Performance evaluation of zero-biased VCSEL for high speed data transmission

2010 JINST 5 C11012

(http://iopscience.iop.org/1748-0221/5/11/C11012)

PUBLISHED BY IOP PUBLISHING FOR SISSA

RECEIVED: *September 28, 2010*
ACCEPTED: *November 4, 2010*
PUBLISHED: *November 22, 2010*

TOPICAL WORKSHOP ON ELECTRONICS FOR PARTICLE PHYSICS 2010,
20–24 SEPTEMBER 2010,
AACHEN, GERMANY

Performance evaluation of zero-biased VCSEL for high speed data transmission

S. Silva,[a,1] **L. Pessoa,**[a,b] **J. Oliveira,**[a,b] **D. Coelho,**[a,b] **J.C.S. Castro**[a,b] **and H.M. Salgado**[a,b]

[a] *INESC Porto,*
Rua Dr. Roberto Frias, 378, 4200 - 465 Porto, Portugal
[b] *Faculty of Engineering, Porto University,*
Rua Dr. Roberto Frias, S/N, 4200 - 465 Porto, Portugal

E-mail: ssilva@inescporto.pt

ABSTRACT: In an optical transceiver, the power consumption related to the operation of the laser device takes a significant parcel of the total consumed power. Thus, in optical networks where a large number of transceiver devices are interconnected, e.g. large distributed sensor networks, it is of great importance to reduce this power consumption. In this work an analysis and simulation results are presented regarding the operation of a bias-free vertical-cavity surface-emitting laser (VCSEL) device, which is based on a previously developed model. The impact on bit-error rate (BER) of the increased turn-on jitter due to the bit-pattern and spontaneous emission is considered. A method for mitigating the eye-diagram distortion penalty based on the received signal equalization is also illustrated.

KEYWORDS: Front-end electronics for detector readout; Optical detector readout concepts

[1] Corresponding author.

doi:10.1088/1748-0221/5/11/C11012

Contents

1 Introduction

Large distributed optical networks are becoming a reality not only for connecting homes but also for applications were a large number of sensors distributed through a large area require high speed digital data. These scenarios are typical in the interconnection of instrumentation found in particle physics experiments but also in critical avionic sensor and actuator data transmission systems. Low power consumption and low weight are determinant for the performance and practical deployment of these networks.

By operating the laser device with no bias-current (0 current at the logic "0" stage) a significant power saving in the order of 25 to 50% can be made compared to the optimum bias current operation mode. Nevertheless, a penalty in the eye diagram shape will occur and, consequently, in the BER. This is due to the turn-on delay increased jitter (about 50 picoseconds in the obtained simulation results), which is dependent on bit-pattern effects and spontaneous emission.

Since the laser will only output optical power during the logic "1" stage, no clutter noise due to the residual optical output power at the logic "0" stage will be present in the network, which may allow a simplification at the passive optical network receiver architecture or bus like medium access. Moreover, the zero-bias modulation format eliminates the need for optical monitoring and feedback control of the bias point. Operating a laser device in a bias-free mode can save power, lower transmitter complexity, mass and increase system reliability [1].

2 Large signal operation of a semiconductor laser

At a bias current lower than the threshold current, spontaneous emission dominates and leads to significant turn-on delay, turn-on jitter and bit pattern dependent distortion effects. Simulation of the device operation in these conditions is determinant and only possible through large signal analysis. By using a complete laser model [2], the bias-free operation of a VCSEL device below threshold can be simulated and the BER penalty estimated. Hence the trade off between bellow and above threshold current biasing can be evaluated [3, 4]. The data transmission speed limit can also

2010 JINST 5 C11012

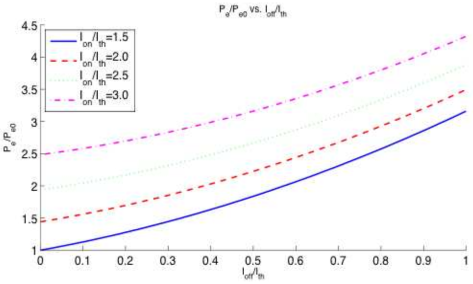


Figure 1. Power consumption in the laser device as a function of the $I_{off}/I_{th}$for several I_{on}/I_{th}.

