

New applications boost VCSEL quantities: recent developments at Philips

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Abstract

Besides the mature and steadily growing datacom market for which VCSELs are key components in Transceivers, Active Optical Cables (AOC), Mid Board Optical Modules (MBOM) or Embedded Optical Modules (EOM), VCSELs have proven to be key components also for other volume applications. Laser mice emerged 2004, just after the burst of the dotcom bubble and the related downturn in the Datacom industry, and dominated the shipped quantities for some years, accompanied by various smaller applications like atomic clock, oxygen sensing, encoders, and many more. Over the past years, two other major applications came into focus: optical interconnects in high performance computers or datacenters and smart sensors for mobile devices. In addition, VCSELs are penetrating into more and more power applications, primarily for illumination or IR heating. We present recent developments in technology, products, and addressed market segments that will have a major impact on the VCSEL industry

Keywords: VCSEL, optical interconnects, smart sensors, IR heating

Introduction

The total number of VCSELs sold over the last 20 years is estimated to be in the order of one billion pcs [1]. Finisar Corp. reported the 150 millionth shipped VCSEL in 2013 [2], II-VI reported the 200 millionth shipped VCSEL in 2013 [3]. Philips U-L-M Photonics has reached more than 100 million VCSELs shipped by 2014.

Until recent years, the unique technical features of VCSEL technology have supported the market entry and market penetration of VCSELs. The technology was enabling new solutions, e.g., simplified fiber coupling and assembly in transceivers, or low power low cost coherent light sources for laser mouse tracking systems, or specific wavelengths in combination with tuneability for spectroscopic applications. High quality levels, especially for Datacom applications, are mandatory. The industrial and commercial break through over the recent years has been supported by increasing productivity. Smaller footprints, larger wafer sizes, and automation significantly improved the level of industrialization of VCSEL manufacturing. Increasing on-wafer yields further support the productivity improvements and enable parallel optics even towards large scale 2D arrays. The preservation of success for VCSEL technology will require further performance improvement, but in parallel, sustainability considerations must be included

as well. Obviously, power consumption in operation is a topic of interest, but also energy consumption in production and minimized use of raw materials is of concern as the demand for VCSELs is growing from millions of pieces per year in the past, to hundreds of millions of channels per year today, towards billions of channels per year within the upcoming years.

Some of the main drivers for the drastic increase of demand for VCSELs are presented in the following sections. The aim of the discussion is not to provide a comprehensive market survey, but to explain, that the VCSEL industry has passed major milestones recently.

Key component for optical interconnects

Since the late 1990s, optical interconnects have been discussed as most promising candidates for Gigabit data links and higher data rates. Both, the amazing improvements in copper based data links over the past 15 years and the burst of the dotcom bubble in 2002 have resulted in a significant drawback for the optics industry. With 25 Gbps being the next answer to the ever growing demand in bandwidth (and this time for real as there are end customers with existing equipment asking for the bandwidth), the crossing point for optics versus copper has been reached. The main markets for VCSELs in terms of channel count will be cabling in data centers, interconnects in High Performance Computers, and Routers. For example, a need of several hundred million VCSELs operated at 25 Gbps for High Performance Computers (HPC) is expected by IBM in 2020 [4].

In order to address this significant demand, major performance requirements have to be met: Within the next years VCSELs need to 25/28 Gbps today and up to 50/56 Gbps directly modulated or with advanced signal conditioning. Feasibility to reach such very high data rates is already proven by IBM in cooperation with Chalmers University [5]. Low energy consumption of the VCSEL [6] and the entire link with a target in the fJ/bit regime is mandatory in order to keep the power consumption in large scale systems. Parallel optics (1x14, 1x12 or even larger scale and two dimensional arrangements) will be required to scale up to the required aggregate bandwidths.

Additional requirements derived from system aspects may include flip-chip capability, although today most of the transceivers are still based on wire bonded VCSEL and PD arrays. But higher bandwidths, more dense transceiver architecture, and the demand for low assembly costs will require to switch to flip-chip solutions. Dimensions of modern datacenters require fiber lengths in excess of 100m. Reduced spectral width of the VCSEL emission, e.g. by mode selection, may support extended reach over multi-mode fibers [7, 8].

