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Optimization of VCSEL photon lifetime for minimum energy consumption at varying bit rates

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Abstract: Optimum photon lifetimes of vertical-cavity surface-emitting lasers (VCSELs) are shown to be target bit rate dependent. A comparison of the power budget in fJ/bit for optimized VCSELs operating at 25 Gb/s and 50 Gb/s is given. At 25 Gbit/s, the energy per bit ratio is lower than 100 fJ/bit presenting a 75% reduction as compared to the 50 Gb/s values. The cavity dip / gain peak detuning for maximizing temperature stability must be similarly adjusted to the bit rate as shown here. These conclusions are valid for any VCSELs, e.g. those emitting at 850 nm, 880 nm, 910 nm, 940 nm or 980 nm, presently investigated by us.

1. Introduction

The explosive growth of internet use leads to an explosion of the energy consumption of data centers, presently leading to large concern about their environmental impact and CO_2 imprint. Vertical cavity surface emitting lasers VCSELs are key enabling devices meeting the requirements of optical interconnects in such data centers up to a few hundred meters of single or multimode fiber [1,2] due to their simplicity [3], low cost, and large data transmission rates. VCSEL-based interconnects are also rapidly replacing electrical versions for short distances and are becoming heterogeneously integrated with Si-based driver electronics [4], thereby presenting a novel type of Si photonics. Achieving larger bit rates has been the stated goal of research and development during the last years. The bit rate can be increased by individual VCSEL optimization, that increases bandwidth and by approaches that increase the spectral efficiency M using e.g. predistortion or forward error correction, by higher modulation formats like PAM4 [5–7]. These optimizations seem to reach now intrinsic device limits [8].

The next challenge will be to focus on reducing the energy consumption of the lasers and drivers as well as improving their temperature stability in order to avoid external temperature stabilization — all a function of the bit rate. The energy cost of transmission at potentially the largest possible bit rates, use of predistortion or forward error correction [9] needs to be compared with the energy cost of data transmission and device life time at lower bit rates. Finally, end of life considerations of the total cost of data centers will move the focus of operators of such centers. Novel multiplexing approaches and their standardization (e.g. Ethernet 802.3bs and CEI-56G) are helping to implement strategies for the optimization of energy consumption of a link or a complete data center and the lifetime of the devices.

We developed VCSELs emitting at 850 nm, 880 nm, 910 nm, 940 nm and 980 nm, which were optimized to achieve 50+ Gb/s, enabling 200+ Gb/s data transmission across a multimode fiber. This was based on the most simple PAM2-modulation scheme without any kind of predistortion leading to a spectral efficiency around 2 bit [10]. Systematic tuning of the cavity photon lifetime

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was demonstrated to increase the maximum data rate in concert with a reduction of the energy to data ratio (*EDR*) at 50 Gb/s [11,12]. The increase of the data transmission rate is one benefit of multiplexing. The number of independent devices that are used for multiplexing presents an additional degree of freedom for reducing total energy consumption. Joint optimization of the maximum bit rate of a system, the device lifetime, and the system's energy consumption is now possible. Here, the total energy to operate the lasers and drivers as well as the energy for cooling needs to be taken into account.

2. Experimental setup

The large-signal measurement setup used by here was previously described in detail [13]. The scattering parameters of VCSEL measured with a Hewlett-Packard 8722C vector network analyzer with a constant modulation amplitude of -25 dBm and a New Focus 1434-50 photoreceiver with a bandwidth of 26.1 GHz. We fit the S21 data to the standard laser diode transfer function [14]:

$$H(f) = C * \frac{f_R^2}{f_R^2 * -f^2 + i\frac{\gamma}{2\pi}f} * \frac{1}{1 + \frac{f}{f_p}}, \tag{1}$$

to extract the relaxation resonance frequency f_R, the -3 dB bandwidth (BW) f_3dB, the damping γ, and the parasitic frequency f_p. C is a constant normalizing term. The threshold current is derived from a fit to the linear portion of the *L-I* characteristic and the intersection with the abscissa. Electrical power P_{el} and resistance R are derived from the *I-V* characteristic Fig. 1(b).

