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Impact of Damping on High-Speed Large Signal VCSEL Dynamics

Emanuel P. Haglund, *Student Member, IEEE*, Petter Westbergh, Johan S. Gustavsson, and Anders Larsson, *Fellow, IEEE*

Abstract—An investigation of the optimal relaxation oscillation damping for high-speed 850 nm vertical-cavity surface-emitting laser under large signal operation is presented, using devices with K -factors ranging from 0.1 to 0.4 ns. Time-domain measurements of turn-on transients are used to quantify damping dependent rise times, overshoots, and signal amplitudes. Optical eye diagrams together with timing jitter and bit error rate measurements reveal a trade-off between the rise time and the duration of the relaxation oscillations. To produce a high quality eye at a specific data rate, a proper amount of damping is needed to simultaneously obtain sufficiently high bandwidth and low timing jitter. We found that for error-free transmission, a VCSEL with a 0.3 ns K -factor achieved the best receiver sensitivity at 10 and 25 Gbps, whereas a less damped VCSEL with a 0.2 ns K -factor achieved the best sensitivity at 40 Gbps.

Index Terms—Damping, high-speed modulation, large signal modulation, photon lifetime, relaxation oscillation, semiconductor lasers, vertical cavity surface-emitting laser (VCSEL).

I. INTRODUCTION

THE development and evolution of datacenters and high performance computers calls for short reach optical interconnects operating beyond the current data rates of 25-28 Gbps. Large efforts have already been invested in increasing the direct modulation speed of the 850 nm oxide confined vertical-cavity surface-emitting laser (VCSEL) [1]–[4], which is a key component in such systems. In a previous study, we showed that a reduction of the relaxation oscillation damping yielded a modulation response with a significantly increased small signal modulation bandwidth, and that there exists a certain damping level that maximizes the bandwidth [5]. However, damping also affects the large signal dynamics and the generation of high quality optical eyes requires a proper amount of damping, which is not necessarily at the same level as that providing maximum small signal bandwidth [6]. Low damping can provide the high bandwidth

and fast rise time needed to produce a vertical eye opening at very high speed modulation, but it also causes horizontal eye closure due to larger transient overshoot and duration of the ringing resulting in data history dependent timing jitter [7]. In contrast, higher damping reduces overshoot and ringing, and the resulting timing jitter, but it also leads to vertical eye closure due to the reduced bandwidth. Thus, an optimum damping level exists for large signal modulation, and it will depend on the specific data rate. Lower bit rates will afford more damping, whereas higher bit rates will require less damping.

In this paper, we present results from an investigation of the impact of damping on large signal 850 nm VCSEL dynamics. From a small signal analysis, the increase of damping with resonance frequency is quantified via the K -factor [8]. VCSELs with K -factors ranging from 0.1 to 0.4 ns are here studied in search of an optimum damping for best receiver sensitivity. The dependencies of rise time, overshoot, and signal amplitude on damping are extracted from measurements of turn-on transients. Eye diagrams are recorded and analyzed, revealing the trade-off between rise time and timing jitter for sufficiently large vertical and horizontal eye opening. The amount of timing jitter is also quantified through measurement of bathtub curves [9]. Moreover, transmission experiments are conducted, revealing power penalties for VCSELs with too much or too little damping at a specific data rate. Finally, we show that the use of a limiting instead of a linear optical receiver does not change the requirements on VCSEL damping for the transmission link.

The paper is organized as follows. Section II describes the VCSEL design and the static performance of the devices. The small signal modulation response is presented in Section III and the large signal dynamics is investigated in Section IV. Finally, the paper is concluded in Section V.

II. VCSEL DESIGN AND STATIC PERFORMANCE

The epitaxial structure and device layout of the high-speed 850 nm VCSEL have been described in detail elsewhere [10]. To enable a high modulation bandwidth it comprises strained quantum wells, low electrical resistance and low optical loss distributed Bragg reflectors (DBRs), and multiple oxide apertures. The two smallest oxide apertures (closest to the active region) are 9 μm in diameter. For four different VCSELs, at most 5 mm apart on the same wafer, the top DBR reflectivity was reduced to different values by reductions of

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the thickness of the topmost DBR layer using low power Ar ion milling. Reducing the top DBR reflectivity reduces the photon lifetime of the VCSEL cavity, and consequently also the damping [10]. The photon lifetimes of the VCSELs (referred to as VCSELs A-D), as calculated using an effective index optical model which accounts for outcoupling through the DBRs and internal optical loss through free carrier absorption [11], are ~ 2 , 3, 5 and 6 ps, respectively. This corresponds to K -factors of 0.1, 0.2, 0.3 and 0.4 ns (see Section III).