In addition to the electro-optical performance of the VCSEL there are further boundary conditions to be considered. Volume capability has to be built up to provide several 100 million channels per year, corresponding to thousands of 4 inch wafers. This requests for tenfold of

today's shipments which are assumed to be about 34 million channels into Datacom applications in 2013 [1].

Philips is addressing the discussed demand by the development of 25/28 Gbps capable VCSELs [9] and PDs, which are designed for different form factors like 1x4 or 1x12 linear arrays. The 25 Gbps capable VCSELs are based on GaAs QWs. The short cavity provides good optical confinement and the highly damped resonator results in good optical eye diagram performance. The eye diagram in Fig. 1 has been recorded for a 5 μ m aperture VCSEL operated at 6 mA. As the average chip temperature in a HPC or a datacenter is assumed to be rather high, the chip backside temperature has been chosen to be 85°C.

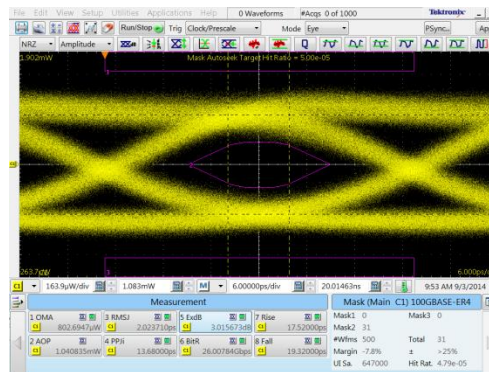


Fig. 1: 25 Gbps eye diagram for a 5 μ m VCSEL operated at 6 mA and 85°C chip backside temperature. ER is set to 3 dB.



Fig. 2: The r10004 core router by Compass EOS is unique in compactness and power consumption while offering 1.34 Tbps aggregate bandwidth (Source: Compass EOS)

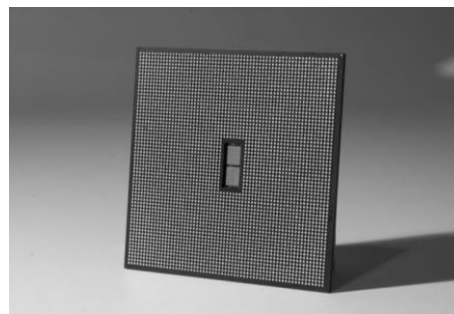


Fig. 3: VCSEL and PD arrays flip chip mounted onto the CMOS router chip and placed on a PCB with BGA. (Source: Compass EOS)

A remarkable example for the enabling performance of VCSEL technology is the r10004 core router that has been introduced by Compass EOS, see Fig. 2. The according VCSEL array consists of 168 channels, each operating at 8 Gbps, in a 2D 14x16 arrangement [10]. The VCSEL

array is directly flip-chip mounted onto the CMOS router chip. The optical subassembly is shown in Fig. 3. The specific requirements for this VCSEL solution are the backside emission through the substrate, the high channel yield to support a 168 channel 2D array, and the flip-chip capability of the VCSEL array.

KW power for industrial heating from large scale arrays

The simultaneous processing of hundreds of thousands of VCSELs on a single wafer does enable generic upscaling of total power into the Kilowatt regime by simply increasing the channel count in 2D matrix arrangements. Fig. 4 is showing a 4.8 kW VCSEL based cw IR light source [11]. Blocks of VCSELs are individually addressable which provide dedicated heat or illumination patterns at the point of use. The system is equipped with water cooling and beam shaping optics.

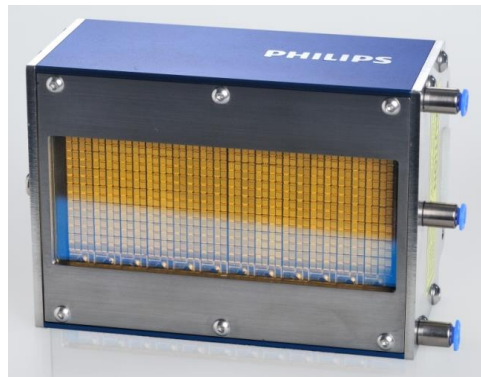


Fig. 4: 4.8 kW standard Philips heating module based on VCSELs emitting at 808 nm.