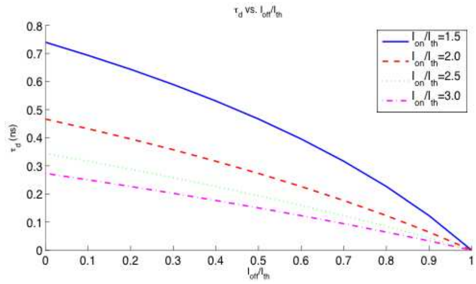


Figure 2. Turn on delay time as a function of the $I_{off}/I_{th}$for several I_{on}/I_{th}.

be determined and its operation optimized by changing the I_{off}/I_{th} and I_{on}/I_{th} ratios. For the work presented here we will define the bias current (I_{bias}) as the laser current at the lower optical power level, $I_{bias} = I_{off}$. Considering this, the modulating pulse current (I_m) will have an amplitude given by the difference between the off current (I_{off}, logic level 0) and the on current (I_{on}, logic level 1): $I_m = I_{on} - I_{off}$. In a common case, I_{off} is set above the lasing threshold current I_{th}, while for the case we wish to discuss here, I_{off} is set below the threshold current or even to zero. While not transmitting, the current through the laser remains at I_{off}. This also means that if I_{off} is below the threshold current, the laser will not output any optical signal and its power consumption will be at its lowest. The electrical power consumption (P_e) of the laser device can be calculated considering the modulation and constant components of the current through the laser device given its internal impedance (Z_0) and its threshold voltage $(V_0) : P_e = \frac{1}{2} I_m(V_0 + I_m Z_0) + I_{bias}(V_0 + I_{bias} Z_0)$.

Figure 1 shows the laser device power consumption in the laser device normalized by the power consumption with a bias current of zero (P_{e_0}) as a function of the I_{off}/I_{th} current ratio for several I_{on} currents when a forward voltage of 1.5V and an internal real impedance of 100 Ω are considered. As it can be seen, the power consumption due to the off current increases faster than with the on current, suggesting that reducing the off current can lead to an advantageous power consumption decrease (a reduction of more than a half). The problem of reducing the off current below threshold is that the level of the initial carrier density (N_i) is below the threshold carrier density necessary for lasing to occur (N_{th}). So, by injecting an I_{on} the carrier density level will have to first rise from the previous level of carrier density to the threshold carrier density level, which inevitably delays the lasing phenomenon. If we first consider the case where the carrier density is null, the turn on delay will be proportional to the laser characteristic carrier lifetime (τ_n) as given by [5–7]:

$$\tau_D = \tau_n \ln\left(\frac{I_{on} - I_{off}}{I_{on} - I_{th}}\right)\bigg|_{I_{off}=0} \approx \tau_n \frac{I_{th}}{I_{on}} \tag{2.1}$$

Figure 2 shows a graphic depicting the laser turn on delay time as a function of I_{off}/I_{th} for several I_{on} currents. Note how this turn on delay tends to zero as the I_{off} reaches I_{th}, meaning that there is no time needed to build up carrier density. In this way the laser off current is set to be above the laser threshold current as is in common applications. Note also that the delay is lower for higher I_{on} currents, as in this case the carrier density being injected into the device so that the threshold carrier density is reached more rapidly. However, the issue is not these delay times, but the jitter caused by the random accumulation of carrier due to the last laser states or bit pattern. There are

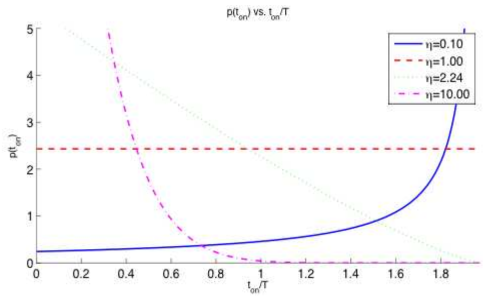


Figure 3. Turn on delay probability distribution function for several I_{on} and I_{off} to I_{th} ratios.

two extreme cases: the first one is with a long string of 0s before switching to 1; the second is with a long string of 1s followed by a single 0 bit before switching back to 1.

In the first case, during the long strings of 0s, carriers have a long time to decay to a low value before switching to 1, so the time needed for the carrier density to reach the threshold value is large, resulting in a long turn-on delay time. Regarding the second case, since the carriers have only one 0 bit length of time to decay before switching to 1, the carrier density right before the turn-on occurs is higher. Therefore it takes less time for the carrier density to reach the threshold value, and thus the turn-on delay is shorter, resulting in a variation of the turn-on delay time dependent on the bit pattern of the driving current. Considering that the photon density in the laser cavity is approximately zero at a current below threshold, the carrier density can be obtained for a current pulse of amplitude I_m by [4] (q is the electron charge):