The light-current-voltage characteristics (Fig. 1) for the four VCSELs, measured at 25°C with a free-space large area Si-detector, show that reduced photon lifetime causes the threshold current, slope efficiency, and maximum output power to increase. Table 1 summarizes the static performance parameters. The increase in slope efficiency leads to higher optical modulation amplitude (OMA) and therefore increased vertical eye opening during large signal modulation. As can also be seen in Fig. 1, the modification of the top DBR reflectivity only affects the optical characteristics. The current-voltage characteristics remain essentially the same. The small variation in differential resistance is due to small variations in the aperture size and/or the contact resistance. All VCSELs are multimode with very similar emission spectra. A typical spectrum is shown as an inset in Fig. 1.

In previous work, we found that VCSELs with a reduced reflectivity of the top DBR have a lower internal temperature, due to reduced internal optical absorption loss [12]. Here, the internal temperature difference between VCSEL A and D at the bias currents used for large signal modulation is estimated to be $\sim 15^\circ\text{C}$. This relatively small temperature difference is expected to have a minor impact on VCSEL dynamics. In addition, in real systems the VCSELs operate under the same environmental conditions. Therefore, the ambient temperature was held constant at 25°C during all measurements to enable a fair comparison.

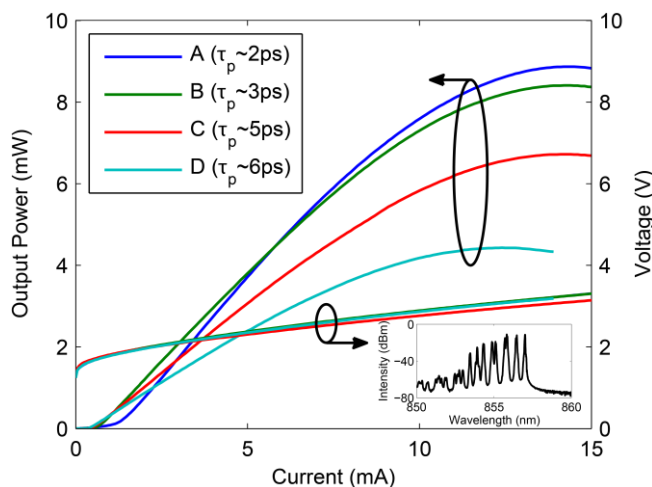


Fig. 1. Optical output power and voltage vs. current for VCSELs A-D with increasing photon lifetime. Inset: Optical spectrum for VCSEL D at 9.0 mA.

TABLE I
STATIC PERFORMANCE PARAMETERS

	Threshold current [mA]	Max. output power [mW]	Rollover current [mA]	Slope efficiency [W/A]	Differential resistance at 9mA [Ω]
A ($\tau_p \sim 2\text{ps}$)	1.30	8.9	14.3	0.96	96
B ($\tau_p \sim 3\text{ps}$)	0.70	8.4	14.2	0.89	95
C ($\tau_p \sim 5\text{ps}$)	0.54	6.7	14.3	0.68	86
D ($\tau_p \sim 6\text{ps}$)	0.42	4.4	12.4	0.54	96

III. SMALL SIGNAL MODULATION CHARACTERISTICS

The small signal modulation response (S_{21}) was measured using a 65 GHz vector network analyzer (Anritsu 37397C) connected to the VCSEL under test through a high-speed bias-T and a high-speed RF probe (Picoprobe 40A-GSG-100P). The VCSELs were probed directly on wafer and the light was coupled into an angled multimode fiber through an AR-coated lens package to avoid optical feedback and then fed to a 25 GHz photodetector (New Focus 1481-S-50) via a variable optical attenuator (VOA) to avoid saturation of the detector. The measured data was corrected for the limited frequency response of the probe and detector.

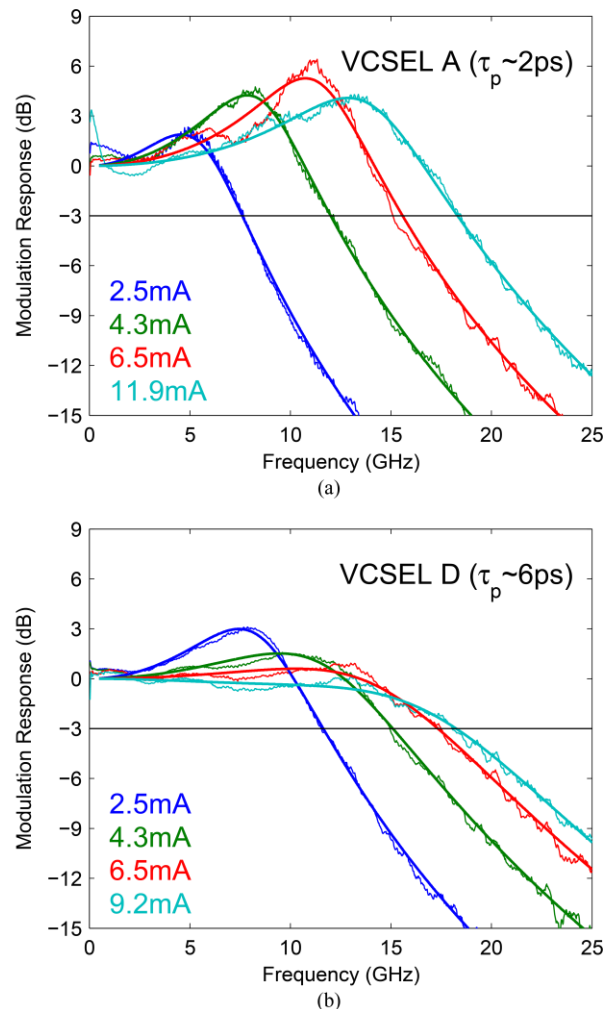


Fig. 2. Small signal modulation response for (a) VCSEL A and (b) VCSEL D at indicated bias currents.

