Operation Range of VCSEL-Interconnect Links with “Below-Threshold”-Biasing

L. Zei, K. Petermann, *Senior Member, IEEE,* R. Jäger, and K. J. Ebeling, *Senior Member, IEEE*

***Abstract*—Biasing lasers below threshold in interconnect links yields a lower effort for the monitoring circuitry, but it leads to a significant turn-on jitter due to the bit-pattern effects and spontaneous emission. An analytical expression describing the probability density function (pdf) of the total turn-on delay for a single-mode vertical-cavity surface-emitting laser (VCSEL) biased below threshold is derived, which accounts for both bit-pattern effects and spontaneous emission. In a high speed digital transmission system both timing jitter as well as the signal-to-noise ratio (SNR) limit the system-performance, which can be measured by the resulting bit-error rate (BER). The measured BER is compared with the calculated BER yielding good agreement. Therefore, following the quite general guideline as presented here, the operation range for “below-threshold”-biased VCSEL-interconnect links can be determined.**

***Index Terms*—Below-threshold-biasing, bit-error rate (BER), bit-pattern effects, probability density function (pdf), spontaneous emission, turn-on jitter, zero-bias.**

I. INTRODUCTION

FOR APPLICATIONS such as optical interconnects vertical-cavity surface-emitting lasers (VCSEL’s) are proven to be appropriate devices due to their excellent properties. Especially zero-bias operation of VCSEL’s is of great interest in order to simplify the driving circuits as well as to reduce the electrical power consumption. On the other hand, biasing a laser below threshold results in a significant turn-on jitter due to the bit-pattern effects and spontaneous emission. Depending on the applied data sequence, the turn-on delay varies substantially due to the bit-pattern effects. Additionally, because of the spontaneous emission, a further turn-on jitter should be added to the timing jitter caused by the bit-pattern effects. The timing jitter can be considerably reduced by biasing the laser above threshold, but it leads to the requirement of a monitor bias circuit and the costs raise. Raising costs should be also considered if the timing jitter is reduced by increasing the current step yielding enhanced electrical power consumption. To minimize the costs without affecting the system performance, knowledge of the required operation range for a certain bit-error rate (BER) is necessary.

Analytical expressions describing the estimated BER for zero-bias operation have been derived in several publications [1]–[3], but they take only the turn-on jitter due to the bit-pattern effects into account. Bit-pattern effects and spontaneous emission are dealt with in [4] for edge-emitting lasers, which show some differences compared to VCSEL’s. As shown in [5], [6], VCSEL’s show always two polarization states during the turn-on event in contrast to the single polarization state of edge-emitting lasers. In this paper, an analytical expression describing the BER for a single-mode VCSEL will be derived, which accounts for both the bit-pattern effects and spontaneous emission under consideration of two polarization states.

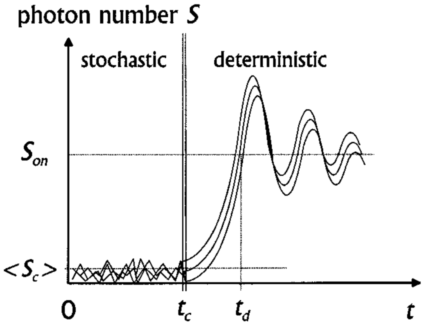

Fig. 1. Illustration of the turn-on event from below threshold. Fluctuation of the photon number due to the spontaneous emission leads to turn-on jitter.

In order to verify the derived equation, some BER-measurements have been carried out for a nearly single-mode, selective-oxidized VCSEL with a data rate of 1 Gb/s. Assuming that the derived equation is valid for all the considered current steps, this approach for estimating the BER allows to determine the required operating range for a given BER.

II. PDF OF THE TURN-ON DELAY

If the laser is driven by a step-current-pulse, the onset of optical power emission will be delayed by a delay time t_d, and a damped ringing with the relaxation resonance frequency f_r occurs. The turn-on event as sketched in Fig. 1 can be split into a stochastic and a deterministic regime. At $t = 0$ the laser drive current is switched from $I_{\rm off}$ below the threshold current I_{th} to $I_{\rm on}$ above the threshold. In the stochastic region ($t < t_c$), the carrier density n in the active layer of the VCSEL increases rapidly and reaches the threshold carrier density n_{th} at $t = t_c$. For $t > t_c$ the laser enters the deterministic region where the photon number S grows to the stationary value $S_{\rm on}$ after an additional time $t_{\rm on} = t_d - t_c$.