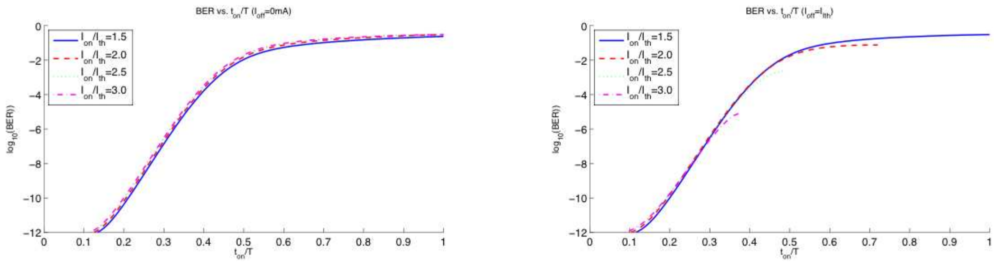
$$N(t) = \tau_n \frac{I_m}{q}\left[1 - e^{-t/\tau_s}\right] + N_i \approx t\frac{I_m}{q} + N_i \tag{2.2}$$

As previously explained, the value of $N_i$depends on the number of “0s” that preceded the “1” bit and its value decays exponentially with a time constant given by the carrier life time and the number of preceding “0” bits N and is given at $t = T$ by $N_i = N_{th}e^{-NT/\tau_n}$ [4]. Solving equation (2.2) for $N(t_{on}) = N_{th}$, we get the turn on delay time dependence with the number of preceding “0” bits [4] $t_{on} = \tau_D\left(1 - e^{-NT\tau_n}\right)$.

Considering that the modulation pulses follow a random bit pattern the statistic of N are of a geometric distribution $p(N) = \gamma(2^{-N}), \gamma = \ln(2)$, and letting $\eta = \ln(2)\tau_n/T$, be the ratio of carrier life time to bit duration, the probability distribution function of t_{on} can be given using $p(N)$ by [3]:

$$p\left(t_{on}\right) = \frac{\eta}{\tau_D}\left(1 - \frac{t_{on}}{\tau_D}\right)^{\eta-1} \tag{2.3}$$

Figure 3 shows the turn on delay probability distribution function ($p(t_{on})$) for several I_{on} and I_{off} to I_{th} ratios [5–7]. When the carrier lifetime is long compared to the bit period ($T = 1/4.8$Gbits/s, for the examples given here), it has a large influence on the carrier density relaxation between bits ($\eta = 0.1$) and the corresponding time to reach threshold. This turn on jitter will cause a penalty to the digital transmission system that can be measured in terms of the estimated bit error rate (BER) as a function of the I_{on}/I_{th} and I_{off} currents [5–7] (figure 4). Since no other penalty was considered in the link, when I_{off} reaches I_{th}, the BER tends to zero. As expected the BER increases with t_{on}/T.



(a) $I_{off} = 0$ (b) $I_{off} = I_{th}$

Figure 4. BER estimate for I_{on}/I_{th} as a function of t_{on}/T for $I_{off} = 0$ and $I_{off} = I_{th}$.

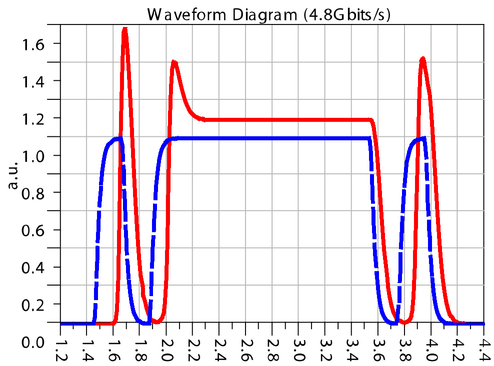


Figure 5. Turn on delay difference due to bit pattern. ‘dashed’: current into the laser; ‘solid’: laser optical output.

3 Simulation results

Using a previously developed model and laser parameters obtained for VCSEL devices operating at 850nm and 1310nm [2], it is possible to study the behavior of these devices when operated with a below threshold off current. Figure 5 shows the turn on delay difference due to bit pattern for two particular extreme cases: “00000010” and “11111101” sequences. Note how the optical output (solid curve) representing the first “1” after the zeros occur at the end of the current pulse (dashed curve) while the last “1” occurs in the middle of the current pulse: this is due to the build up of carrier density in the laser due to the previous string of “1”s.