The challenges for such high power modules are somewhat different from the previously discussed VCSELs designed for datacom. Current supply and current distribution across the chip area and especially distinguished heat management solutions (which still have to match the cost expectations for industrial applications) are key parameters for superior performance. An optimized design of the individual emitter (e.g., the typical aperture size of 8 μm) in combination with the most suited pitch (typically 40 μm) results in a sweet spot for the combination of output power, brightness, and power conversion efficiency. Power conversion efficiency (PCE) is of course a key performance parameter, as both the laser current and the power that needs to be dissipated can be significantly lowered by good overall efficiency. Typical wall plug efficiency levels reach and exceed 40 % at operating conditions. An example of output power and PCE versus laser current for a single VCSEL module consisting of about 125.000 channels is depicted in Fig. 5.

Due to the multimode nature of the chosen VCSEL designs that provide highest efficiencies, the spread of emitters across rather wide area of chip surfaces, and the arrangement of multiple modules to total system power, a kW VCSEL system does not reach brightness levels that can be

achieved with edge emitters. On the other hand the directed beam of each emitter, even if thousands of emitters are superposed, is beneficial compared to IR lamps or LED based solutions. The small spectral width of VCSEL based solutions and the specific wavelength design and selection does also offer superior fit to the respective application. The target applications for VCSEL based high power laser systems listed in Fig. 6 are addressing a range of examples from illumination, plastics processing, up to sintering, providing power levels from Watts to tens of kilo Watts.

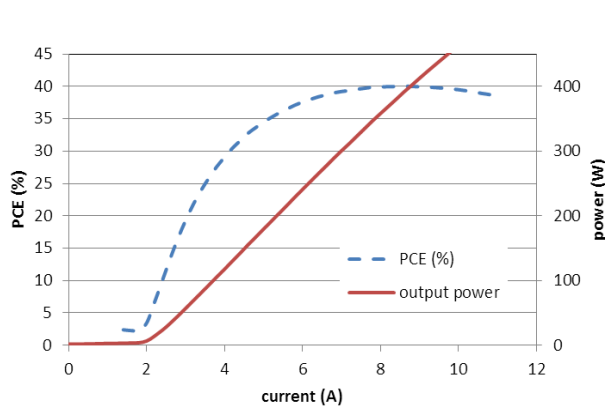


Fig. 5: Output power and respective power conversion efficiency versus drive current for a 808 nm VCSEL module consisting of about 125.000 emitters.

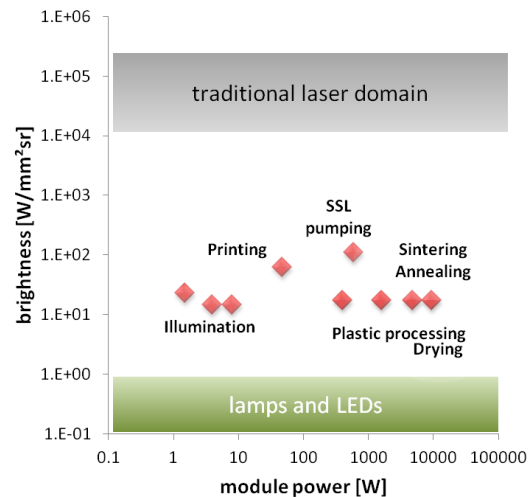


Fig. 6: Target applications of VCSEL based IR power systems. Brightness performance is positioned between lamps or LEDs and edge emitters on the low and high side, respectively.

The potential of heating and illumination applications in terms of scaling VCSEL quantities is apparent by the following calculations: A single 10 kW VCSEL based system consists of several million VCSELs driven in parallel. A total of 10 MW installed VCSEL based IR power, which would just be small number of individual systems, correspond to some billion VCSELs already. Obviously, the individual emitter wouldn't be of interest, but the chip area consumed. Limited by a cost effective heat sinking one can assume a typical optical power density of 2 W/mm². The example of 10 MW installed power would calculate to about 1000 pcs 4 inch VCSEL wafers.

Smart sensors in consumer electronic devices

Started with the introduction of tracking engines for laser mice in 2004 by AVAGO Technologies [12], the number of VCSELs used in laser mice and similar position sensing applications shipped to the world has accumulated to about 300 million pcs [1]. Recently, VCSEL based Time-of-Flight (TOF) sensors have entered the smart phone market [13]. Used for distance measurement

in fast autofocus systems first and supporting proximity sensing next may cumulate in a total demand of 100s of million pcs in the upcoming years.