The crossing time t_c denotes the time when the threshold carrier density n_{th} is reached and is strongly data dependent. As sketched in Fig. 2, the number N of zeros preceding the “1” bit

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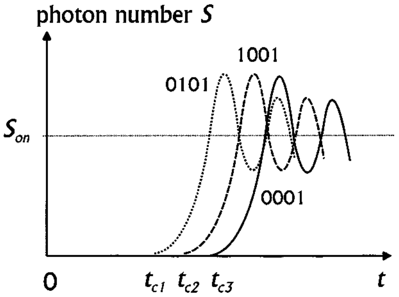

Fig. 2. Illustration of bit-pattern effects on the turn-on jitter. Various bit-patterns "1010," "1001," and "0001" lead to different turn-on delays t_{c1}, t_{c2}, and t_{c3}.

affects the time t_c considerably, which suffers from the bit-pattern effects. The pdf of t_c is given by [1]–[3]

$$p_c(t_c) = \ln 2 \cdot B \cdot \frac{\tau_e}{t_0} \cdot \left(1 - \frac{t_c}{t_0}\right)^{\ln 2 \cdot B \cdot \tau_e - 1} \tag{1}$$

where B and τ_e denote the bit rate and the carrier lifetime. The time t_0 corresponds to the delay time below threshold for low bit rate ($B\tau_e \ll 1$) and is defined as

$$t_0 = \tau_e \cdot \ln\left(\frac{I_{\text{on}} - I_{\text{off}}}{I_{\text{on}} - I_{th}}\right) \approx \tau_e \cdot \frac{I_{\text{on}} - I_{th}}{I_{\text{on}} - I_{\text{off}}}. \tag{2}$$

As shown in Fig. 1, at the crossing time t_c the photon number S_c is very small and fluctuates strongly due to the dominance of spontaneous emission. This fluctuation leads to a further jitter of the additional turn-on delay t_{on}. An analytical expression for the pdf of t_{on} which accounts for both polarization states has been derived in [7] and is given by

$$\begin{aligned} p_{\text{on}}(t_{\text{on}}) = {} & 4 \cdot \omega_r^2 \cdot \frac{S_{\text{on}}^2}{\langle S_c \rangle^2} \cdot t_{\text{on}} \cdot \exp[-(\omega_r \cdot t_{\text{on}})^2] \\ & \cdot \exp\left[-2 \cdot \frac{S_{\text{on}}}{\langle S_c \rangle} \cdot \exp\left(-\frac{(\omega_r \cdot t_{\text{on}})^2}{2}\right)\right] \end{aligned} \tag{3}$$

where $\langle S_c \rangle$ denotes the average photon number at $t = t_c$ and corresponds to the "absorbing barrier" in [4]. Once we have determined the value of $\langle S_c \rangle$, the pdf according to (3) depends only on the relaxation resonance frequency f_r and the photon number S_{on} at the on-state. Since $f_r \propto (S_{\text{on}})^{1/2}$, the relaxation resonance frequency can be considered as the main parameter.

Equation (3) together with (1) allows to determine the total turn-on jitter accounting for both bit-pattern effects and spontaneous emission. Since there is no correlation between these two processes, the pdf p_{tot} of the total turn-on delay t_d results from the convolution of the individual pdf's yielding [4]

$$p_{\text{tot}}(t_d) = \int_0^{t_0} p_c(t_c) \cdot p_{\text{on}}(t_d - t_c) \cdot dt_c \tag{4}$$

where $p_{\text{on}} = 0$ for $t_d < t_c$.