In any practical application a line code is always applied to the bit stream to simultaneously achieve DC-balance and let enough state changes to allow reasonable clock recovery [8, 9]. For example with 8B10B coding, used in Fibre Channel or Gigabit Ethernet, the largest number of “0”s or “1”s in a row is 5 [8]. This means that the maximum turn on delay will be limited and related to the maximum of allowed “0s” in a row. By keeping this number low, the turn on delay and consequently jitter is also kept low.

Figure 6 illustrates the results of the simulation of an 850nm and 1310nm VCSEL with and without bias current at 4.8Gbit/s and the same on current. A pseudorandom (PRBS) bit sequence of 2^7-1 word length is used with a non-return-to-zero (NRZ) modulation. The effects of pattern dependent jitter are visible in figure 6. Nevertheless this jitter is lower than 40ps for the 850nm

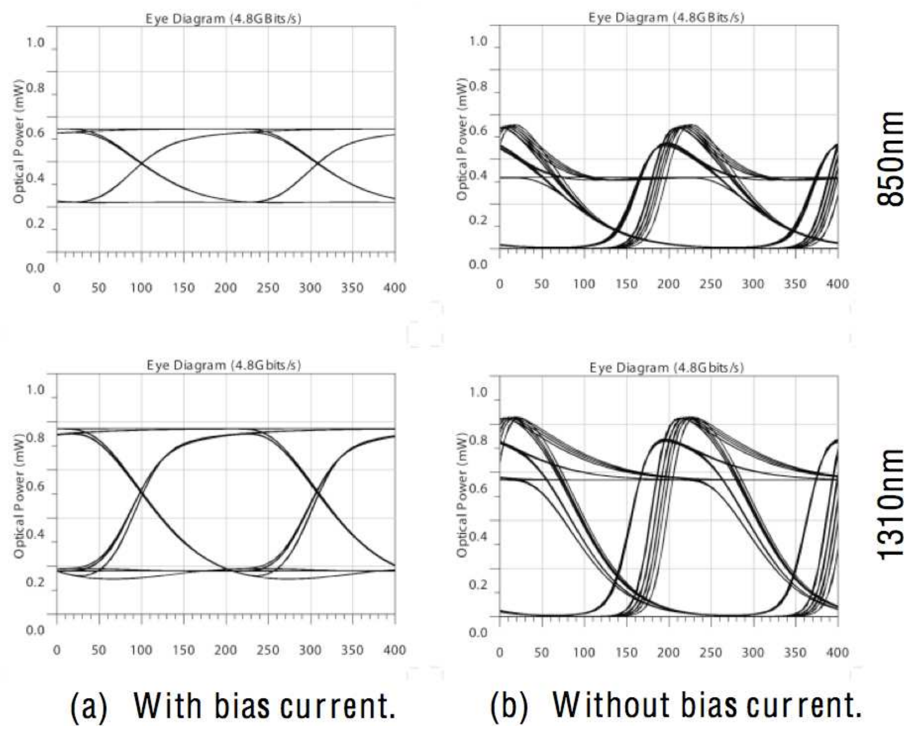


Figure 6. Simulation of the operation of a 850nm (top) and 1310nm (bottom) VCSEL with (left) and without (right) bias current at 4.8Gbits/s.

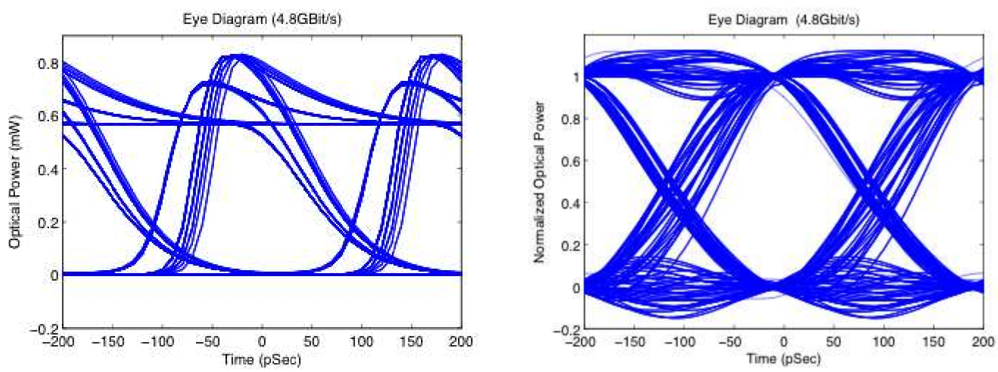


Figure 7. Eye diagram equalization results for the 1310nm VCSEL device at 4.8Gbit/s: (a) with and (b) without equalization filter.

device and 50ps for the 1310nm device. Although the eye diagram is distorted, data transmission could be achieved with a bit error rate below 10^{-10} and 10^{-9}, respectively (see figure 4).