Whilst laser mice are struggling with the advent of Tablets, Smartphones, and other devices offering navigation by touch screens or even voice and gesture recognition, several other smart sensors in such devices are based on advanced optical solutions.

Having a closer look at sensors and other subsystems in today's Smartphones, indicated in Fig.7, opens a huge potential for VCSELs:

1. Laser Autofocus – already in the market
2. Proximity sensor – already in the market
3. Video signal to the display
4. Video signal from one or more cameras
5. Low noise microphone
6. Gesture recognition



Fig. 7: Potential VCSEL based sensors in a Smartphone. (1) Autofocus, (2) Proximity, (3) + (4) video signal to display and from camera, (5) low noise microphone, (6) gesture recognition

In an extremely optimistic scenario, one could imagine 5 to 10 VCSELs being used in a single Smartphone. For 2014 the number of Smartphones shipped in the world has been 1.3 billion units [14].

With increasing resolution of displays and cameras in smartphones, the respective stream of data is rapidly increasing. The corresponding need for higher data rates is challenging for electrical cables in terms of on board distances, EMI, power consumption, and mechanical flexibility. Optical links using VCSELs as emitters have been designed for this specific approach in order to address these constraints [15].

With speech recognition as human machine interface becoming more and more popular, the requirements for high quality low noise microphones even in consumer electronic devices are increasing. Again VCSELs may play an important role in this application, as optical microphones have been introduced and designed to address these needs already [16, 17]. One proposal of a VCSEL based low noise microphone by the Georgia Institute of Technology is shown in Fig. 8.

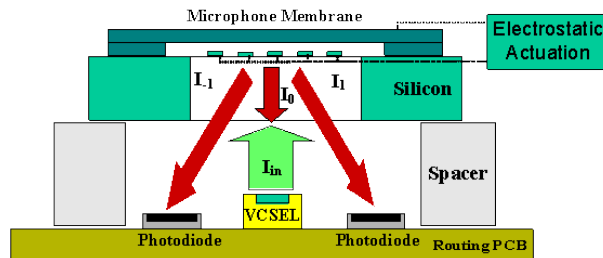


Fig. 8: Example of a VCSEL based optical microphone
(Source: Georgia Institute of Technology [17])

Example: VCSEL for TOF sensors

Light sources designed for TOF consumer applications need to address several criteria:

Provide enough power, directed to the point of use, turn on and off within very short time which directly relates to the resolution in distance, being compact in size, being scalable to very high volumes. And they should not be power hungry.

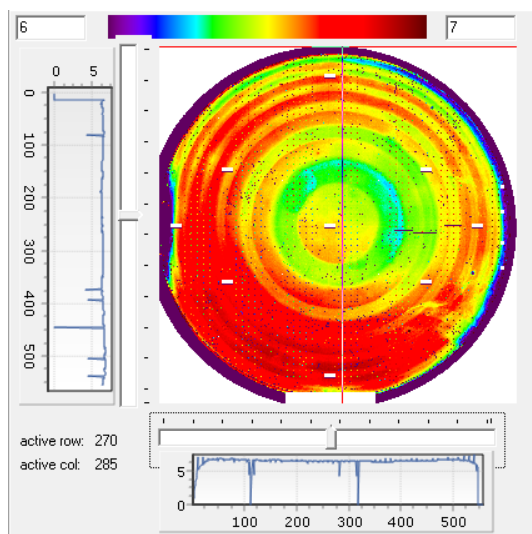


Fig. 9: Wafer map and line scans of output power at 12 mA laser current and room temperature. The circular symmetric distribution ranges between 6 and 7 mW.

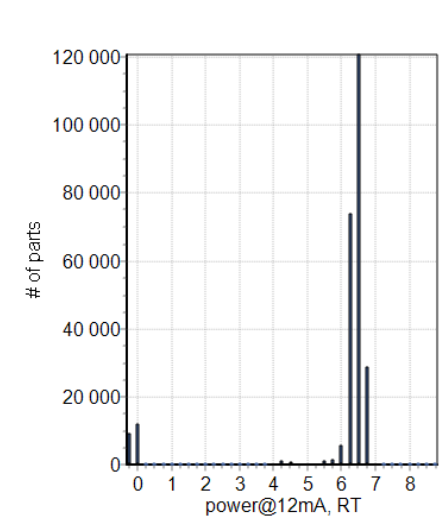


Fig. 10: Histogram of output power at 12 mA laser current and room temperature. More than 220.000 pcs are within the 6 to 7 mW power range.