III. BER-ESTIMATION

The main criterion in evaluating the performance of a digital transmission system is the resulting BER. Considering the eye-diagram of the received signal, both vertical and horizontal eye-opening limit the reachable BER. The vertical eye-opening is mainly limited by the receiver noise whereas the timing jitter affects the horizontal eye-opening. Assuming that the received signal has the simple form

$$u(t) = \frac{u_0}{2} \cdot [1 + \cos(\pi \cdot B \cdot t)] \tag{5}$$

with the signal amplitude

$$u_0 = \eta_{\text{link}} \cdot R_{\text{load}} \cdot (I_{\text{on}} - I_{th}) \tag{6}$$

whereby η_{link} and R_{load} denote the total link efficiency and the receiver load, and that the decision level u_D equals $u_0/2$, the sample time t_s equals $1/2B$, and that there is only Gaussian thermal receiver noise with equal variance σ^2 of the "1"-bits and "0"-bits, the BER can be expressed by [4]

$$\begin{aligned} \text{BER} = \frac{1}{4}\Bigg[&\text{erfc}\left(\frac{u_D}{\sigma \cdot \sqrt{2}}\right) + \int_0^{1/\text{B}} \\ & \cdot \left\{p_{\text{tot}}(t_d) \cdot \text{erfc}\left(\frac{u_D \cdot \cos(\pi \cdot B \cdot t_d)}{\sigma \cdot \sqrt{2}}\right)\right\} \cdot dt_d\Bigg] \end{aligned} \tag{7}$$

where erfc is the complementary error function. Inserting (1), (3), and (4) into (7), we obtain the simple expression

$$\begin{aligned} \text{BER} = \frac{1}{4}\Bigg[&\text{erfc}\left(\frac{u_D}{\sigma \cdot \sqrt{2}}\right) + \ln 2 \cdot B \cdot \frac{\tau_e}{t_0} \cdot 4 \cdot \omega_r^2 \cdot \frac{S_{\text{on}}^2}{\langle S_c \rangle^2} \\ & \cdot \int_0^{1/B} \int_0^{t_0} \Bigg\{\left(1 - \frac{t_c}{t_0}\right)^{\ln 2 \cdot B \cdot \tau_e - 1} \\ & \cdot \exp[-\omega_r^2 (t_d - t_c)^2] \\ & \cdot \exp\left[-2\frac{S_{\text{on}}}{\langle S_c \rangle} \cdot \exp\left(-\frac{\omega_r^2 (t_d - t_c)^2}{2}\right)\right] \\ & \cdot (t_d - t_c) \cdot \text{erfc}\left(\frac{u_D \cdot \cos(\pi \cdot B \cdot t_d)}{\sigma \cdot \sqrt{2}}\right)\Bigg\}\, dt_c\, dt_d. \end{aligned} \tag{8}$$

Equation (8) allows to estimate the BER of a given digital optical transmission system by a certain bit rate as well as to predict the margin of the reachable bit rate. In addition to the carrier lifetime τ_e which can be determined by t_0 for low bit rate, the only necessary parameters are the relaxation resonance frequency f_r, the photon number S_{on} at the on-state, the average photon number $\langle S_c \rangle$ at the crossing time t_c, the amplitude $2u_D$ of the received signal and the average standard deviation σ of the receiver noise. Since f_r is proportional to the square-root of the optical power P_{on} at the on-state, f_r can be directly calculated by the injected current I_{on} and the threshold current I_{th} after we have determined the proportionality constant $C = f_r/P_{\text{on}}^{1/2}$ and measured the light-current-slope dP/dI of the VCSEL. Additionally, if the photon lifetime τ_{ph} can be determined from the proportionality constant C, the photon number S_{on} at the on-state is then simply given by $S_{\text{on}} = (I_{\text{on}} - I_{th})\tau_{ph}/e$, whereby e denotes the electron charge. Similar to [7], the average photon number $\langle S_c \rangle$ can be estimated by fitting the turn-on jitters measured and calculated according to (3).

TABLE I
VCSEL-PARAMETERS AND THEIR VALUES FOR BER-ESTIMATION

Parameter	Symbol	Value
Threshold Current	I_{th}	0.9 mA
Light-Current Slope	dP / dI	0.67 W/A
Proportionality Constant	$C = f_r / P_{on}^{1/2}$	$1.13*10^{11}$ Hz/W$^{1/2}$
Carrier Lifetime	τ_e	1.01 ns
Photon Lifetime	τ_{ph}	3.4 ps
Average Photon Number at $t = t_c$	$<S_c>$	180
Total Link Efficiency	η_{link}	17
Receiver Load	R_{load}	50 Ω
Standard Deviation of Receiver Noise	σ	2.4 mV

