

VCSEL based sensors for distance and velocity

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ABSTRACT

VCSEL based sensors can measure distance and velocity in three dimensional space and are already produced in high quantities for professional and consumer applications. Several physical principles are used:

VCSELs are applied as infrared illumination for surveillance cameras. High power arrays combined with imaging optics provide a uniform illumination of scenes up to a distance of several hundred meters.

Time-of-flight methods use a pulsed VCSEL as light source, either with strong single pulses at low duty cycle or with pulse trains. Because of the sensitivity to background light and the strong decrease of the signal with distance several Watts of laser power are needed at a distance of up to 100m. VCSEL arrays enable power scaling and can provide very short pulses at higher power density. Applications range from extended functions in a smartphone over industrial sensors up to automotive LIDAR for driver assistance and autonomous driving.

Self-mixing interference works with coherent laser photons scattered back into the cavity. It is therefore insensitive to environmental light. The method is used to measure target velocity and distance with very high accuracy at distances up to one meter. Single-mode VCSELs with integrated photodiode and grating stabilized polarization enable very compact and cost effective products. Besides the well know application as computer input device new applications with even higher accuracy or for speed over ground measurement in automobiles and up to 250km/h are investigated.

All measurement methods exploit the known VCSEL properties like robustness, stability over temperature and the potential for packages with integrated optics and electronics. This makes VCSEL sensors ideally suited for new mass applications in consumer and automotive markets.

1. INTRODUCTION

VCSELs are an ideal radiation source for illumination. Individual VCSELs are limited in output power but scalable in arrays with tens to thousands of VCSELs on one chip enabling high power devices. Figure 1 shows a hexagonal VCSEL array with 8μm active diameter per VCSEL and a 40μm pitch between the centers of neighboring VCSEL mesas. VCSEL array emission is typically incoherent thus reducing speckle. The large number of individual emitters offers redundancy and very low failure rates. The emission is spectrally only 1-2nm wide, spectral spread in production is only a few nm and the thermal shift of the emission wavelength is only 0.07nm/K. Thus the emission of a high power VCSEL array is within less than ±10nm for all operating temperatures and variations of products which is a clear advantage compared to edge emitting lasers or even LEDs.

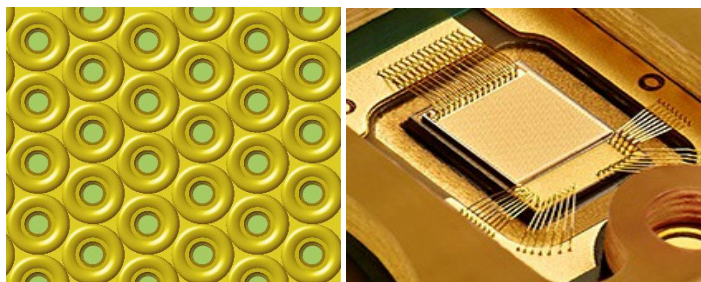


Figure 1: High power VCSEL array and assembled chip with more than 2000 individual mesas.

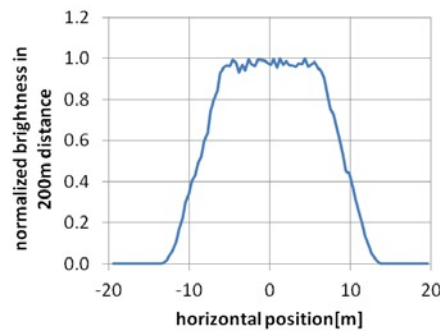
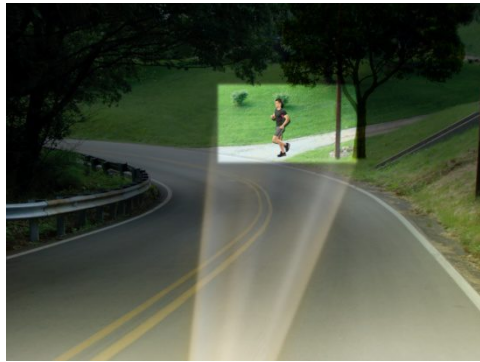
The emission of VCSELs is directed perpendicular to the wafer surface and rotationally symmetric. Due to the short resonator the divergence angle is in the order of 20° (FW1/e²) which is a good starting point to illuminate a scene however not sufficient for

scanning 3D systems. The combination with micro-optics as well as the option for longer resonators are further discussed in this paper.