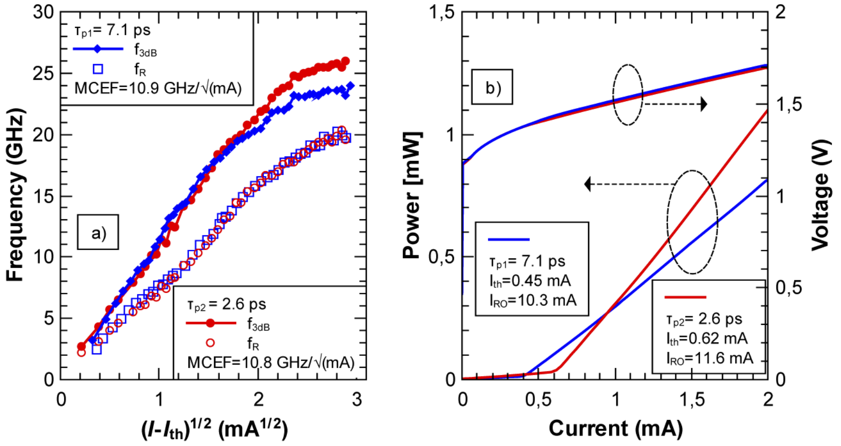

Fig. 1. Characterization of the DUT for two different photon lifetimes (blue – long / red – short). a) Bandwidth (filled symbols) and relaxation resonance frequency (open symbols) versus square root of current above threshold current shows a MCEF of 10.9 GHz/$\sqrt{\mathrm{mA}}$ and 10.8 GHz/$\sqrt{\mathrm{mA}}$ for long and short photon lifetimes respectively. b) L-I-V characteristic of DUT. The threshold current increases from 0.45 mA to 0.62 mA as a result of the reduced photon lifetime.

The device under test (DUT) (a ~5 µm aperture diameter VCSEL emitting at 980 nm) was fully characterized for two different photon lifetimes. The change of the photon lifetime was done by deposition of an additional SiN-layer onto the outcoupling mirror as described in [11]. The extraction of the associated cavity photon lifetimes was done for the fundamental longitudinal mode as described in [13]. The laser shows modulation current efficiency factors (*MCEFs*) of 10.9 GHz/$\sqrt{\mathrm{mA}}$ and 10.8 GHz/$\sqrt{\mathrm{mA}}$ for 7.1 ps and 2.6 ps cavity phone lifetime, respectively. The threshold current increases from 0.45 mA to 0.62 mA as a result of the reduced photon lifetime.

3. Bit rate versus dependent power consumption

According to the Shannon theorem [15], the maximum bit rate is limited by the -3dB bandwidth of the laser and the spectral efficiency M

$$BR_{max} = M * f_{3dB}. \tag{2}$$

An increase of a VCSEL bias current I increases the electrical power consumption quadratically

$$P_{el} = U * I = I^2 * R, \tag{3}$$

but increases the bandwidth f_{3dB} only following a square root dependence

$$f_{3dB} = MCEF * \sqrt{I - I_{th}}, \tag{4}$$

where I_{th} is the threshold current and $MCEF$ is the modulation current efficiency factor. As long as the spectral efficiency and modulation current efficiency factor are constant, the bit rate scales linearly with $\sqrt{I - I_{th}}$

$$n * BR = \sqrt{I - I_{th}} \quad ; \quad n = \frac{1}{M * MCEF}. \tag{5}$$

Assuming the threshold current density to be much smaller than the operating current density, the electrical power consumption as a function of bandwidth or bit rate is unfortunately following a fourth power law

$$P_{el} = R\left(\frac{f_{3dB}}{MCEF}\right)^4 \text{ or } P_{el} = R(n \cdot BR)^4 \tag{6}$$

The electrical resistance R as a function of I converges to the differential resistance at large currents. A reduction of bit rate (BR) leads thus to an enormous reduction of power consumption. Lower photon lifetime results in a slightly larger threshold current. To investigate in detail the correlation between power consumption and data rate we are using the energy to data ratio [16,17]

$$EDR = \frac{P_{el}}{BR} = BR^3 \cdot n^4 R. \tag{7}$$

Figure 2 shows EDR versus BR assuming M and $MCEF$ to be constant, neglecting thermal influences, derived from the static L-I-V data shown in Fig. 1(b). For the smaller photon lifetime τ_{p2} (red) the threshold power is larger and the bandwidth is smaller for a given current above threshold current caused by a smaller $MCEF$. It leads to a larger EDR compared to the larger photon lifetime τ_{p1} (blue). The impact of the threshold current/power decreases with the increase of the bit rate, resulting in a decrease of EDR, until the quadratic growth of the total power with current leads to a power to the third growth of EDR with the BR. This relationship is aperture diameter independent, although the power consumption itself of course decreases with size [11].

Under realistic conditions, the increase of the relaxation resonance frequency (f_R) with increasing current will saturate due to thermal effects. This effect is shown in Fig. 1(a) as being independent of the cavity photon lifetime tuning and the rollover current. The $MCEF$ depends on the D-factor because of the constant ratio between f_{3dB} and f_R at low currents [18]. A large damping caused by e.g. the increasing relaxation resonance frequency (Eq. (8)) can impact that ratio [11].

$$\gamma = \kappa * f_R^2 + \gamma_0. \tag{8}$$

Both mechanisms (saturation and damping) are leading to a fast increase of power consumption for larger bit rates. The dashed lines in Fig. 2 are showing qualitatively the impact of thermal effects and large damping on the EDR in accordance to Fig. 1(a). A reduction of photon lifetime reduces the impact of the $MCEF$ reduction (blue dashed line) leading to a larger bandwidth [11]. For low currents and low bit rates, however, a large photon lifetime is advantageous.