The measured S_{21} for the least (VCSEL A) and most (VCSEL D) damped VCSELs (shortest and longest photon lifetime) is shown in Fig. 2 at increasing bias currents. The highest bias currents represent the currents producing the maximum modulation bandwidth for the respective VCSEL. The large impact of damping on the modulation response is evident from VCSEL A exhibiting clear resonance peaks even at large bias currents, whereas the more damped response of VCSEL D is almost flat.

A three-pole transfer function was fitted to the measured data to extract the resonance frequency and the damping rate [8], which were used to extract the K - and D -factors as shown in Fig. 3. The extracted K -factors range from 0.1 to 0.4 ns and the D -factors from 4.9 to 6.2 GHz/mA^{1/2} for VCSELs A-D. Both K - and D -factors increase with increasing photon lifetime, as expected [10]. From Fig. 3(a) it is obvious that there is a relatively large uncertainty associated with the extraction of the K -factors, in particular for the least damped VCSEL A. Also, the K -factors were extracted from the low current regime, before thermal saturation begins. Therefore, the extracted K -factors should only be viewed as indicators of the amount of damping.

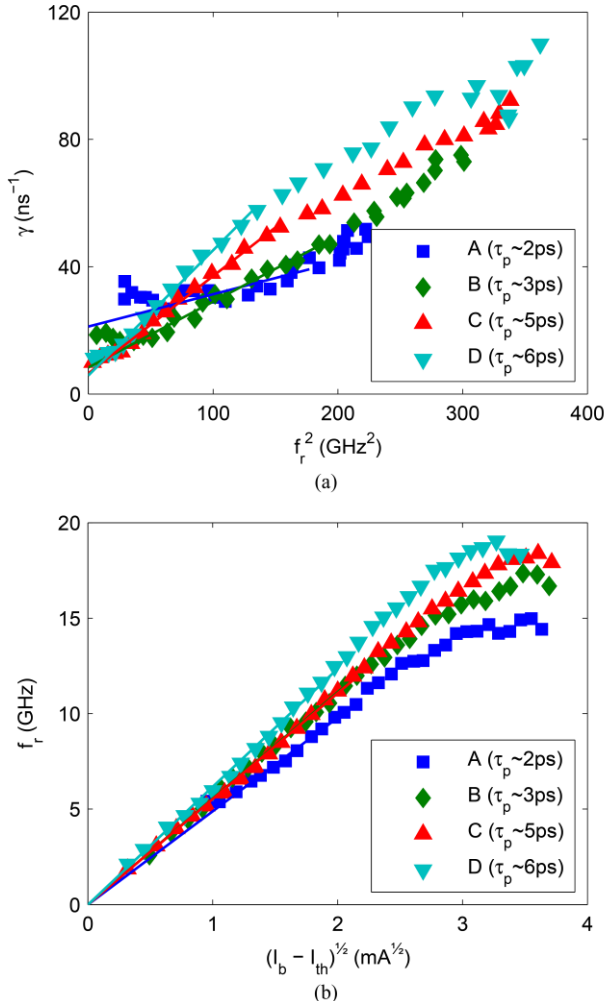


Fig. 3. (a) Damping rate vs. resonance frequency squared. Fits used to extract the K -factors are shown. (b) Resonance frequency vs. square root of bias current above threshold. Fits used to extract the D -factors are shown.

TABLE II
DYNAMIC PERFORMANCE PARAMETERS

	Max. bandwidth [GHz]	K-factor [ns]	D-factor [GHz/mA ^{1/2}]
A ($\tau_p \sim 2$ ps)	18.3	0.1	4.9
B ($\tau_p \sim 3$ ps)	20.8	0.2	5.6
C ($\tau_p \sim 5$ ps)	19.7	0.3	5.5
D ($\tau_p \sim 6$ ps)	18.2	0.4	6.2

Table II summarizes the dynamic performance parameters. The highest 3 dB modulation bandwidth is attained for VCSEL B ($K=0.2$ ns) at ~ 21 GHz. Reduced resonance frequency for lower K -factors and excessive damping for higher K -factors results in smaller modulation bandwidths for the other VCSELs [10]. A parasitic cut-off frequency close to 20 GHz was also extracted from the fits, which implies that the modulation bandwidth is also to a certain extent limited by the electrical parasitics. It is expected that a VCSEL with a lower parasitics limited bandwidth would benefit from less damping (lower K), both in terms of the small signal modulation bandwidth and the vertical eye opening under large signal modulation.

