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Energy Efficiency of VCSELs in the Context of Short-Range Optical Links.

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***Abstract*—We present results from an investigation of the energy efficiency of VCSELs under large signal modulation. We show that the most important factor influencing the energy consumption of the VCSELs is the required optical modulation amplitude, which drives other VCSEL design requirements. The required optical modulation amplitude also depends on the optical link design. Through this dependence it is possible to better understand the energy consumption of complete short-range optical links.**

***Index Terms*—optical communication, VCSEL, energy efficiency, datacom, optical modulation amplitude, energy consumption, optical link, optical interconnect.**

I. Introduction

SHORT-range (below 300 m) optical links in datacom applications are typically built using directly modulated low-cost vertical cavity surface emitting lasers (VCSELs), operating at the wavelength of 850 nm. Multimode fiber (MMF) is usually used as the transmission medium. Data transmission is done by intensity modulation and direct detection (IM/DD).

VCSELs offer several advantages in this type of link. They can be directly modulated at very high data rates, recently demonstrated as high as 57 Gbps using on-off keying (OOK) without equalization [1] and 71 Gbps using OOK with equalization [2]. VCSELs are also energy efficient, for example the energy consumption in [1] was 510 fJ/bit at 57 Gbps and 340 fJ/bit at 50 Gbps and in [2] it was reported to be 260 fJ/bit at 71 Gbps. At lower bit-rates even lower energy consumption is reported, e.g. 140 fJ/bit at 34 Gbps [3], 108 fJ/bit at 40 Gbps [4] and 56 fJ/bit at 25 Gbps [5]. Link energy consumption of 1 pJ/bit at 25 Gb/s and 2.7 pJ/bit at 35 Gb/s for links with 850 nm VCSELs are reported in [6] and 1.1 pJ/bit energy consumption at 26 Gb/s for a link using a 1060 nm VCSEL in [7].

It was shown that a reduction in oxide aperture size results in a reduction of energy consumption per bit [8], because the D-factor is inversely proportional to the oxide aperture size. The resonance frequency is linearly dependent on the D-factor and therefore a VCSELs with smaller oxide aperture will reach higher bandwidths at low bias currents.

The oxide aperture also influences the maximum output power of the VCSEL. Reduced oxide aperture diameter increases the VCSEL resistance which leads to thermal roll-over at lower current and optical output power. Therefore, reduced oxide aperture diameter results in reduced maximum optical output power.

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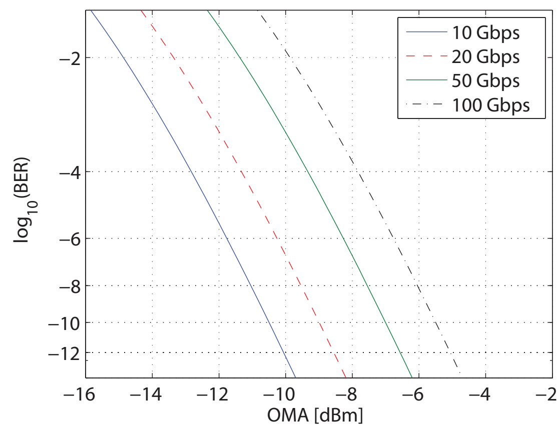


Fig. 1: BER as a function of OMA at the receiver for an IM/DD system with OOK, assuming a photodiode responsivity of 0.4 A/W

For successful data transmission, the bit error rate (BER) must be sufficiently low. The BER depends on the signal-to-noise ratio (SNR), which depends on the optical modulation amplitude (OMA) and noise in the receiver. Therefore, the BER requirement and the receiver performance give a lower limit on the OMA.

In this letter we present the results of an experimental investigation of the relations between VCSEL oxide aperture diameter, modulation bandwidth, OMA at the VCSEL output and VCSEL energy consumption.