Many Internet-of-Things applications need eyes which provide a measurement of the distance to objects in 3D space. A prominent as well as challenging application are autonomously moving vehicles. On the high end side there are autonomously driving cars with severe safety requirements. Industrial and household robots or toys will become feasible much earlier and offer a first entry for new sensors and algorithms. 3D recognition is needed for indoor navigation (of humans) as well as for a scanning of spaces and products. Gesture recognition as a new type of human machine interface can benefit from 3D information and many new applications are currently developed [1]. Such systems can find widespread use in smartphones and other portable devices and have to be very compact and affordable.

Light based 3D measurements are superior to e.g. radar (low angular accuracy, bulky) or ultra-sound (very low accuracy). Lasers are mature in mass production, compact and efficient as are the corresponding detector technologies for light. Therefore a system comprising a detector (photodiode or camera) and a laser as light source is an ideal solution. This holds especially true for VCSELs offering many similarities with LEDs for packaging combined with the superior performance of lasers, notably the ability for ns-Pulses, the high brightness and the narrow spectrum are advantageous in 3D applications.

VCSEL can do more than just illuminate the scene. In a laser-Doppler interferometer they can be used to accurately measure velocity and distance. Although the physics of the self-mixing interference effect is totally different from the illumination case discussed so far the application areas are overlapping and therefore all technologies are discussed here.



2. CAMERA ILLUMINATION

Active illumination with near infrared is used in camera systems for surveillance and inspection [2]. It allows pictures of objects at high speed and under difficult imaging conditions. The emission characteristics of a VCSEL array makes it a favorable radiation source because of the efficient and easy combination with simple

(zoom-) lenses avoiding the complicated optics needed for LEDs with their wide emission angle. Furthermore the brilliance of a VCSEL array is 10-100 times higher than that of the brightest LEDs enabling focused illumination at large distance up to several hundred meters. An important advantage in this application is the very uniform illumination of a field of interest with an aspect ratio which can be tailored to the needs of the camera. Figure 2 illustrates the application of a tailored illumination pattern and shows a measurement of a cross section. The light distribution is uniform and without disturbing speckle. Industrial inspection and consumer applications are a promising field for future use of such VCSEL arrays. 3D capabilities can be enabled by structured light patterns where many thousand spots of light can be projected on a scene and the position of objects in space can be derived from a standard camera image measuring the deflection of individual points. The high brilliance of VCSELs facilitates the generation of structured light patterns.



Figure 3: Photograph of an illumination product. The high power VCSEL array is emphasized by the illustrated emission cone.

Figure 3 shows a photograph of an illumination product where the 2x2mm² sized chip is soldered to a 20x20mm² MCPCB with a frame for lens mounting and electrical contacts. This product emits at least 4W of laser radiation under adverse

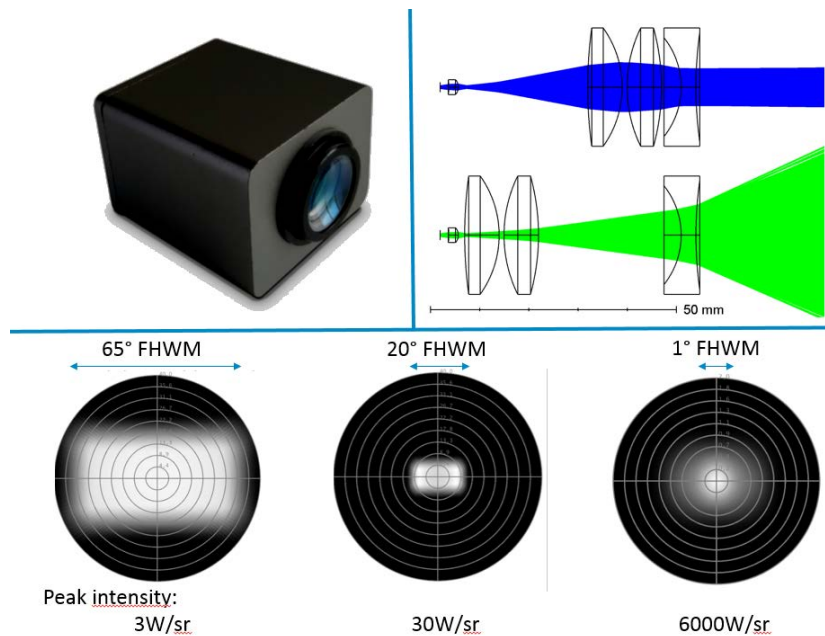


Figure 4: Photograph of the zoom-illumination module (upper left), schematic drawing of the zoom optic for the smallest and the largest zoom angle (upper right) and three exemplary illumination profiles (bottom).

conditions (60°C heat sink temperature). Other chip sizes mounted to the same platform complete a full a range of products from 1-8W.

