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Quad 14Gbps L-Band VCSEL-based System for WDM Migration of 4-lanes 56 Gbps Optical Data Links

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Abstract *We report on migrating multiple lane link into a single WDM L-band VCSEL-based system. Experimental validation successfully achieves 10 km of SMF reach with 4x14Gbps and less than 0.5dB inter-channel crosstalk penalty.*

Introduction

Over the past few years, the quick proliferation of Internet use and cloud computing applications has substantially increased the bandwidth needs not only in backbones but prominently in data processing centers (DPCs)[1]. Albeit great part of the traffic will continue to flow between end-users and such computer centers, an increasing fraction is flowing within the DPCs themselves[2,3]. This trend is forcing the major data link protocols to hit the 10Gbps barrier, and therefore recently solutions such as fourteen data rate (FDR) of InfiniBand technology[4] have been proposed. FDR Infiniband generically specifies ports with 4 lanes with 14 Gbps data transmission speed each[4]. However, the need to scale to higher and bidirectional transmission capacities (bandwidths reaching 300Gbps by the end 2012/early 2013)[4] is also accompanied by the demand to secure high density, low cost, efficiency and reliability.

In this context, wavelength division multiplexing (WDM) techniques in combination with compact integration of light sources and detectors, is an interesting technology candidate for delivering scalable and flexible optical data links with low power consumption, high data throughput, longer transmission distance, and the cost effectiveness needed to efficiently cope with present and future stringent bandwidth requirements in data centers[1,5-7].

In concordance, regarding light sources, VCSELs' offer an attractive combination of high bit rates, low power consumption and array integration that along with their tuning capabilities make them perfectly suitable for compact and wideband optical interconnects[6,8].

Long-wavelength technology is relatively new in vertical-cavity surface-emitting lasers (VCSELs). Some investigations[9,10] have demonstrated the feasibility of long-reach WDM transmissions at 2.5 Gbps, where L-band is especially suitable due to the lower impact of four-wave mixing (FWM) and the possibility of seizing upon distributed Raman amplification.

In this paper we look, however, into high-speed, cost-efficient and power-efficient VCSEL-based WDM system oriented towards short-range optical fiber connectivity. Four L-band VCSELs are directly modulated with 4-PAM signal at 7Gbauds to generate a total data rate of 56Gbps. 7 Gbauds is chosen as attempt to keep the electronic bandwidth requirement low. The 4 lanes are launched into a 50 GHz spaced WDM system. Bit-error rate (BER), crosstalk penalty and power margin are measured for one of the middle carriers. Post-forward error

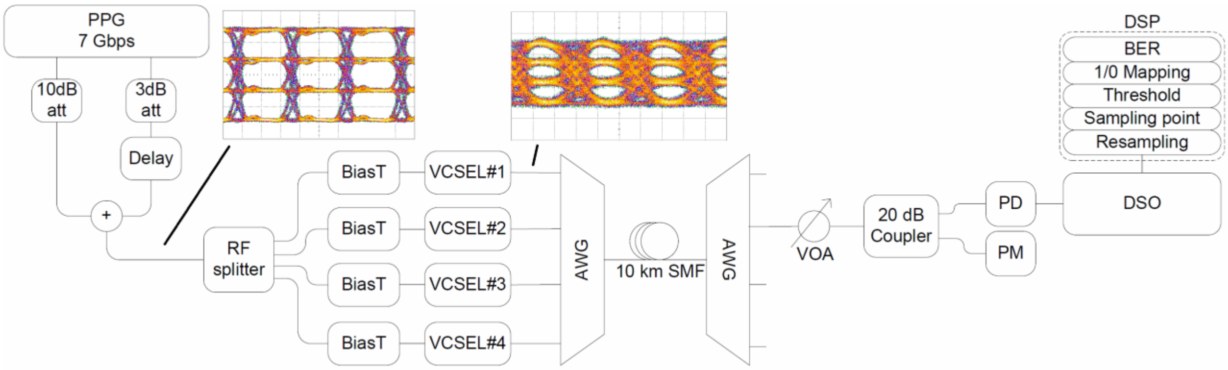

Figure 1: Experimental setup. Pulse pattern generator (PPG), array waveguide grating (AWG), singlemode fiber (SMF), digital storage oscilloscope (DSO), digital signal processing (DSP)

correcting (FEC) error free operation is attained.