Philips has designed a VCSEL product that offers performance in the sweet spot of the above listed requirements: The VCSELs are produced on 4 inch wafers. The footprint is as small as $150 \times 150 \mu\text{m}^2$. The number of potentially good dice on wafer is 250.000 pcs.

The laser cw output power of about 6.5 mW in multi-mode operation at 850 nm is achieved homogeneously across the entire area of the 4 inch wafer. The circular symmetric distribution seen in Fig. 9 is due to the epitaxial growth. The concentric rings denote a minor variation of few 100 μW and are an artefact of the laser processing. The narrow distribution of output power shown in the histogram in Fig. 10 results in more than 220.000 VCSELs emitting between 6 and 7 mW at 12 mA laser current.

The respective voltage drop at 12 mA laser current is typically 1.9 V, resulting in a typical power conversion efficiency of 30 %. Again the on wafer distribution of the operating voltage is circular symmetric and uniform across the 4 inch wafer (Fig. 11) and the histogram in Fig. 12 is showing a narrow distribution of the applied voltage, which indicates an excellent process uniformity and process control.

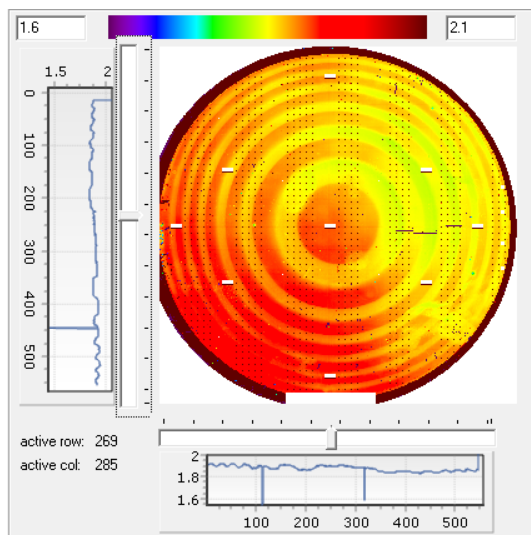


Fig. 11: Wafer map of applied voltage at 12 mA laser current and room temperature. The circular symmetric distribution ranges between 1.8 and 2.0 V.

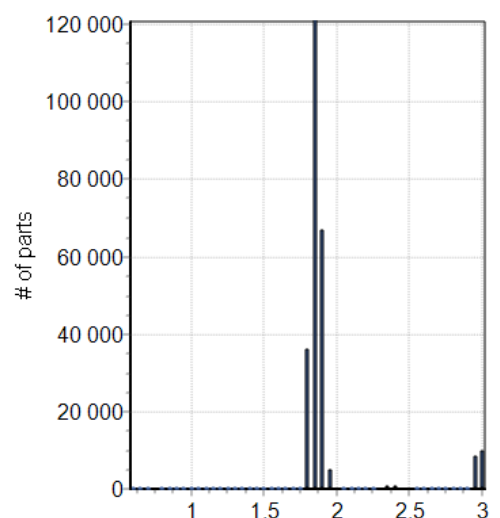


Fig. 12: Histogram of applied voltage at 12 mA laser current and room temperature.

For direct comparison of VCSELs selected from all areas on the 4 inch wafer, we have chosen 4 VCSELs positioned at the outer range of the main axis (distance between opposite VCSELs is 80 mm) and one in the center of the wafer. In Fig. 13 the respective LIVs are plotted. The threshold current variation is as small as 0.5 mA, the slope efficiency is very similar at 0.7 W/A. The resulting power variation at 12 mA laser current is as small as 0.5 mW. The biggest variation is

seen for the applied voltage which varies from 1.85 to 1.95 V, due to minor inhomogeneity of doping levels in the VCSEL structure and a minor gradient of the laser aperture size.