II. OMA requirements in short-range optical links

In a typical optical link without forward error correction (FEC) the bit error rate (BER) for "error-free" transmission must be below 10^{-12}. In general, the BER is a function of the SNR. In IM/DD systems, the main noise sources are the thermal noise in the receiver, shot noise and relative intensity noise (RIN) of the laser. For simplicity it is assumed that the system is dominated by thermal noise with variance σ. RIN will cause a sensitivity penalty, which can be calculated as given in [9, Ch. 5.4.2]. For RIN below -145 dBm/Hz and received optical power below 0 dBm this penalty is negligible. In a direct detection system the electrical signal current I is proportional to the optical signal power P through the photodiode responsivity R_{PD} as $I = R_{PD}P$. For OOK the BER at the receiver is [9, Ch. 5.3.1]

$$\text{BER} = \frac{1}{4}\left[\text{erfc}\left(\frac{I_1 - I_{th}}{\sigma\sqrt{2}}\right) + \text{erfc}\left(\frac{I_{th} - I_0}{\sigma\sqrt{2}}\right)\right], \quad (1)$$

where I_0, I_1 and I_{th} are currents at, respectively, bit 0, bit 1 and the decision threshold. The optical power levels corresponding to 0 and 1 are denoted P_0, P_1 and $\text{OMA} = P_1 - P_0$. If the decision threshold is placed half way in between the levels 0 and 1 then (1) can be simplified to

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{R_{PD}\text{OMA}}{\sigma 2\sqrt{2}},\right). \quad (2)$$

The responsivity depends on wavelength and receiver. The noise variance depends on bandwidth (and therefore bit-rate), temperature, noise figure and load resistance. The OMA at the receiver has to be large enough to achieve the required BER. An example theoretical BER as a function of the OMA at the receiver for a system dominated by thermal noise, with $R_{PD} = 0.4$ A/W, RIN $= -145$ dB/Hz, 5 dB receiver noise figure and for bit-rates in the range between 10 Gbps and 100 Gbps is shown in Fig. 1. Note that this is best-case BER, assuming thermal noise dominated system. The OMA at the VCSEL output has to be larger because of coupling and fiber losses, intersymbol interference penalty, mode partition noise, RIN, and performance degradation due to ageing. The link budgets of short-range optical links are typically around 8 dB as specified in the Ethernet and Infiniband standards [10], [11]. The theoretical required transmitter OMA required to reach BER below 10^{-12}, based on results in Fig. 1 and including 8 dB link budget is shown in Table I, including assumed noise variance. There are no VCSELs capable of supporting 100 Gbps OOK tranmission at the time of writing, however, it is expected that 100 Gbps will be achievable in the future.

From the system perspective, a more power efficient VCSEL is the one that delivers a required OMA at a energy to data ratio (EDR), defined as in [8]. The EDR is calculated from the DC and RF input power and the data-rate. Another commonly used figure of merit is the heat to data ratio (HDR) which is the ratio between the dissipated power (difference between the electrical input power and optical output power) and the data-rate [8].

III. Measurements

The EDR was measured as a function of the following paramters: OMA, oxide aperture diameter and extinction ratio

TABLE I: Reqired launch OMA for selected bit-rates, assuming OOK and 8 dB link budget.

Bit-rate [Gbps]	Required OMA [dBm]	Required OMA [mW]	noise variance[µA]
10	-2	0.63	2.8
20	-0.5	0.89	3.8
50	1.5	1.4	6.3
100	3	2	8.9

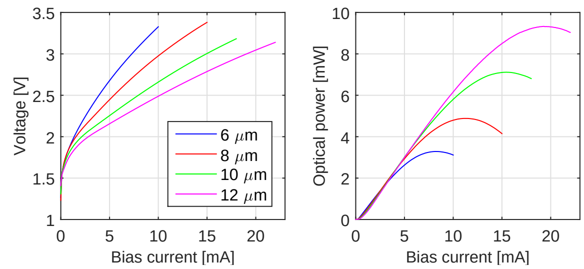
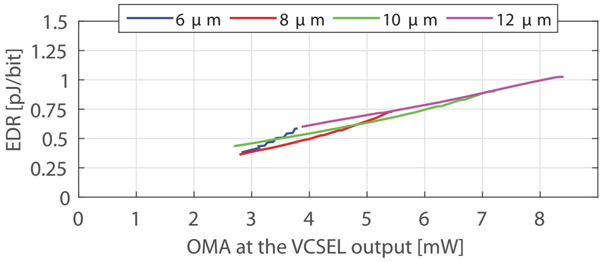


Fig. 2: Static characteristics of the VCSELs used in the measurements. The legend gives the oxide aperture diameters.