The low numerical aperture of the VCSEL array enables the use of simple zoom systems. The principle is the same as for a regular camera zoom objective, with the focal plane of the zoom system about 1mm before or behind the laser chip. Furthermore, even simpler zoom optics can be used, which allow a slight shift of the focal plane, thus needing only one moving lens group instead of two in camera zoom objectives. Figure 4 shows a zoom-illumination module based on the VCSEL illumination product described above. The zoom optics consists of four lenses, one being an asphere and three being simple spherical lenses. Two of the four lenses move as group with a stepper motor to adapt the illumination field between 1° and 65° full angle half maximum of the intensity (FWHM). The optical system is quite compact with a

total length of about 50mm and a diameter of 25mm, which allows easy integration in most surveillance cameras. The radiant intensity can be as large as 6000W/sr, allowing bright images even in distances of up to 200m.

3. TIME OF FLIGHT BASED 3D MEASUREMENTS

3.1 Competing with the sun

Illumination in the sense of the preceding paragraph is only needed in the dark and becomes superfluous if there is sufficient light from other sources. A well-known method of distance measurement relies on the time a photon is traveling from the laser to the scene and back to a detector, the so called time of flight (ToF) method. Here one has to ensure that the detected photon has been emitted by the laser and is not from any other source occasionally detected. Photons emitted from the VCSEL illumination have to compete with the photons emitted continuously by the sun or artificial light sources. In practice this is the major limitation for distance measurement based on the ToF principle. This limitation calls for measures to suppress sunlight. VCSELs allow limiting the spectral bandwidth of the detector using a narrow filter because of the small spectrum (compared to LEDs) and the low shift with temperature (compared to edge emitters and LEDs). Spectral filtering can be applied for all technologies of ToF distance measurement and is especially effective with VCSELs.

The sun is emitting continuously while the VCSEL is operated in short pulses. Further background suppression can be achieved by gating the detector to times during pulse emission plus the maximum time the light needs to travel the largest distances of interest (meaning that gating is less efficient for large distance ranges). Additional lock-in techniques help suppressing the background further for technologies working with phase shifted pulse trains. The dynamics of the detector puts an upper limit as a pixel already saturated by sunlight will not measure additional photons. We assume in a model calculation further below a factor 100 suppression of the sunlight. Improved detectors and algorithms however can leverage higher factors which are needed for distances of a few 10m at moderate laser power of a few W.

The ultimate technology in 3D imaging are scanning systems, which illuminate only a single pixel at a time and can therefore use a much higher power level per pixel. Typically 100-1000 times less average power are needed and still more photons from the laser can be received than from the sun. For outdoor distances larger than a few meters scanning systems

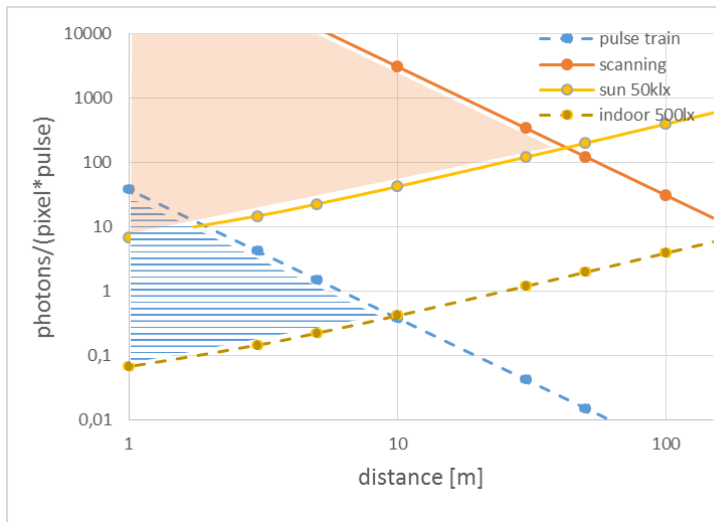


Figure 5: Simulation of photons received from laser or sun on one pixel per pulse (per 100 pulses for pulse train) with different detection principles as described in the text.