IV. LARGE SIGNAL MODULATION CHARACTERISTICS

A. Turn-on transients

A ~ 0.9 V_{pp} voltage step generated with a bit pattern generator (SHF 12103A) programmed with repeated series of 16 ones and 16 zeroes at a bit rate of 10 Gbps (1.6 ns pulse length) was used to study the turn-on transients. The signal was fed to the VCSEL under test using the same stage as previously, but the New Focus detector was replaced with a faster 30 GHz detector (VI Systems D30-850M) to better map the intrinsic rise times of the VCSELs. After detection, the signal was recorded by a 70 GHz equivalent time sampling oscilloscope (Agilent Infiniium DCA-J 86100C). The detector was reverse biased at -4 V through a high-speed bias-T to obtain the fastest response time possible. Due to an impedance mismatch between the detector and the oscilloscope, a 10 dB RF attenuator was included here to minimize signal degradation from electrical reflections. The VOA between the VCSEL and detector was set to 3 dB attenuation.

The measured step responses with the VCSELs biased at 9.0 mA are shown in Fig. 4(a). The extracted 20-80% rise time (undeconvolved), overshoot, and signal amplitude for the respective VCSELs are shown in Fig. 4(b-d). It is clear that the rise time is reduced with reduced damping (K -factor), even though the bandwidth of the photodetector largely limits the measured rise times. A fast rise time will contribute to larger vertical eye opening at high data rates, since the VCSEL can respond faster to the applied signal. Moreover, the signal amplitude is increased with reduced damping as a result of higher slope efficiency at the bias point, again contributing to a larger vertical eye opening. However, the step response also shows that reduced damping leads to increased overshoot and settling time for the relaxation oscillations. This will induce data history dependent timing jitter when the time slot of a data bit is shorter than the time needed for the relaxation oscillations to settle. The amount of timing jitter will normally

