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# Impact of Damping on Large Signal VCSEL Dynamics

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**Abstract**—The dependence of large signal VCSEL dynamics on damping is studied through time-domain measurements of turn-on transients and timing jitter for VCSELs having  $K$ -factors from 0.1 to 0.4 ns.

## I. INTRODUCTION

The increasing demand for high-speed optical interconnects has resulted in large efforts to increase the speed of the 850 nm oxide confined VCSEL. We have previously shown that a significant increase of the small signal modulation bandwidth can be achieved by reducing the damping of the modulation response [1]. However, damping also has an effect on the large signal dynamics and proper damping is needed for high quality optical eyes. While low damping offers the high bandwidth and fast rise time needed for very high speed modulation, it gives rise to higher transient overshoot and more data dependent timing jitter, resulting in horizontal eye closure. Higher damping reduces overshoot and jitter but too much damping results in insufficient bandwidth and vertical eye closure. The optimum amount of damping therefore depends on the bit rate, with less damping expected to be required at higher bit rates.

Here we present results from a study of the dependence of large signal VCSEL dynamics on damping with the  $K$ -factor (which quantifies the increase of damping with resonance frequency) varied from 0.1 to 0.4 ns.

## II. DESIGN AND BASIC PERFORMANCE

The VCSELs used in this study have been described in detail elsewhere [2]. Strained quantum wells, low resistance and low loss distributed Bragg reflectors (DBRs), and multiple oxide apertures are employed to enable high speed modulation. The size of the oxide apertures closest to the active region is  $9\ \mu\text{m}$ . Damping was varied by varying the photon lifetime from  $\sim 2$  to 6 ps (VCSELs A to D). This was achieved by shallow surface etching to modify the top DBR reflectivity of individual VCSELs [2].

The power-current characteristics (Fig. 1) show that both threshold current and slope efficiency increases with reduced photon lifetime. Increased slope efficiency is expected to increase the vertical eye opening under binary large signal modulation.

The small signal modulation response for VCSELs having the shortest and longest photon lifetime (least and most damped) is shown in Fig. 2. Extracted  $K$ - and  $D$ -factors for VCSELs A–D range from 0.1 to 0.4 ns and 4.9 to 6.4 GHz/mA<sup>-1/2</sup>, respectively (Fig. 3). The modulation bandwidth has a maximum value of 21 GHz at  $K = 0.2$  ns (VCSEL B). Lower and higher  $K$  results in smaller bandwidth due to reduced resonance frequency and excessive damping, respectively [2].

## III. LARGE SIGNAL DYNAMICS

Turn-on transients were studied by applying a voltage step generated by an SHF 12103A bit pattern generator programmed with repeated series of 16 one's and 16 zero's at a bit rate of 10 Gbps (1.6 ns pulse length). Optical waveforms were recorded by a 30 GHz detector (VI Systems D30-850M) connected to a 70 GHz equivalent time sampling oscilloscope (Agilent Infiniium DCA-J 86100C). The recorded waveforms at a bias current of 9 mA, along with extracted rise times, overshoots and signal amplitudes, are shown in Fig. 4. Although the measured rise times were largely limited by the bandwidth of the measurement system it is clear that the rise time is reduced with reduced damping. In addition, the signal amplitude increases with reduced damping. This contributes to a larger vertical eye opening. However, the recorded waveforms also show that the overshoot and the settling time for the relaxation oscillation increase with reduced damping. This gives rise to data dependent timing jitter when the bit period is shorter than the settling time.

Total jitter (TJ) was measured by detecting the optical signal using a linear 22 GHz photoreceiver (New Focus 1484-A-50) connected to an error analyzer (SHF 11100B). The linear receiver was used to study the intrinsic behaviour of the VCSELs. The sampling instant was swept across the transition region to obtain bathtub curves which were fitted to the Dual-Dirac model. The TJ is the width of the transition region at BER =  $10^{-12}$  in the extrapolation from the fit. The TJ at 10 and 25 Gbps PRBS  $2^7-1$  versus  $K$  at 9 mA bias current, together with the corresponding eye diagrams at 25 Gbps, is shown in Fig. 5. Clearly, reduced damping increases the TJ which results in horizontal eye closure.

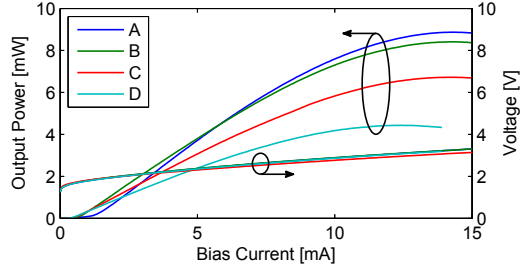


Fig. 1. Optical output power and voltage vs. current for VCSELs A–D with increasing photon lifetime.