4 Equalization

By taking into account the bit pattern dependence of the distortion induced by the zero-bias operation, one could expect that a finite impulse response filter having coefficients spanning several bit

2010 JINST 5 C11012

periods would mitigate these effects. In fact, we have found through simulations that it is possible to obtain a filter that minimizes the signal standard deviation at the sampling time.

This filter needs to span several bit periods in order to make an observable impact, in this case, 18 bit periods were used. The impulse response is obtained with an adaptive algorithm, the Least Mean Squares (LMS), with a step size of 5.10^{-4}, and a training sequence of 20 bits. From figure 7, it can be seen that, although the timing jitter has remained in the 50ps range, there is clearly an opening of the eye as well as negligible amplitude distortion. Note also that the Q factor has improved from 15.84dB to 35.47dB at the sample time.

5 Conclusion

Operating a VCSEL device with an off current below threshold can lead to high power savings. Although there is a considerable penalty in the eye diagram, transmission of data is still possible at low bit error rates. Decreasing the I_{off} to I_{th} ratio causes an increase of the turn on jitter and, consequently, an increase of the bit error rate. Also, the lower the device threshold current, the lower the jitter. High drive currents help to control the jitter levels but at a lower extent. The jitter is highly dependent on the bit pattern, and especially in the number of trailing zeros, suggesting that a suitable coding scheme for the bit stream could optimize the performance of a zero-biased VCSEL transceiver system. Equalization of the received signal leads to an improvement in the link performance, mitigating the impact of bias free operation. Reducing the large turn-on delay and the resultant eye degeneration is crucial for efficient bias-free transmission of high data rates. Ultimately, turn-on jitter sets a limit on the achievable bit rates to be transmitted under bias-free conditions.

Acknowledgments

This work was supported in part by EC Framework 7 (FP7) project DAPHNE (www.fp7daphne.eu) – Developing aircraft photonic networks (grant ACP8-GA-2009-233709). We acknowledge funding from FCT and program POCTI/FEDER under the National Plan for Scientific Hardware Renewal with grant REEQ/1272/EEI/2005. J. Oliveira, L. Pessoa and D. Coelho also acknowledge support from FCT through a PhD grant.

References

[1] S. Ly Khadijetou, A. Rissons, E. Gambardella, D. Bajon and J-C. Mollier, *Modeling and characterization of VCSEL-based Avionics Full Duplex Ethernet (AFDX) gigabit links*, in *Proceedings of the Vertical-cavity surface-emitting lasers Conference*, San Jose CA, *Proc. SPIE* **6908** (2008) 69080J.1.

[2] S. Silva and H. Salgado, *VCSEL Laser Characterization and Modelling for future Optical Transceiver at the Super Large Hadron Collider*, in *Proceedings of the ICTON2009*, Conference, Azores, Portugal, July 2009.

[3] L. Zei, K. Petermann, R. Jager and K.J. Ebeling, *Operation range of VCSEL-interconnect links with "below-threshold"-biasing*, *J. Lightwave Technol.* **18** (2000) 477.

[4] D.M. Cutrer and K.Y. Lau, *Ultralow power optical interconnect with zero-biased, ultralow threshold laser-how low a threshold is low enough?*, *IEEE Photon. Technol. Lett.* **7** (1995) 4.

[5] R.W. Dixon and W.B. Joyce, *Generalized expressions for the turn-on delay in semiconductor lasers*, *J. Appl. Phys.* **50** (1979) 4591.

[6] X.X. Zhang, W. Pan, J.G. Chen and H. Zhang, *Theoretical calculation of turn-on delay time of VCSEL and effect of carriers recombination*, *Optics Laser Technol.* **39** (2007) 997.

[7] S.W. Corzine, M.R. Tan, S.-Y. Wang and G. Ding, *Modeling of Turn-On delay time jitter in vertical-cavity surface-emitting lasers*, Report HPL-95-136, Communications and Optics research Laboratory, December 1995.

[8] Al X. Widmer and P.A. Franaszek, *A DC-Balanced, Partitioned-Block, 8B/10B Transmission Code*, *IBM Journal of Research and Development* **27** (1983) 440.

[9] M. Reinecke and K. Hansen, *Advanced 3b4b channel coding for low error-rate optical links at 2.488 Gbit/s*, in *Proceedings International Conference on Information Technology: Coding and Computing*, pp. 524–528, April (2001).

2010 JINST 5 C11012