$\text{ER} = \text{P}_1/\text{P}_0$. The EDR includes both the DC and RF power fed into the VCSEL.

Four VCSELs with the following oxide aperture diameters were used: 6, 8, 10 and 12 µm. The VCSELs were of a design described in detail in [12]. The design uses strained InGaAs quantum wells in the active region for high differential gain and binary AlAs in the bottom DBR to facilitate heat transfer. Two confining oxide apertures were incorporated to reduce the device capacitance. The static characteristics of the VCSELs are shown in Fig. 2. It can be seen that devices with smaller aperture diameters reach lower maximum optical output power. Small aperture devices have also lower threshold currents, but the threshold currents are all below 1 mA and thus the differences are hardly visible in Fig. 2. For each VCSEL the input impedance, frequency response and their dependency on bias current were also measured. The frequency response was used to calculate achievable bit-rate, assuming that data rate of 1.43 times the -3 dB bandwidth is possible with negligible intersymbol interference. Equalization was ruled out to constrain the problem.

The test setup to measure the EDR and HDR comprised an arbitrary waveform generator (AWG) with 5 GHz analog bandwidth as a source of the RF signal and a DC current source. The DC bias and RF signals were combined in a bias-T and fed to the VCSEL, which was connected using a microwave probe. The optical output of the VCSEL was coupled to a 2 m MMF patchcord through a lens package. The signal was detected with a 25 GHz photodiode and analyzed on an oscilloscope. The AWG was programmed with a 1 Gbps OOK pattern because it could be supported by all VCSELs even at low bias currents and simplified automatic eye opening measurement on the oscilloscope in presence of e.g. ringing due to resonance peaks. The RF input power from to the VCSEL was calculated from the AWG output power and reflection due to impedance mismatch, similarly to [8]. For each VCSEL the bias current was swept in a range between the threshold current and 1.3 times the thermal roll-over current and the modulating signal amplitude in the range between 0.5 and 1 V, which was limited by the AWG. The OMA was automatically measured from the eye diagrams on the oscilloscope. The average optical power was measured from the photodiode current monitor and compared with the known optical output power at a given bias point for each VCSEL (as given in fig. 2) in order to calculate the link loss, which was around 3 dB, but varied within 0.5 dB with bias current



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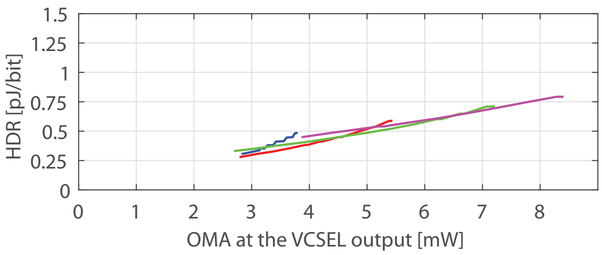

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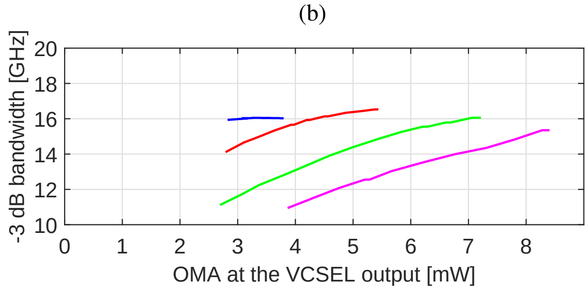


(c)

Fig. 3: EDR as a function of the OMA (a), HDR as a function of the OMA (b) and −3 dB bandwidth at a given OMA (c) at 10 dB ER for VCSELs with 6, 8, 10 and 12 µm oxide aperture diameters (given in the legend).