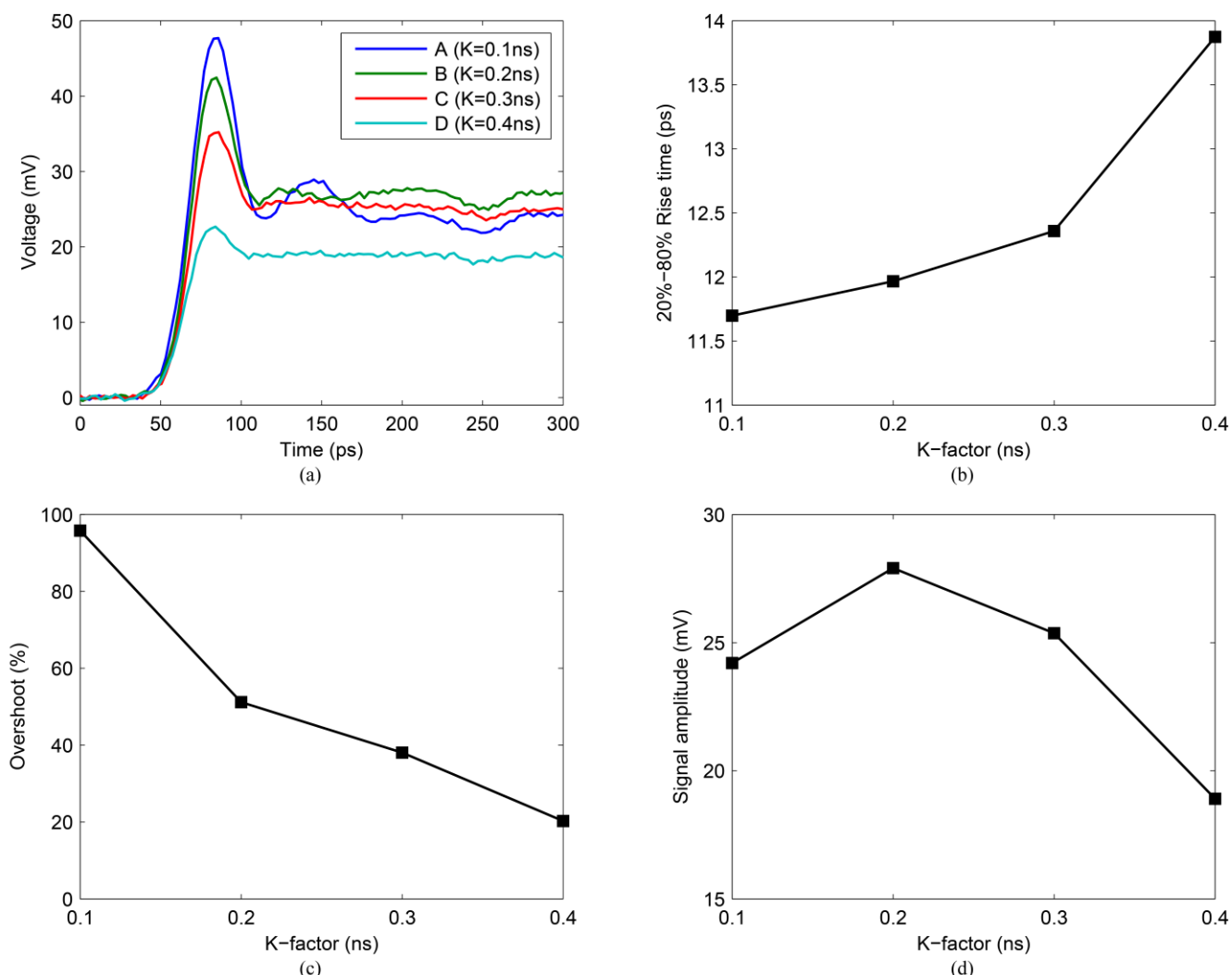


Fig. 4. (a) Step response for VCSELs A-D. (b-c) Rise time, overshoot, and signal amplitude vs. K -factor. The VCSELs are all biased at 9.0 mA.

increase with the data rate since then more data history dependent variations of the signal levels are present at the transitions points.

B. Optical eye diagrams

A $\sim 1.0 V_{pp}$ non-return-to-zero signal consisting of pseudorandom binary sequences (PRBSs) with a word length of 2^7-1 was generated with the bit pattern generator in combination with a 55 GHz broadband amplifier (SHF 804 TL 22 dB) and 10+3 dB RF attenuators. A short word length was used in order to emulate the short run codes typically employed in data communication links (e.g. 8B10B) [13]. Optical eyes were recorded by detecting the optical signal using a linear 22 GHz photoreceiver (New Focus 1484-A-50) connected to the equivalent time sampling oscilloscope, while the VOA was set to 3 dB attenuation. Matrices of eyes are shown in Fig. 5 for VCSELs A-D operated at 10, 25, and 40 Gbps with bias currents spanning from 8.0 to 14.0 mA. The bias currents are all far above threshold and therefore the impact of varying threshold currents on the eyes at a given current is small. By biasing the VCSELs at the same currents and keeping the modulation voltage constant, the modulation

currents are also expected to be the same for all VCSELs. From Fig. 5 it can be seen that the damping of the relaxation oscillations increases with increasing K -factor and bias current, as expected.

At 10 Gbps, all VCSELs are able to produce open eyes at all bias currents. However, the low damping for the low K -factor VCSELs results in a large overshoot and long duration of the relaxation oscillations, particularly at low currents. Since the data rate is moderate, the vertical eye opening is not limited by the rise time, but rather the slope efficiency. This is clearly seen by comparing the eyes of VCSEL B and D, where the vertical eye opening is reduced when the slope efficiency is reduced. At this relative low bit rate, one can afford large damping to obtain high quality eyes at a low bias current. Increasing the data rate to 25 Gbps causes the eyes of the least damped VCSEL A to start to close horizontally due to excessive data history dependent timing jitter. This data rate requires a slightly larger bias current to increase the bandwidth and damping enough to obtain high quality eyes. At 40 Gbps, VCSEL A has completely closed eyes due to the severe overshoot and timing jitter, and insufficient bandwidth, whereas the highest damped

VCSEL D has eyes that are beginning to close vertically due to a bandwidth limited rise time and a lower slope efficiency. The results indicate that a VCSEL with reduced damping operated at higher bias current is needed to obtain the fast rise time and the proper damping needed for high quality eyes at high bit rates, where the fast rise time provides for a large vertical eye opening, and the higher bias current gives reduced overshoot and duration of the relaxation oscillations. However, a too high bias current decreases the vertical eye opening (reduced OMA) since the slope efficiency is reduced at higher currents. In the light of this, the bias currents for 10, 25, and 40 Gbps were set at 8.0, 9.0, and 10.0 mA, respectively, for the measurements presented below.

C. Timing jitter

The linear photoreceiver was connected to an error analyzer (SHF 11100B) to measure the total timing jitter (TJ), while keeping the VOA at 3 dB. By sweeping the time sampling instant across the transition region, i.e. varying the signal delay in the error analyzer, bathtub curves were obtained. The measured data was fitted to the dual-Dirac model [14], where the TJ is defined as the transition region width at a bit error rate (BER) of 10^{-12} in the fitted extrapolation, here measured in terms of UI (unit interval, normalized to the bit period). An example of a bathtub curve for VCSEL D at 40 Gbps biased at 10.0 mA is shown in Fig. 6. To obtain reasonable statistical confidence, 10 errors were required at the lowest BER used in the fit ($\text{BER}=10^{-10}$), which corresponds to a measurement time of 10.0, 4.0, and 2.5 s for 10, 25, and 40 Gbps, respectively, at each sampling instant. For an accurate fit, the maximum BER should not exceed $\text{BER} = 1/(10 \cdot \text{pattern length})$ [14], which for PRBS 2^7-1 corresponds to a maximum BER of 10^{-5} .