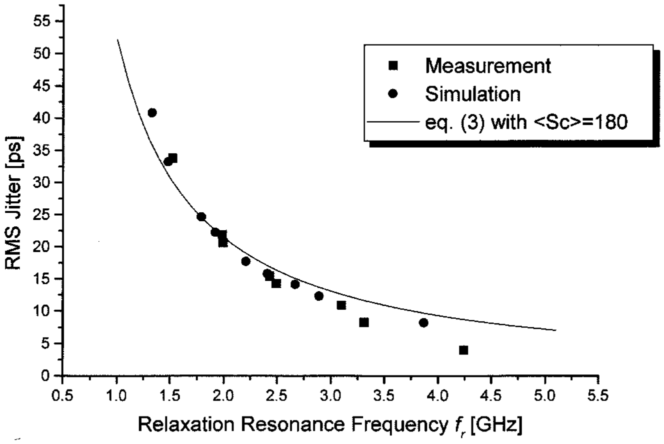

Fig. 3. Turn-on jitter caused by spontaneous emission versus relaxation resonance frequency f_r.

Finally, for a given transmission system with a certain link efficiency η_{link}, receiver load R_{load} and receiver noise, the resulting BER can be predicted according to (8).

IV. MEASUREMENT AND THEORETICAL RESULTS

The investigated laser is a selective-oxidized and nearly single-mode GaAs-VCSEL [8], which has an aperture diameter of 4 μm and an emission wavelength near 870 nm. The required VCSEL-parameters and their values for estimating the BER are listed in Table I. For determining the average photon number $\langle S_c \rangle$ at the crossing time t_c, some jitter-measurements were carried out by 300 Mb/s using a 1010 fixed periodic pattern. Since the use of a fixed periodic pattern of alternating 1’s and 0’s eliminates the bit-pattern effects, the resulting turn-on jitter describes only the fluctuation due to the spontaneous emission. The measured turn-on jitter (square) versus relaxation resonance frequency is depicted in Fig. 3. By fitting the data with the calculated curve according to (3), $\langle S_c \rangle$ was found as 180. A mismatch between theory and measurement occurs for $f_r > 3$ GHz, which can be attributed to the existence of higher transversal modes for higher f_r. Considering Fig. 4, where several emission spectra corresponding to the relaxation resonance frequency f_r are depicted, it can be seen, that higher transversal modes occur for $f_r > 3$ GHz. Results from computer simulation (circles in Fig. 3), which was developed for single-mode VCSEL with 2 transient polarization states, verify the validity of (3) for single-mode VCSEL. In this simulation, two independent rate equations of the photon number for both polarization states and one rate equation for the corporate carrier number have been solved numerically which include the Langevin noise sources [9]. The good agreement between the simulation and the theory emphasize the fact, that the existence of higher transversal mode leads to a reduction of turn-on jitter due to the enhanced degree of freedom for the VCSEL to reach the stationary value at the on-state. If we neglect the spatial filtering effects of a multimode transmission, calculations according to (3) can be considered as worst-case estimations.

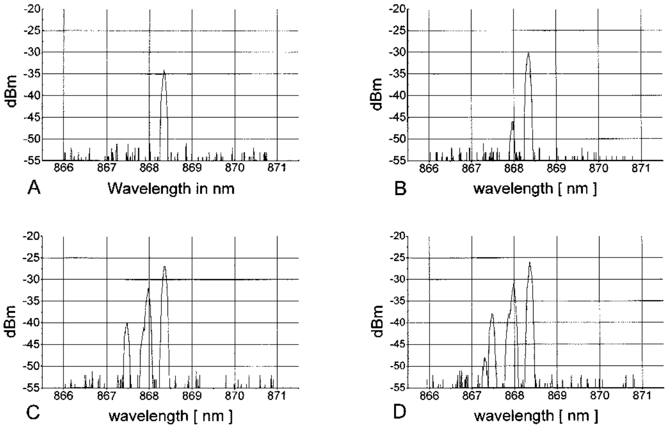

Fig. 4. Emission spectra of the investigated VCSEL by varying the current step describing by the relaxation resonance frequency f_r: (a) 2 GHz, (b) 2.78 GHz, (c) 3.33 GHz, and (d) 3.7 GHz.

