration leads to a depletion region which is associated to a capacitance proportional to $(d_{bm}^2 - d_{btj}^2)$. The double-mesa VCSEL employs a dielectric outcoupling distributed Bragg reflector (DBR) and a hybrid bottom DBR with reflectivity of 99.3% and 99.9%, respectively.

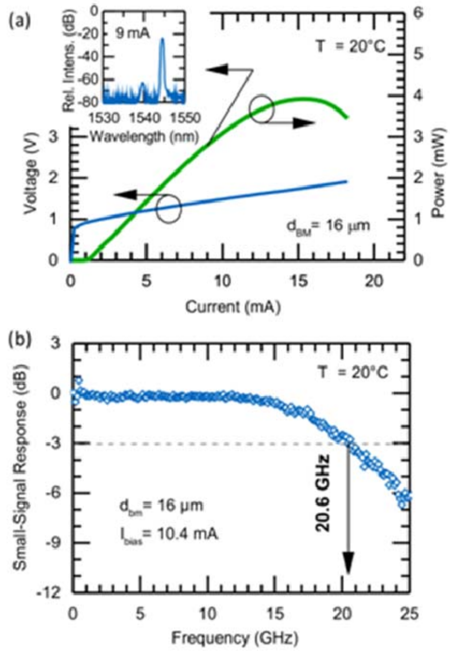

Fig 1: (a) LIV characteristics and, in inset, optical spectrum (b) S_{21} measurement of a 16 µm double-mesa VCSEL.

At room temperature, the threshold is in the order of 1.0 mA and the maximum output power is slightly below 4 mW. The measured differential resistance is of 52 Ω. The inset shows the optical spectrum of the 16-µm mesa VCSEL biased at 9 mA. The VCSEL´s small-signal modulation response was measured with an HP 8510C Vector Network Analyzer. The room-temperature S_{21} measurement of the 16-µm mesa VCSEL is shown in Fig. 1 (b). As observed, a maximum modulation bandwidth of 20.6 GHz is achieved biasing the laser at 10.4 mA.

III. Concept and Experimental Setup

The concept lies on the idea of generating a four level signal directly in the optical domain by polarization-multiplexing the binary outputs of two single-polarization VCSELs. This obviates the need for an electrical DAC thus avoiding the associated complexity and power consumption. Moreover, the necessity of driving the VCSEL within its linear regime is skipped offering a broader dynamic range. As a result the generated signal is less limited in terms of amplitude and its levels and transitions are more discrete. To verify the concept, the experimental procedure involved the generation of an optical NRZ signal that was subsequently split and delayed in order to produce two different, de-correlated data streams. One of the data streams was attenuated to serve as the least significant bit (LSB) whereas the other constituted the most significant bit (MSB). The MSB and LSB data streams were finally combined on vertical polarizations to avoid phase instabilities that are caused by coherent addition effects, forming a polarization-multiplexed four-level signal.

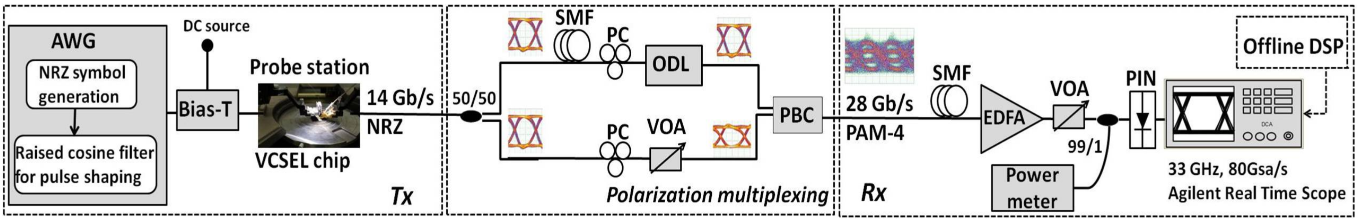

Fig. 2: Experimental setup

It should be noted that the complexity of the aforementioned setup is only for testing purposes and can be skipped in an integrated scenario as described in [11] with only few extra components that will enable the on-chip polarization multiplexing.