Experimental setup

The setup of the experiment is presented in Figure 1. Two 2^{15}-1 pseudorandom sequences (PRBS) at 7 Gbps are generated with a pulse pattern generator (PPG). Both binary streams are added up through a 6dB power combiner to form a 14 Gbps 4-PAM signal. In order to avoid reflections, 10 dB and 3 dB attenuators are utilized at the output ports. Time decorrelation matching is adjusted with a mechanical delay-line inserted into the higher power branch. An active RF splitter divides the 4-PAM waveform into four. The use RF slitter comprises delay-lines that are configured to grant decorrelation among all channels. Amplitudes are adjusted to generate around 0.6 V_{pp} at the splitter's output. The offsets are tuned to locate the input within the most linear range of the integrated amplifier.

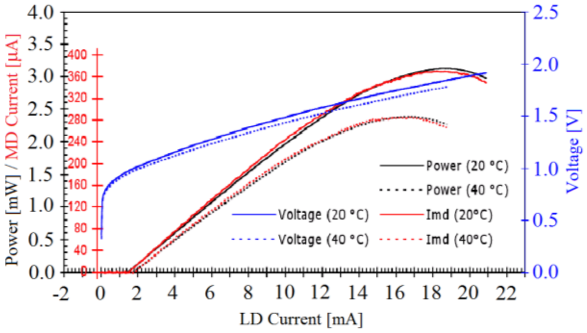

Figure 2 L-I-V curve of VCSEL#3 and monitor diode (MD) current.

The outputs of the splitter are driven into the L-band VCSELs. Bias-Ts and evaluation boards are used. Such devices exhibit a maximum output power around 3 mW and a 3-dB modulation bandwidth of 10 GHz at 20°C. The bias currents are initially set at 10.5 mA for the wavelength measurement and subsequently modified to make them match the corresponding 50 GHz-spaced AWGs' channels. The center wavelengths are 1580.24 nm, 1580.66 nm, 1581.03 nm and 1581.43 nm. Table 1 presents further information about the laser's tunability at 20°C. As an example, the L-I-V curve of VCSEL#3 is shown in Figure 2.

Table 1: Bias current and their corresponding wavelength interval delimiters for each VCSEL.

	Bias Current (mA)	**Wavelength (nm)**
VCSEL#1	6.82 / 15.51	1577.87 / 1580.37
VCSEL#2	6.25 / 14.89	1578.44 / 1580.90
VCSEL#3	6.2 / 14.48	1579.24 / 1581.90
VCSEL#4	6.86 / 14.53	1579.97 / 1582.57

Given in our experiment we use TO-can packaging, the light beams are coupled into respective cleaved single mode fibers (SMFs) fibers. Optical power coupling is improved through the application of index-matching liquid to the fibers' end tip. Minor adjustments of the bias currents, fiber alignment and modulation amplitudes are performed at this stage in order to optimize the individual eye diagrams (see Figure 4).

The WDM signal is launched into a 10 km pool of standard SMF. The received spectrum of the modulated carriers is shown in Figure 3. At the receiver side, a variable attenuator and a 20dB coupler are used to control and monitor the incoming optical power, respectively. A high sensitivity 10 GHz photodiode is used to detect the signal. Finally, a 13 GHz digital storage oscilloscope (DSO) at 40 GS/s is used to store the signal for offline processing.

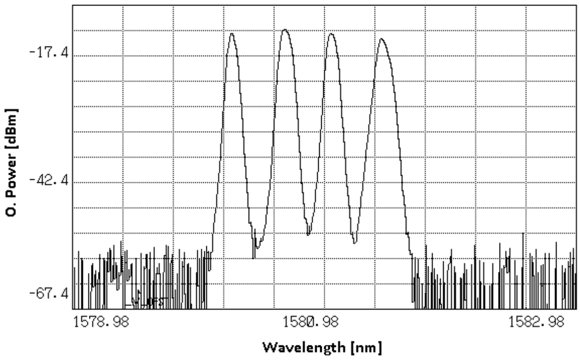

Figure 3: Measured B2B optical spectrum of the four L-band VCSELs.

Demodulation is performed by using digital signal processing (DSP) comprising frame synchronization as well as adaptive decision threshold and sampling time gating. In order to facilitate the demodulation, the signal is up-sampled by a factor 20. For each power level, sequences of 327670 bits are evaluated in chunks of 2^{15}-1 (10 frames).