The TJ at 10, 25, and 40 Gbps PRBS 2^7-1 versus K-factor at 8.0, 9.0, and 10.0 mA bias current, respectively, is shown in Fig. 7. Reduced damping leads to increased TJ due to overshoot and duration of the relaxation oscillations, resulting in horizontal eye closure. Since the bit period is longer at lower data rates, the relaxation oscillations have time to settle before the transitions and the TJ is lower than at higher data rates. This is further magnified in the figure where the TJ is normalized to the bit period.

D. Bit error rate measurements

The BER was measured versus received optical power using the same setup as for measuring the TJ and by varying the attenuation of the VOA. The results at 10, 25, and 40 Gbps with 8.0, 9.0, and 10.0 mA bias current, respectively, are shown in Fig. 8. All VCSELs operate error-free up to 25 Gbps. At 40 Gbps, VCSEL A could not reach a BER below 10^{-2} , wherefore it is not included in Fig. 8(c). The lowest received power at 10 and 25 Gbps was achieved using VCSEL C. We attribute this to the fairly large vertical eye opening resulting from a sufficiently high bandwidth at these bit rates together with high enough damping to suppress excessive overshoot and duration of ringing. At 10 Gbps, VCSEL A, B, and D yields receiver power penalties of approximately 1.1, 0.5, and 0.2 dB, respectively, whereas at 25 Gbps VCSEL A,

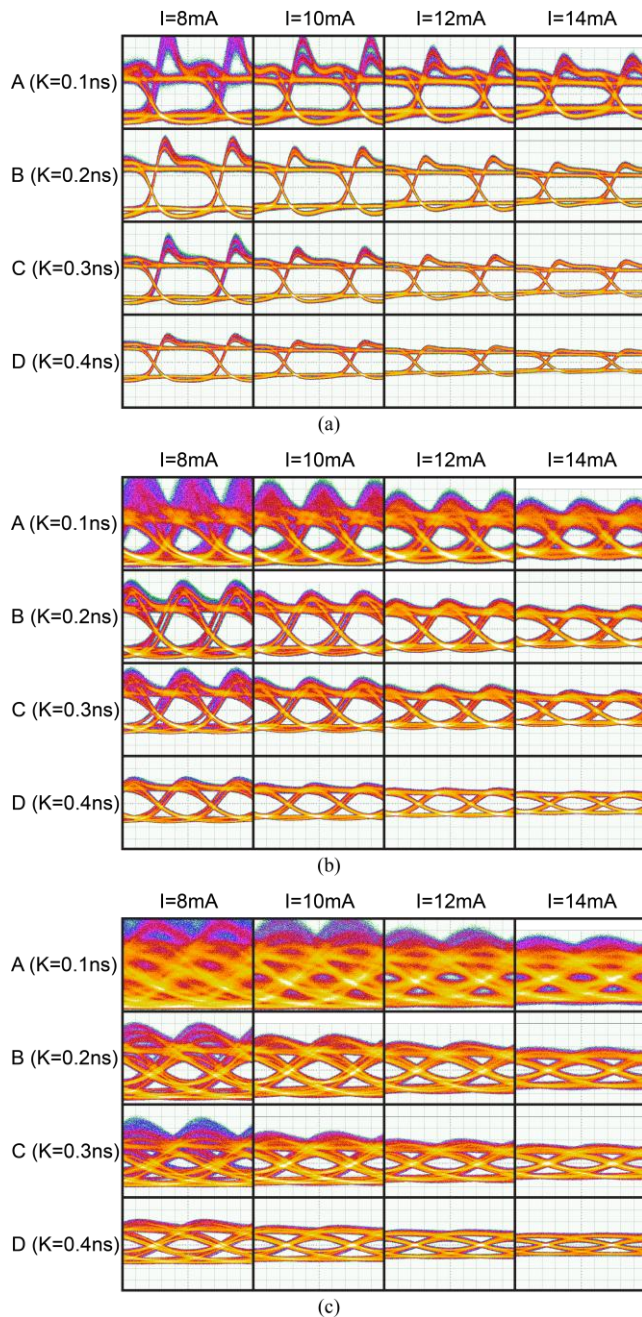


Fig. 5. Eye diagrams at (a) 10 Gbps, (b) 25 Gbps, and (c) 40 Gbps for VCSELs A-D ($K=0.1-0.4$ ns), recorded using a linear receiver. Scale: 50 mV/div and 20, 10, and 5 ps/div at 10, 25, and 40 Gbps, respectively.