The optical power of the applied VCSEL is directly coupled into a multimode fiber which is connected with a pin-diode cascaded with a 32 dB gain amplifier. The receiver load is $R_{\text{load}} = 50\ \Omega$, the total link efficiency η_{link} is determined as 17 and the standard deviation σ of receiver noise is 2.4 mV. The VCSEL is modulated by a pseudo-random $2^{23} - 1$ NRZ-signal with a bit rate of 1 Gb/s and variable signal amplitudes under different bias conditions. In Fig. 5, the measured (dots) and the calculated BER (lines) according to (8) are compared to each other versus the injected current step $I_{\text{on}}/I_{\text{th}}$. Clearly, for BER up to 10^{-9} the measurement results are in good agreement with the theory.

As shown in Fig. 5, for zero-bias transmission with a bit rate of 1 Gb/s a BER $< 10^{-9}$ is reachable for $I_{\text{on}}/I_{\text{th}} > 3.2$ which is similar to the results reported in [10]. For the same system performance it is well known that increasing the bias current results in a decrease of turn-on delay yielding a reduction of the required $I_{\text{on}}/I_{\text{th}}$, which is only 2.4 by biasing the laser with $I_{\text{off}}/I_{\text{th}} = 0.55$. If some bias current can be tolerated, Fig. 6 shows the operating range for reaching BER $< 10^{-9}$ with a bit rate of 1 Gb/s. While the measured BER (square) matches well

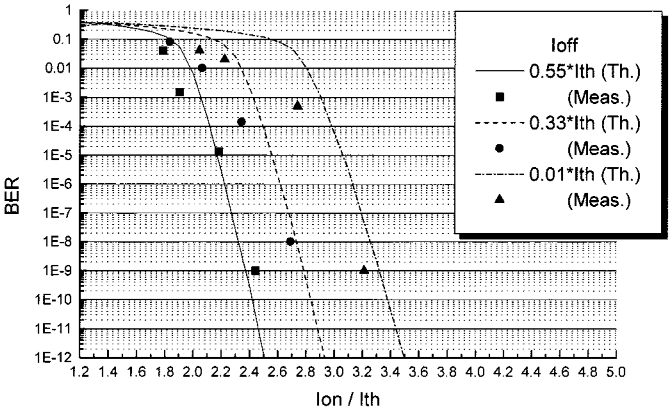

Fig. 5. Measured and calculated BER versus applied current step for 1 Gb/s data transmission with PRB23 NRZ-modulation.

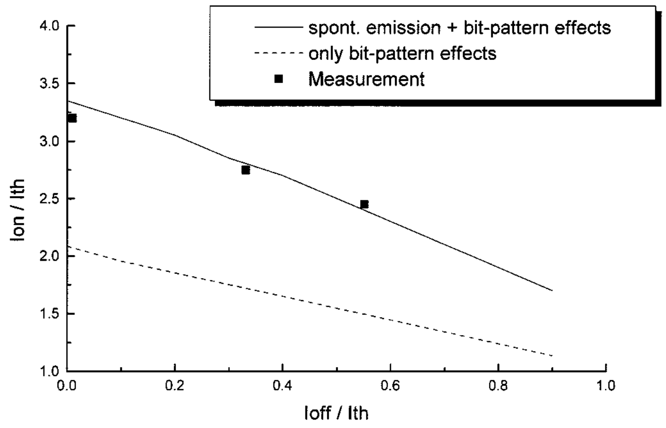

Fig. 6. Operating range of 1 Gb/s transmission for BER $< 10^{-9}$.

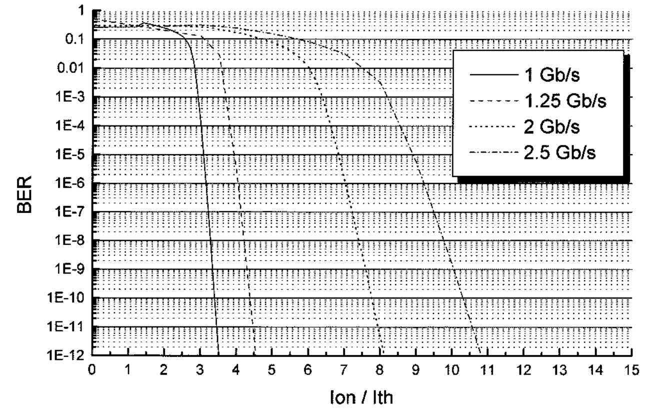

Fig. 7. Calculated BER versus $I_{\mathrm{on}}/I_{\mathrm{th}}$ for various bit rates under zero-bias condition.