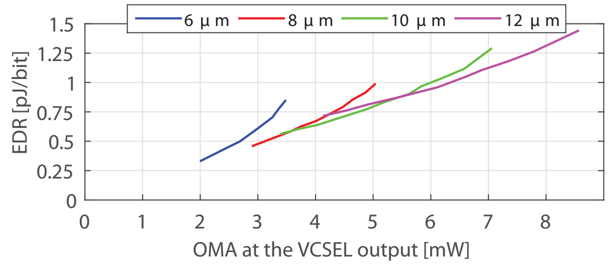
and oxide aperture. The loss was deembedded to calculate the OMA at the VCSEL output.

IV. Results

The DC power, which was in the range 5 to 50 mW, depending on the bias, contributed the majority (at least 87%) of the total input power. The −3 dB bandwidth was used to calculate the EDR, assuming data rate of 1.43 time the -3 dB bandwidth. The EDR, the HDR and the corresponding −3 dB bandwidth for the four VCSELs, plotted against the OMA, are shown in Figs. 3-5 at ER of 10 dB, 6 dB and 3 dB, respectively.

A. 10 dB ER

At the 10 dB ER the EDR and the HDR are nearly linearly dependent on the OMA, decreasing with decreasing OMA, as illustrated in Fig. 3. The ratio of HDR to the input energy per bit is in between 77% and 87%, depending on the bias point and the aperture size. The EDR and HDR at a given OMA value do not depend strongly on the oxide aperture size. The modulation bandwidth, on the other hand, depends strongly on the oxide aperture diameter is the modulation bandwidth. At



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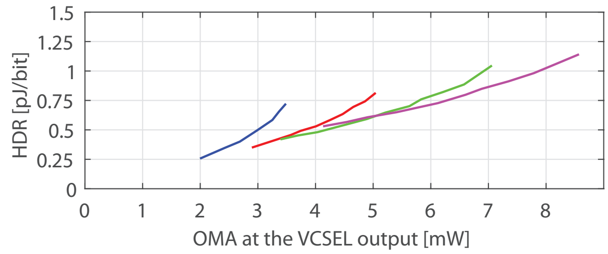

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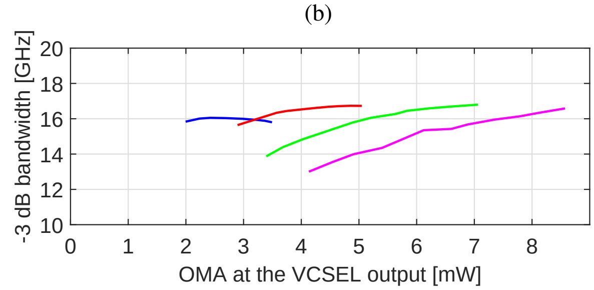


(c)

Fig. 4: Same as in Fig. 3, at 6 dB ER.

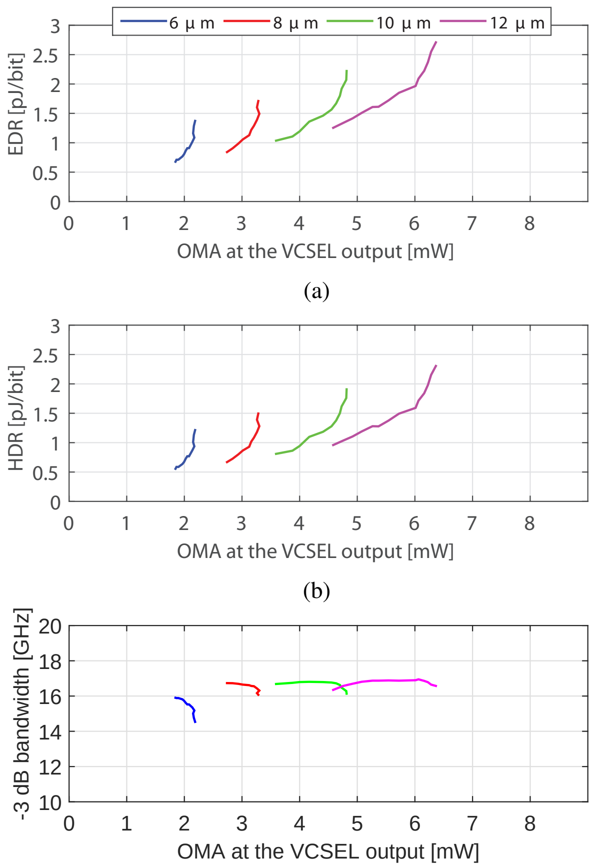
the same OMA, small aperture VCSELs achieve significantly higher bandwidths. The increased bandwidth should reduce the energy consumption per bit, but it is counteracted by increased impedance of the small aperture VCSELs.