B, and D yields receiver power penalties of approximately 3.5, 1.1, and 0.4 dB, respectively. At 40 Gbps, the lowest received power is obtained with VCSEL B, due to the faster rise time at reduced damping. At this high bit rate the bandwidth of VCSEL C and D is not sufficiently high and vertical eye closure leads to receiver power penalties of approximately 1.0 dB for both VCSELs. The results are well in line with the qualitative analysis of the eye diagrams: low data rates can afford more damping and therefore benefit from using a high K-factor VCSEL biased at a relatively low current, whereas higher data rates require higher bandwidth through reduced damping (i.e. using a lower K-factor VCSEL) in combination

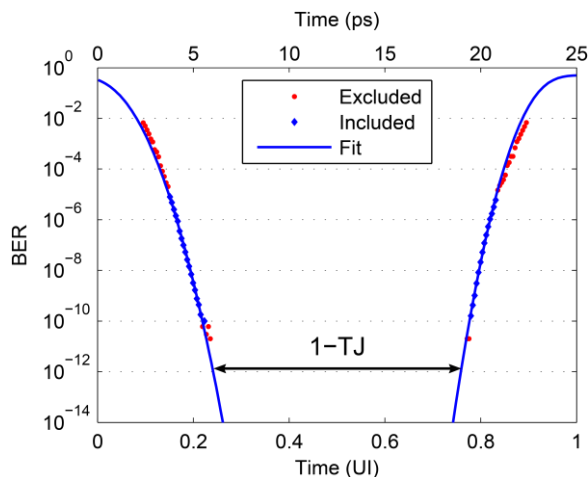


Fig. 6. Example of bathtub curve for VCSEL D at 40 Gbps biased at 10.0 mA with the time axis in both absolute and relative units. The definition of TJ is indicated.

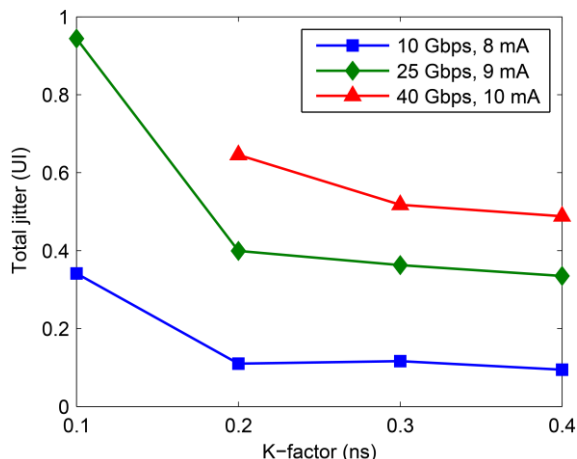


Fig. 7. Total jitter vs. K -factor at 10, 25, and 40 Gbps with corresponding bias currents of 8.0, 9.0, and 10.0 mA, respectively.

with a higher bias current to maintain a short duration of the relaxation oscillations. However, the higher bias current may lead to reduced energy-efficiency and may have a negative impact on reliability.

E. Linear versus limiting optical receiver

To investigate whether the optical link performance is similar when using a limiting receiver, which is commonly the case in real systems, eye diagrams were also recorded with a 30 GHz limiting photoreceiver (VI Systems R40-850) using the same bias currents and data rates as in the jitter and BER measurements. The eyes are shown in Fig. 9. In the limiting receiver case, at high bit rates, the excessive overshoot and duration of the relaxation oscillations for VCSEL A is translated into additional timing jitter, causing more horizontal eye closure, whereas the insufficient bandwidth and slope efficiency of VCSEL D causes more vertical eye closure. The general trend of the requirement on damping therefore becomes the same as for the linear receiver case: reduced damping is needed at higher data rates and more damping is affordable at lower data rates for achieving sufficiently large vertical and horizontal eye opening.

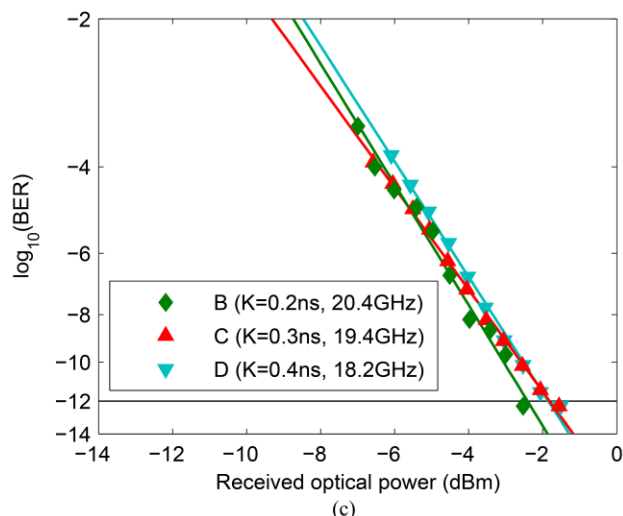
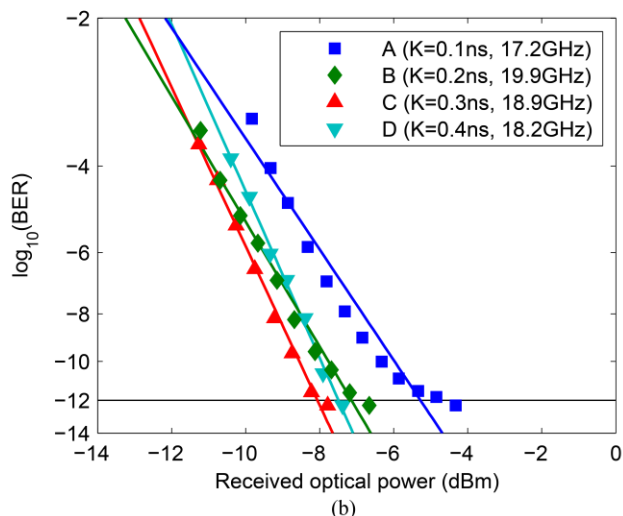
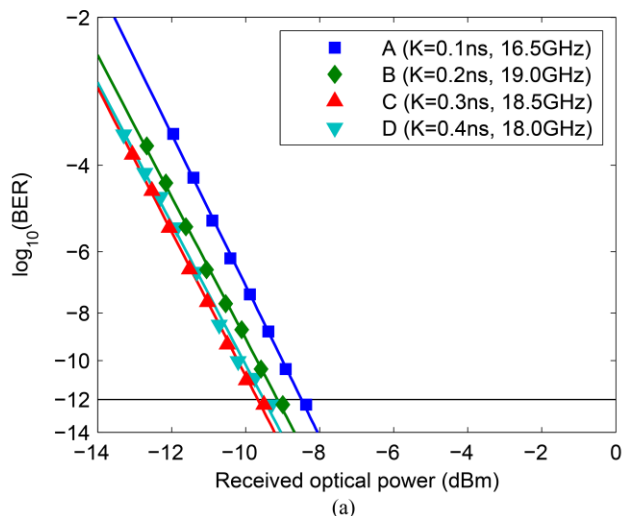