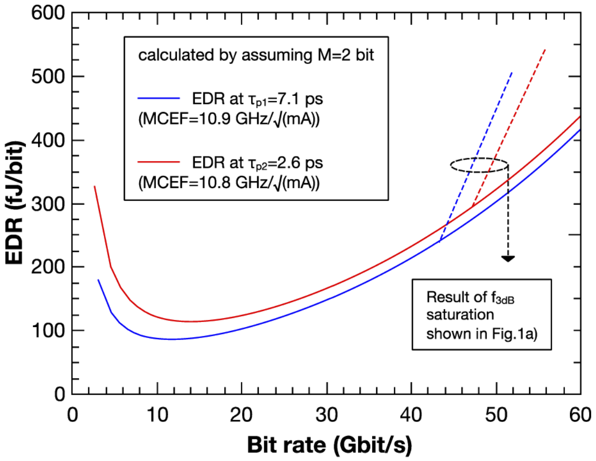

Fig. 2. Bit rate and the energy to data ratio vs bit rate based on experimental I-V characteristics (Fig. 1(b)) assuming $M = 2$ bits and $MCEF = 10.9$ GHz/$\sqrt{\text{mA}}$ for a large photon lifetime τ_{p1} (blue) leading to I_{th1}=0.45mA and $MCEF = 10.8$ GHz/$\sqrt{\text{mA}}$ for short photon lifetime τ_{p2} (red) leading I_{th2}=0.62mA. The influence of thermal effects and a decreasing $MCEF$ at larger bit rates are marked by the blue and red lines, respectively.

4. Target bit rate - dynamic measurement results

The number of lasers used for wavelength-division multiplexing (WDM) presents not only a tool to increase the maximum bandwidth of a given link. Choosing the optimum number presents a new degree of freedom for design, optimizing the link energy consumption for a given target bit rate. A doubling of the number of devices in an optical link for fixed bit rate, not presenting the possible maximum one can additionally lead to a large reduction of end of life cost.

Figure 3 shows EDR and BR calculated from small signal measurements by assuming a spectral efficiency of $M = 2.1$ bit, for a long photon lifetime τ_{p1} (blue) and a short photon lifetime τ_{p2} (red) considering temperature and damping effects as well. The spectral efficiency is proofed experimentally by the large signal measurement results marked with (a) and (c) for both photon lifetimes. The data shown in Fig. 2 and Fig. 3 are based on the measurements shown in Fig. 1. The large signal results marked with (a), (b), and (c) in Fig. 3 [13,19] were achieved with the identical device. Only exception is datapoint (d) which was measured earlier with a different device having a similar aperture diameter [17]. The datapoint (b) does not completely match the prediction, since the quality of the signal at this bit rate is limited by our large signal equipment specified up to 52 Gb/s. All large signal measurements show a bit error ratio (BER) $< 1 \times 10^{-12}$.

As predicted in the previous chapter, Fig. 3 can be separated into two different sections. These two areas are separated by a grey dashed line. This separation illustrates that bit rate dependent optimization of the lifetime of a photon is necessary and technically easy to achieve [12]. At bit rates larger than 44 Gb/s, a short photon lifetime is advantageous, whereas at medium bit rates a long photon lifetime leads to lower energy consumption per bit. A 25% reduction of EDR is shown in Fig. 3 both for 50 Gb/s as well as 25 Gb/s, however for completely different photon lifetimes. The photon lifetime can be easily changed after final processing of the device [12]. Surprisingly, the maximum bit rate increases to 56 Gb/s for τ_{p2}. The threshold current for τ_{p2} is I_{th2}=0.62mA and is reduced to I_{th1}=0.45mA for τ_{p1}. Adaption of the photon lifetime to the target bit rate is thus of largest importance. Finally, a large potential for the decrease of the EDR is already identified for medium bit rates instead of maximum bit rates.