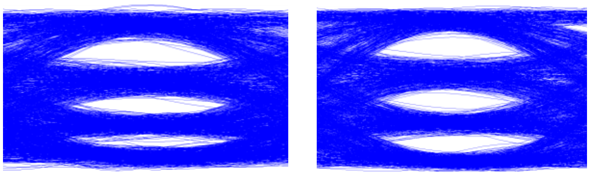

Figure 4: Illustration of a normalized eye diagram before optimization (left) and after optimization (right).

Results and discussion

The experimental results for each of the three measurements conducted are shown in Figure 5. Bit error rates are obtained for one of the middle channels (1580.66 nm) in back-to-back configuration (blue triangles), after 10 km SMF when only that specific channel is transmitted (black squares) and after 10 km SMF when the four lanes are transmitted in parallel (red circles). Targeting post-FEC bit error rate of 10^{-15}, the green line in Figure 5 indicates the threshold $(4.5\cdot10^{-3})^{11}$ of a 7% overhead FEC code. As part of the DSP, the utilization of Gray mapping in the 4-PAM is simulated in order to reduce the number of errors caused by the least significant bit (LSB) and thereby the overall BER.

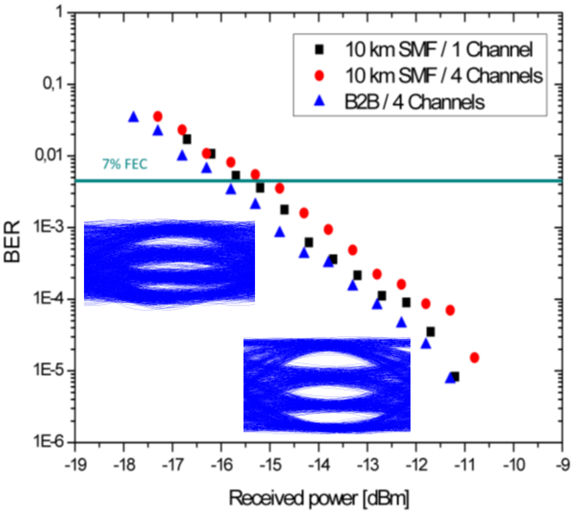

Figure 5 BER versus received optical power.

The performance difference between single-channel and four-channel transmission is negligible below ~16dBm received power. For higher power levels, an average crosstalk penalty of less than 0.5dB is observed. The comparison with back-to-back performance shows a transmission penalty of ~0.5dB with respect to single-lane configuration. Around 1dB penalty is observed as compared to the four-lane case.

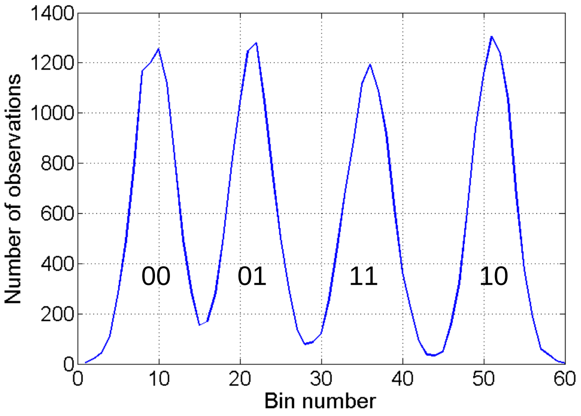

Figure 6: Histogram of four-channel transmission frame (32767 bits) at -15dBm.

No error floors are observed within the tested received power interval and the WDM signal clearly exceeds the 7%-FEC threshold for received power levels higher than -15dBm. This grants error free transmission (BER~10^{-15}) under considerably relaxed power budget conditions allowing hence the allocation of ~6 dB extra loss along the link.

Figure 6 shows the received histogram at the optimum sampling point for a frame of BER~$2.5\cdot10^{-3}$ under full WDM operation at the 7%-FEC threshold, which corresponds to -15dBm. The decision thresholds are calculated from the dips between levels. The slightly higher accumulation of observations between the 00-01 dip is due to slight instabilities in the bias current that displace the optimum working point (effect illustrated in Figure 4).

Conclusions

4x14Gbps L-band VCSEL-based WDM transmission over 10 km of SSMF was investigated. Successful transmission of four channels with quaternary pulse amplitude modulation at 7Gbauds with post-FEC (7% overhead) error free operation has been proven. The crosstalk power penalty was measured to to be ~0.5 dB and the power margin equals ~6dB. Our results show the potential of the reported system to migrate 4-lanes 56Gbps data links into a compact WDM link.

Acknowledgements

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