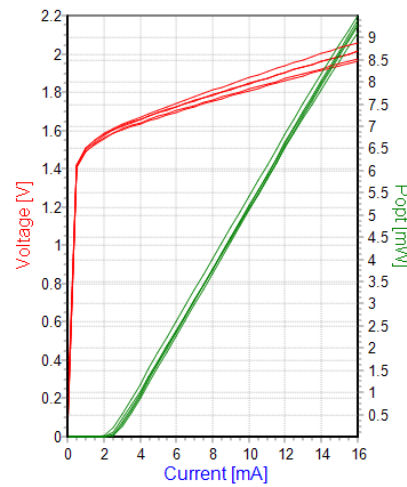


Fig. 13: 5 LIV characteristics of lasers from all different areas on a 4 inch wafer (left, center, right, top, bottom). The maximum distance between the tested lasers is 80 mm.

As expected, also the wavelength distribution is found to be circular symmetric (Fig. 14) and the wavelength ranges from 850 to 860 nm. The vast majority of parts does emit in a very narrow band of 5 nm width, see Fig. 15. The small spectral distribution does allow for a tight specification of optical filters at the detector side. Of course the wafer-to-wafer variation, which is in the same order of magnitude, needs to be considered as well.

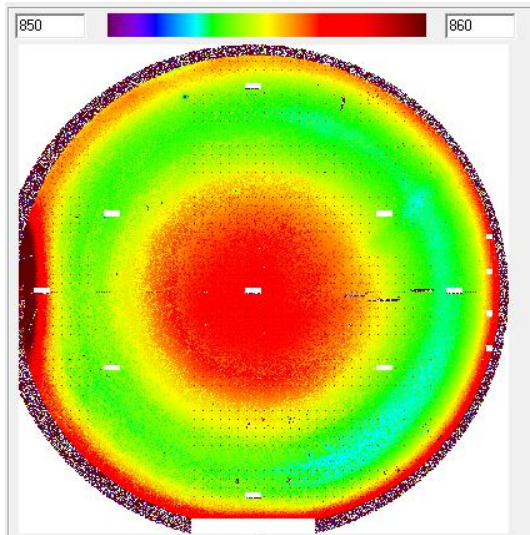


Fig. 14: Wafer map of center wavelength at 12 mA laser current and room temperature

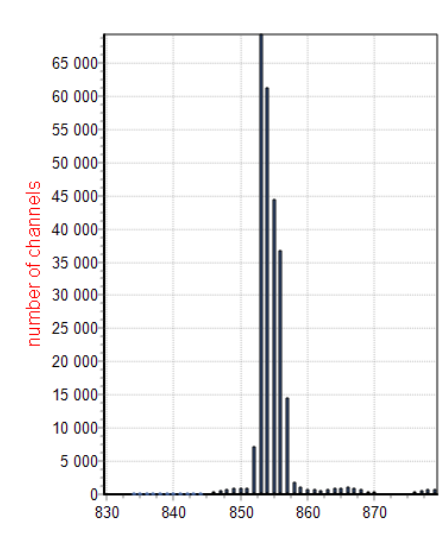


Fig. 15: 3 Histogram of center wavelength at 12 mA laser current and room temperature.

A fundamental performance parameter for TOF sensors is the switching speed of the light source, as the ranging resolution is directly proportional to the rise/fall times. The rise and fall times for the VCSELs introduced here are 50 and 70 ps, respectively.

The optical response to a 3.3 ns long electrical pulse is shown in Fig. 16, when no bias is applied before the electrical pulse. The laser is responding with short rise time, but a significant relaxation oscillation and a turn-on delay. When biasing the laser, the pulse shape shown in Fig. 17 is almost rectangular and both the relaxation oscillation and the turn-on delay can be reduced significantly.