Fig. 2 depicts the experimental setup employed for the realization of the scheme. The 14 Gbaud NRZ and PAM-4 electrical signals were generated from the single-ended output of an 8-bit, 65 GSa/s Keysight Arbitrary Waveform Generator (AWG) with a repeating pattern length of 2^{10} symbols. Raised Cosine (RC) pulse-shaping with a roll-off factor a=1 was implemented in order to suppress the side lobes and confine the bandwidth of the baseband signal to 14 GHz. In case of the proposed PAM-4 generation scheme the voltage swing of the electrical signal was set at 600 mV_{P-P}, whereas the respective swing for the electrical PAM-4 modulated VCSEL was 500 mV_{P-P}. In both cases, the generated electrical signals were fed directly to the 20.5 GHz 3dB-bandwidth VCSEL leading to the generation of an optical signal with approximately 0 dBm output optical power.

To realize the PDM technique, the 14 Gb/s NRZ optical signal was evenly split in two identical data streams which were de-correlated by means of a spool of standard SMF. For accurate bit synchronization, an optical delay line (ODL) was employed in one of the two branches, whereas adjustment of the intensity levels to form the four levels of the PAM-4 signal was made via a variable optical attenuator (VOA). Two polarization controllers, one at each data stream, were used to align the polarization state of the signals with the polarization axes of the polarization beam combiner. A spool of 500 m standard SMF was employed for the transmission scenario. At the receiver side, we used an Erbium Doped Fiber Amplifier followed by an off-the-shelf pin-photodiode with 0.65 responsivity. The absence of a high speed linear photoreceiver did not allow scaling the experiment at higher data rates, but comparative measurements were carried out with a reference system to verify our concept. A variable optical attenuator (VOA) was used at the photodiode's input to facilitate measurements as a function of received signal power. The photocurrent was captured by a digital real time oscilloscope with 33 GHz analog bandwidth and 80 GSa/s sampling rate for signal digitization, followed by off-line processing. To benchmark the proposed PAM-4 generation concept with the conventional approach that involves driving the VCSEL with a multi-level electrical signal (i.e. "direct PAM-4 modulation"), a second experiment was setup for comparison. The same VCSEL was driven by the same AWG, which was configured this time to generate an electrical PAM-4 signal at its output with lower electrical swing (500 mV_{P-P}) compared to the respective of the proposed polarization-multiplexing scheme (600 mV_{P-P}). The same Raised Cosine (RC) pulse-shaping with a roll-off factor a=1 was implemented at the AWG and the signal was evaluated both in the back-to-back and 500 m transmission scenario using the same receiver. It should be mentioned that neither the proposed PAM-4 generation scheme nor the conventional electrical PAM-4 modulation of the VCSEL employed any feed forward equalization (FFE) technique in order to allow comparison of the two schemes under the same conditions. The use of an FFE at the input electrical signals of the VCSEL could scale the system to higher data rates but was not within the scope of this paper.

IV. EXPERIMENTAL RESULTS

The proposed method for optical generation of PAM-4 signal by means of polarization multiplexing was evaluated at 28 Gb/s both in back-to-back configuration and after transmission over 500 m of standard single mode fiber (SMF). Fig. 3 depicts indicative eye diagrams at 28 Gb/s, acquired with an equivalent-time oscilloscope, corresponding to the back-to-back optical signal and the signal after propagation over 500 m.

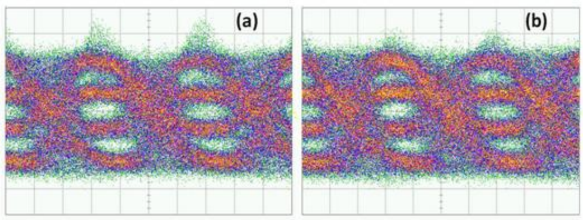

Fig. 3: Eye diagrams of 28 Gb/s PAM-4 polarization multiplexed signal in (a) back-to-back configuration and (b) after propagation over 500m

Fig. 4 presents in turn the corresponding eye diagrams obtained by the electrical PAM-4 modulated VCSEL at 28 Gb/s in the same transmission conditions as in case of the proposed scheme. It can be observed that the eye diagrams of the proposed method are more open compared to the eye diagrams obtained with direct PAM-4 modulation of the VCSEL. The swing of the received eye diagrams was 52mV and 60 mV for our proposed scheme and for the electrical PAM-4 modulated VCSEL respectively. Bit-error-rate (BER) measurements were performed to the digitized signal captured at the real-time oscilloscope after re- sampling and symbol timing recovery followed by a static equalizer (51 tap