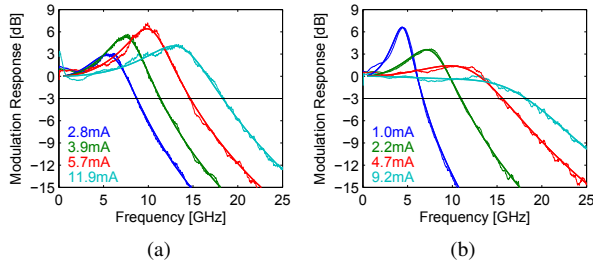


Fig. 2. Small signal modulation response for (a) VCSEL A and (b) D.

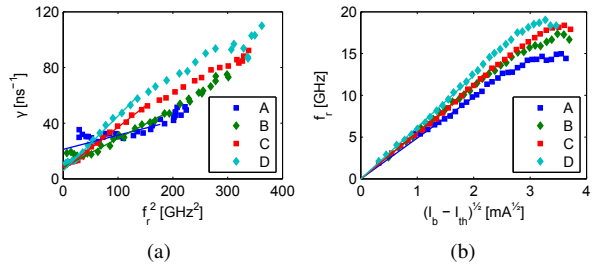


Fig. 3. (a) Damping rate vs. resonance frequency squared. Fits used to extract the  $K$ -factors are shown. (b) Resonance frequency vs. square root of bias current above threshold. Fits used to extract the  $D$ -factors are shown.

At the lower bit rate the TJ is smaller since the bit period approaches the settling time for the relaxation oscillations.

#### IV. CONCLUSION

We have shown that damping has a significant effect on the large signal dynamics of VCSELs. Low damping, which is needed at very high data rates, enables a fast rise time and a large optical signal amplitude but gives rise to a larger overshoot and a longer settling time causing more timing jitter. Lower data rates can afford more damping for high quality optical eyes.

#### ACKNOWLEDGMENT

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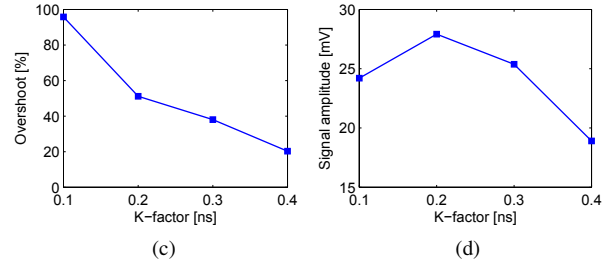
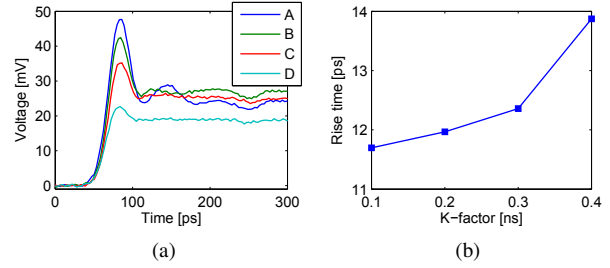


Fig. 4. (a) Step response for VCSELs A–D. (b–c) Rise time, overshoot and signal amplitude at 9 mA vs.  $K$ , respectively.

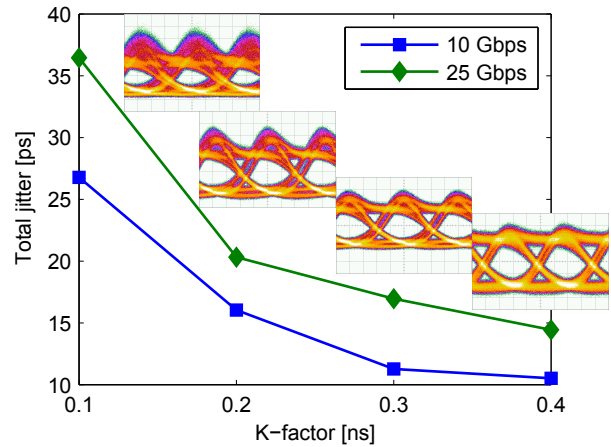


Fig. 5. Total jitter vs.  $K$  at 9 mA. Insets: Eye diagrams at 25 Gbps (vertical scale: 60, 50, 50 and 25 mV/div).

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