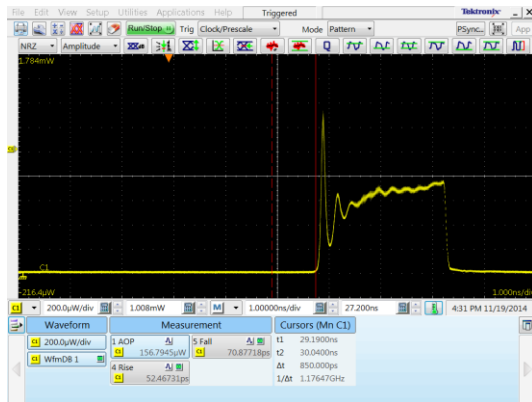


Fig. 16: 3.3 ns pulse, optical response; unbiased

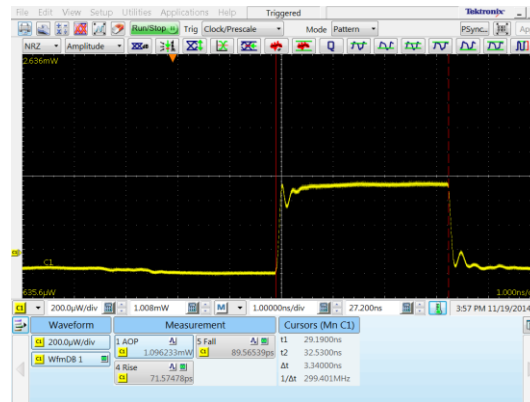


Fig. 17: 3.3 ns pulse, optical response; biased

The first VCSEL based TOF sensor has been introduced by STMicroelectronics in 2014 and is designed for proximity sensing and use in laser autofocus systems [13]. The sensor is very compact in size ($4.8 \times 2.8 \times 1.0 \text{ mm}^3$) and can be reflow soldered.



Fig. 18: Left: VCSEL based TOF sensor by ST Microelectronics (VL6180X). Dimensions $4.8 \times 2.8 \times 1.0 \text{ mm}^3$. Right: Functional concept is the emission of directed laser pulse and the detection of a reflected portion of this optical pulse. The time difference between emission and detection is computed and provided as ranging information. (Source: STMicroelectronics)

Smartphones alone represent a potential market size for VCSELs of billions of pieces. In addition the discussed smart sensors will find further applications in other consumer electronic devices, cars, or even domestic appliances. Not least, the “Internet of Things” is longing for more and more smart sensors.

Outlook

The before mentioned opportunities will take VCSEL technology to a new level. The described markets and applications request for billions of VCSELs within the next years. Obviously, such opportunities are being addressed by competing technologies as well. Among others, Silicon Photonics in Datacom, Fabry Perrot Lasers and Halogen lamps in heating applications, and LEDs used in smart consumer sensors have to be watched closely. Further improvement in performance, cost, and production capabilities for VCSELs are required to stand up against the strong competition. One answer to this challenge is a well known learning from the semiconductor industry: scale up in size, standardization, and automation.

VCSELs will play a major role in high speed data transport, smart sensors, and advanced industrial heating applications.

Side note: What about sustainability?

“Green photonics” is an important hot topic since years. The focus in discussions is mainly about the power consumption in operation. A typical measure is fJ/bit in Datacom applications.

Join me on a brief excursion: Consider 50% production cost of a VCSEL is assigned to energy, incl. all energy used for raw materials etc. The amount of energy spent for producing a single VCSEL die is estimated to approx. 0.5 kWh. Operating a VCSEL at 5 mA over 5 years amounts to 0.4 kWh totally consumed energy. Of course those numbers are not precise and directly comparable, but they are in the same ball park.

Looking at the VCSEL architecture of today, all major elements are built of semiconductor material: The mechanical base (GaAs substrate, which has to be thinned down from more than 600 μm to 150 μm or less during wafer processing), the DBRs, which amount to 90% of the entire epitaxial layer stack, and the active zone containing the QWs. Today, for the final VCSEL die, we are making use of only 20% of the substrate material (which may be even re-used completely), and 10% of the area of the epitaxially grown complex layer stack (already a best case assumption for smallest footprints), of which only 10% needs to be made of semiconductor material for the electro-optical conversion. In an extreme scenario, we may be able to reduce the consumption of semiconductor material in VCSEL production by 2 to 3 orders of magnitude!

Of course, any replacing material needs to be proven as less precious and as identically reliable. But highly pure raw materials like Ga and As are very precious and increasingly rare raw

materials, energy saving is globally getting more and more attention, the toxic waste in the fabs can be minimized, and finally we will have to monitor how REACH will classify GaAs in future. VCSELs may look different in some years from now!

Conclusion

VCSELs have evolved from an anomaly of semiconductor device to a commonly accepted laser source. VCSEL technology is stepping out of its niche and is becoming a mature semiconductor industry with the potential of billion pcs sold per year into various markets. The requirements are changing from predominantly performance driven towards improved productivity.

Acknowledgment

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