B. 6 dB ER

Reducing the ER from 10 to 6 dB results in increased EDR and HDR, as shown in Fig. 4. The increase is between 25% and 30%. The increment is higher when the VCSELs have to be biased closer to thermal roll-over to reach the required OMA. This makes the energy consumption per bit non-linearly dependent on the OMA. If high OMA is required, then from energy efficiency point of view it is better to switch to VCSELs with larger apertures than to drive small VCSELs at high currents.

C. 3 dB ER

A further reduction in the ER to 3 dB results in further increase in energy consumption, as shown in Fig. 5. Increase in OMA results in faster than linear increase in energy consumption. At lower ERs, larger aperture diameters are necessary to reach a given OMA. Compared to the 10 dB ER, the EDR and HDR are at least doubled for given OMA. Low ERs contribute significantly to energy consumption and high ERs are needed for energy efficient operation. For each



(a)

(b)

(c)

Fig. 5: Same as in Fig. 3, at 3 dB ER.

OMA value there is an optimal aperture size which maximizes the modulation bandwidth.

D. Link and laser co-optimization

It is known that smaller VCSEL oxide apertures are better [8] for high bandwidth and good energy efficiency, but the requirement on minimum OMA constrains the minimum oxide aperture diameter. The tested lasers were able to deliver OMA in excess of the best case scenario requirements given in Table I. This means that the apertures and energy consumption could be reduced, until the lower limit of the OMA is reached.

In order to reduce the energy consumption per bit, the OMA requirement itself needs to be reduced. The ER should be kept high, but 10 dB may may problematic because of chirp and modulation close to the threshold, therefore 6 dB may be a reasonable choice.

The transmitter OMA requirement can be reduced by FEC and reduction of the link budget. The FEC can reduce the OMA requirement, but it will introduce additional energy consumption in the encoders and decoders. Reduction of the link budget means reduction of the penalty allocations. This requires careful review of the current assumptions about e.g. RIN, performance loss due to ageing and so forth.

There are also other developments in the field, such as multi-level modulation formats. The appeal of multilevel formats is that the bit-rates can be increased, but at the same time the OMA requirement will increase. This can be mitigated to some extent by the use of FEC. However, for proper system-level optimization, the entire transmitter, including the driver amplifiers has to be included in the analysis.

V. Conclusions

We have demonstrated, that the energy consumption per bit in high-speed VCSELs is depended on the required OMA. In the limit of high ER the energy per bit is linearly dependent on the OMA. The oxide aperture size affects primarily the modulation bandwidth. Reduced oxide aperture sizes allow a larger modulation bandwidth at lower OMA and bias current, but this effect is countered by accompanying increase of the VCSEL impedance. At low ER a larger bias current is necessary to reach the same OMA. Consecutively, thermal effects begin to play important role and the energy consumption per bit increases non-linearly with the OMA.

The OMA requirement is driven by the link design, which can be optimized to reduce the total energy consumption. An example of optimization problem is introduction of FEC. The FEC will reduce the energy consumption in the VCSEL and the driver, but it will add power consumption in the encoder and decoder circuits.

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