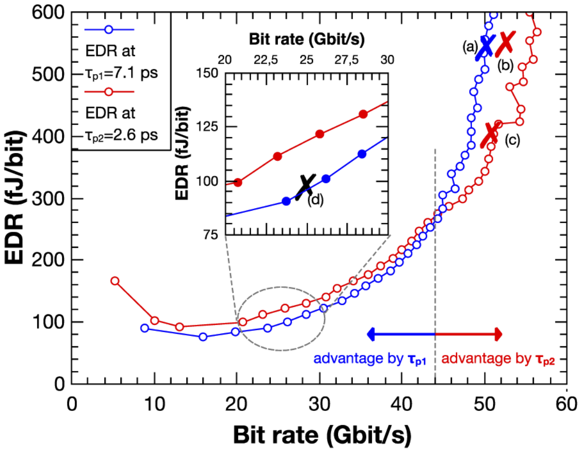

Fig. 3. *EDR* and *BR* calculated from small signal measurements by assuming a spectral efficiency of $M = 2.1$ bit, for a long photon lifetime τ_{p1} (blue) and a short photon lifetime τ_{p2} (red). The spectral efficiency was proofed experimentally by the large signal measurement results marked with (a) and (c) for both photon lifetimes. The datapoints marked with (a), (b), and (c) as well as the calculated curves are achieved with the identical device. Datapoint (d) was measured with a similar aperture device.

In addition to the choice of the target bit rate and the resulting optimum photon lifetime, the cavity dip to gain peak detuning needs to be adapted to the target bit rate. We define temperature stability as temperature independence of the small signal response [11] for a given temperature range. The bandwidth at a given bias current should be preferentially constant between room temperature (RT) and a maximum temperature. Temperature independence can be achieved by a detuning of ~15 nm. Then the D-factor and the bandwidth at medium bit rates like 25 Gb/s are identical at RT and 85°C. In general, the D-factor and MCEF increase at large temperatures for larger detuning. Thus, for larger bit rates like 50 Gb/s the detuning must be larger, about 25 nm, to obtain identical temperature stability. Temperature independence for 50 Gb/s data transmission with absolutely unchanged bias current and modulation voltage from 25°C to 85°C [13] was described by us previously and can be extended easily to 120°C, necessary for applications in future vehicle networks (IEEE 802.3 Multi Gigabit Automotive Optical PHY Study Group). The amount of detuning has, however, to be chosen dependent on the bit rate.

5. Summary

The introduction of multiplexing opens a way to develop new end of life cost reduction strategies, based on photon lifetime tuning. We recently demonstrated WDM for 200+ Gb/s data transmission across a multimode fiber using four lasers at different wavelengths each working at bit rates of 50+ Gb/s based on a simple NRZ modulation scheme [10]. 200 Gb/s transmission also can be achieved by using eight lasers with 25 Gb/s each. Figure 3 shows that the power consumption at 50 Gb/s was reduced to ~400 fJ/bit by photon lifetime tuning. At 25 Gb/s *EDR* is even lower than 100 fJ/bit, presenting a 75% reduction as compared to the 50 Gb/s values. For the same *BR* of 200 Gb/s 50% energy reduction is achieved, although the number of devices has been doubled. In addition, the current density at operating conditions is reduced by 60% and risk of device failure is reduced (see Table 1). Longer device lifetime together with the reduction total energy consumption by 50% will overcompensate the cost of doubling the number of devices. Lower power consumption leads to less heat, and temperature induced roll-over of the output power occurs at larger currents. Finally, less energy for cooling needs to be provided. Thus, the end of life cost is increased dramatically by choosing two lasers at a medium bit rate instead of one laser operating at maximum technically possible bit rate.

Table 1. Energy to data ratio and bias current density at 200 Gb/s achieved by multiplexing of 4 and 8 lasers.

Figure of merit	200 Gb/s by 4 × 50 Gb/s	200 Gb/s by 8 × 25 Gb/s	Savings
EDR	~400 fJ/bit	~100 fJ/bit	-75%
Current density	>25 kA/cm2	~10 kA/cm2	-60%

The experimental determination of M includes the noise of the whole link [15], which is dominated by the VCSEL's noise. An increase of photon lifetime leads to an increase of the κ-factor which reduces the noise due to larger damping [20,21]. The suggested VCSEL operation at medium bit rates in concert with an increase of cavity photon lifetime will lead to an increase of M and a further reduction of *EDR*. Lower noise moreover, might suggest using higher modulation formats.

A decrease of bandwidth due to a reduced bias current (see Eq. (4) and Fig. 1(a)) will lead to reduction of the end of life cost for the laser. Of course, the end of life cost of the system is influenced by the cost for the laser driver circuit too and will vary depending on its complexity. Furthermore, drivers are showing a similar potential of reduction of energy consumption per bit, depending on the reduction of the bit rate [22] so that the reduction of the bit rate for a given driver will lead to large reduction of power consumption. VCSELs with lower power consumption at medium bit rates will enable down sized and simpler low-cost driver units based on CMOS technology with a lower per bit energy consumption. We expect here additional research and circuit developments in the future.

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Disclosures

The authors declare no conflicts of interest.

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