to the results (straight line) calculated according to (8), theoretical results (dash line) accounting for timing jitter caused only by bit-pattern effects [1]–[3] seem to be overoptimistic. For example, if only bit-pattern effects are considered, the theoretically required $I_{\mathrm{on}}/I_{\mathrm{th}}$ for the zero-biased transmission with the same system performance described above is only 2.1, whereby the actual $I_{\mathrm{on}}/I_{\mathrm{th}} > 3.2$.

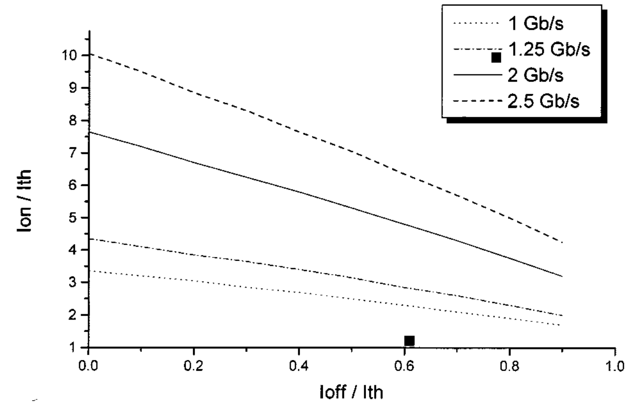

Fig. 8. Operating range of zero-bias transmission for BER $< 10^{-9}$ with various bit rates.

Assuming that the derived equation is also valid for higher data rates, the margin of the realizable bit rate can be determined. As shown in Fig. 7 for zero-bias transmission, the required current step for BER $< 10^{-9}$ grows to $I_{\mathrm{on}}/I_{\mathrm{th}} > 7.5$ for a bit rate of 2 Gb/s and even to $I_{\mathrm{on}}/I_{\mathrm{th}} > 10$ for 2.5 Gb/s. While for 1 Gb/s, the electrical power consumption with $I_{\mathrm{on}}/I_{\mathrm{th}} > 3.2$ can be tolerated, the required current step for 2- or 2.5-Gb/s bias-free transmission may be unacceptably large. If some bias current can be tolerated, the resulting timing jitter will be reduced considerably yielding a decrease of the required electrical power consumption. Fig. 8 shows the operating range for BER $< 10^{-9}$ for various bit rates up to 2.5 Gb/s. While for 2-Gb/s zero-biased transmission a current step of $I_{\mathrm{on}}/I_{\mathrm{th}} > 7.5$ is required, the necessary $I_{\mathrm{on}}/I_{\mathrm{th}}$ is only 5 if the VCSEL is prebiased with $I_{\mathrm{off}}/I_{\mathrm{th}} = 0.6$. According to this, an optimal operating point can be easily found.

V. CONCLUSION

In this paper, we have investigated the influence of the turn-on jitter on the system performance. For estimating these effects, both bit-pattern effects as well as spontaneous emission should be taken into account. Based on the fact that VCSEL's always show 2 polarization states during the turn-on event, an analytical expression describing the BER-estimation for a single-mode VCSEL has been derived here. If the spatial filtering effects are neglected, this analytical expression can also be applied to multimode VCSEL's for a worst-case estimation. For the investigated selective-oxidized VCSEL, we have found a good agreement between the measured and theoretical BER with a bit rate of 1 Gb/s, where BER $< 10^{-9}$ is reachable for $I_{\mathrm{on}}/I_{\mathrm{th}} > 3.2$ in a zero-biased transmission system.

Assuming the derived analytical expression is also valid for higher bit rate, it has been found that increasing bit rate results in enhanced current steps for the same system performance. Reduction of electrical power consumption can be realized by supplying a bias current. According to the approach as presented above, the operation range for "below-threshold"-biased VCSEL-interconnect links can be easily found.

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