Fig. 8. BER measurements at (a) 10 Gbps at 8.0 mA, (b) 25 Gbps at 9.0 mA, and (c) 40 Gbps at 10.0 mA for VCSELs A-D ($K=0.1-0.4$ ns). The small signal modulation bandwidths at the specific bias currents are indicated.

V. CONCLUSION

Through qualitative (eye diagrams) and quantitative (BER) analyzes, we have shown that the large signal dynamics of VCSELs depend significantly on the damping of the

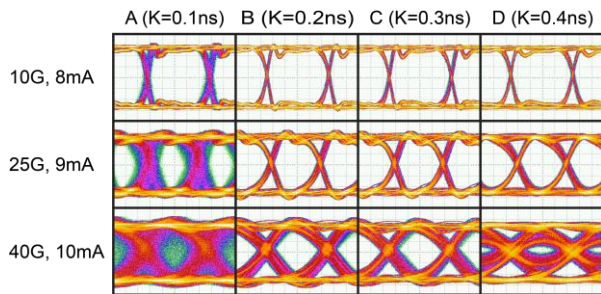


Fig. 9. Eye diagrams at 10, 25, and 40 Gbps for VCSELs A-D ($K=0.1-0.4$ ns), recorded using a limiting receiver. Scale: 70 mV/div and 20, 10, and 5 ps/div at 10, 25, and 40 Gbps, respectively.

relaxation oscillations (K -factor). To obtain the best receiver sensitivity, the damping should be chosen to simultaneously achieve a sufficiently fast rise time, a large signal amplitude, and a sufficiently short duration of the relaxation oscillations. The optimum damping level therefore depends on the specific bit rate. Higher bit rates require reduced damping for fast rise time and large optical signal amplitude. However, the reduced damping also results in a large overshoot and a long settling time for the relaxation oscillations, causing more timing jitter. At lower bit rates, higher damping can be used to produce high quality optical eyes, since the requirement for bandwidth is relaxed. This data rate dependence was proved by BER measurements, showing that VCSEL B, with the highest bandwidth, gives a receiver power penalty of 0.5 dB at 10 Gbps and 1.1 dB at 25 Gbps compared to the slightly more damped VCSEL C with a lower bandwidth, whereas at 40 Gbps VCSEL B gives a receiver power gain of 1.0 dB compared with VCSEL C. We also found that the use of a limiting instead of a linear optical receiver in the transmission link does not change the requirements on damping.

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Petter Westbergh received his M.Sc. degree in Engineering Physics and his Ph.D. degree in Microtechnology and Nanoscience from Chalmers University of Technology, Göteborg, Sweden, in 2007 and 2011, respectively. His thesis focused on the design, fabrication, and characterization of high-speed 850 nm vertical-cavity surface-emitting lasers (VCSELs) intended for application in short-reach communication networks.

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Prof. Larsson co-organized the IEEE Semiconductor Laser Workshop 2004, organized the European Semiconductor Laser Workshop 2004, was a co-program chair for the European Conference on Optical Communication 2004, and was the program and general chair for the IEEE International Semiconductor Laser Conference in 2006 and 2008, respectively. He is a member of the IEEE Photonics Society Board of Governors, an associate editor for IEEE/OSA Journal of Lightwave Technology and a member of the editorial board of IET Optoelectronics. He is a Fellow of IEEE, OSA, and EOS. In 2012 he received the HP Labs Research Innovation Award.