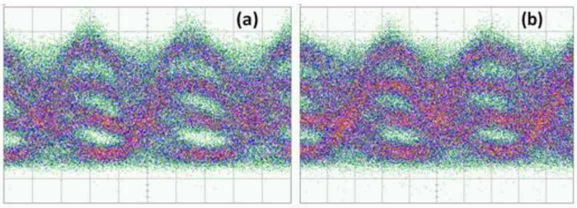

Fig. 4: PAM-4 eye diagrams obtained from the electrical PAM-4 modulated VCSEL at 28 Gb/s in (a) back-to-back configuration and (b) after propagation over 500 m

FFE) to compensate the channel bandwidth limitations. Automatic thresholding for symbol detection followed by BER assessment were performed so as to evaluate the performance of the proposed technique for the optical generation of the PAM-4 signal through polarization multiplexing. The BER performance was evaluated by comparing the received sampled signal to the original bit sequence and counting the actual erroneous bits of the received signal.

Fig. 5 presents the measured BER bathtub curves for the 28 Gb/s PAM-4 signal obtained both by means of the proposed scheme and by the electrical PAM-4 modulated VCSEL. BER curves are plotted against the average received optical power, derived from the measured photocurrent.

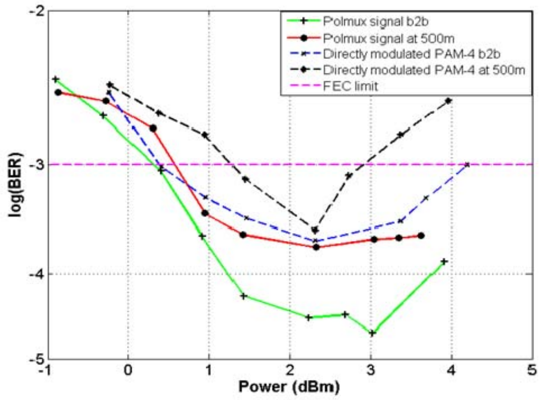

Fig. 5: BER measurements for 28 Gb/s PAM-4 signal obtained by means of polarization multiplexing technique and by the electrical PAM-4 modulated VCSEL, in back-to-back configuration and after propagation over 500 m.

The green and red solid lines correspond to the obtained signal in back-to-back configuration and after propagation over 500 m respectively. Following the same rationale, dotted blue and black lines refer to the received signal after direct PAM-4 modulation of the VCSEL according to the aforementioned transmission scenarios. As it can be observed the BER curves reveal that the polarization multiplexed PAM-4 signal exhibits better performance in terms of the obtained BER measurements compared to the respective measurements from the electrical PAM-4 modulated VCSEL in both transmission scenarios. This occurs because in case of the polarization multiplexed PAM-4 signal the entire VCSEL's transfer function is exploited efficiently, thus avoiding the necessity of driving directly only the VCSEL's linear regime with a multilevel signal (PAM-4). The achieved BER lies below the hard FEC limit (7% overhead) at all cases. For the back-to-back configuration, the polarization multiplexed PAM-4 signal exhibits a 1.5-dB power improvement compared to the electrical PAM-4. After transmission in the 500 m fiber the signals are dominated by dispersion effects in the fiber and thus their BER performance converges. The power penalty after propagation in 500 m of SMF is 0.5 dB for a BER equal to $3 \cdot 10^{-4}$. The electrical PAM-4 modulated VCSEL, exhibits a power penalty of 0.8 dB for a BER in the order of $5 \cdot 10^{-4}$. As is already highlighted a combination of a high speed linear receiver and a feed forward equalizer could result in better performance for the proposed concept in terms of BER measurements and achieved data rates.

V. Conclusion

We have described and experimentally proved a novel technique for optical generation of PAM-4 signals through polarization multiplexing. The concept circumvents the complexity of linear electronic drivers and electronic DACs, whereas direct detection of the signal obviates the need for complex coherent reception with advanced digital signal processing at the receiver side. The concept was enabled by single-polarization single-mode VCSELs with 3-dB bandwidth of 20.5 GHz. Experimental results at back-to-back and at 500 m transmission prove the validity of the concept with BER results within the FEC standards at 28 Gb/s. Comparison with an electrical PAM-4 modulated VCSEL indicates that the concept has overall superior performance.

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