The dashed curve for the pulse train method in Figure 5 shows the number of photons detected in 100 pulses already taking into account a significant benefit from the lock-in technology and is based on 1W pulse power i.e. the laser photons out of 100 pulses compete with the sun photons within 1 pulse to represent the situation incl. lock-in. Photon count rates can be below one and already indicate that further statistical averaging is needed. The solid curve for the scanning method is based on single pulses but with 100W pulse power as this seems to be needed in outdoor applications. The shaded areas indicate typical use cases, at the top for a scanning outdoor application and at the bottom for indoor with a camera approach. It should be noted that for the scanning solution the range can be extended further using higher angular resolution i.e. a more collimated laser beam.

Two practical examples should be mentioned:

1. ToF camera, indoor 500lx, 60x45° camera field of view with 120x90 pixels (0.5° resolution) about 1 W at 25% duty cycle for a distance of less than 10m.
2. Scanning system, outdoor 50000lx, distance 100m, angular resolution 0.15°, field of view 60x15°, 0.5% duty, about 100W pulse power i.e. an average optical power of 0.5W.

3.2 VCSEL solutions for time of flight sensors and cameras

As discussed above significant power in many short pulses are needed in time of flight applications and can be realized by a VCSEL array in an elegant way. An electronic driver can provide pulse trains with individually controlled pulses in the 1-100ns range. It is advantageous to combine driver and VCSEL array in one package in order to have well defined and short electrical connections. A product has been developed in cooperation with the company iC-Haus³ and is shown in Figure 6. A VCSEL array

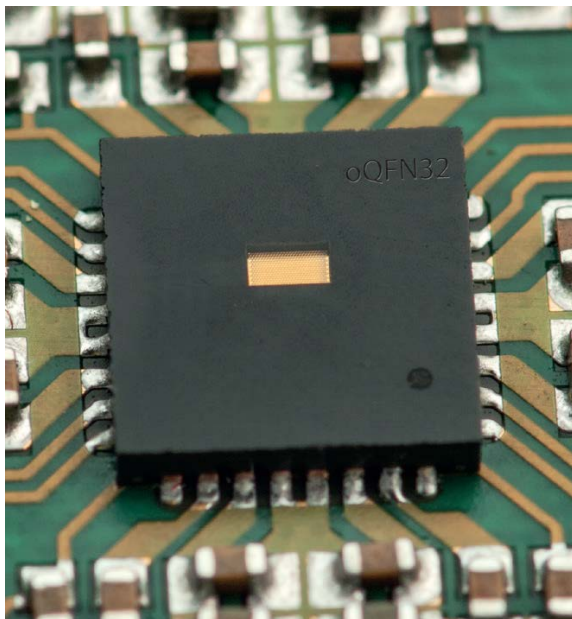


Figure 6: Photograph of the oQFN package containing a driver IC and a 1mm² VCSEL array on top (iC-Haus³).

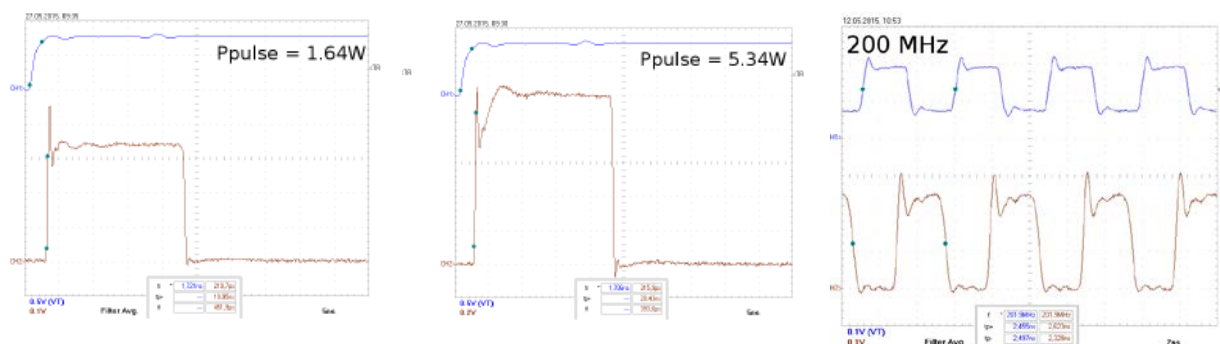


Figure 7: Measurement of the optical output from the device of Figure 6 using a 980nm VCSEL array. Current of 2A (left) and 6A (middle) with a puls duration of 20ns at 2% duty cycle. The right plot shows a measurement of the current (top) and the optical power (bottom) for a modulation frequency of 200 MHz at 50% duty. Phase between both measurements not calibrated.

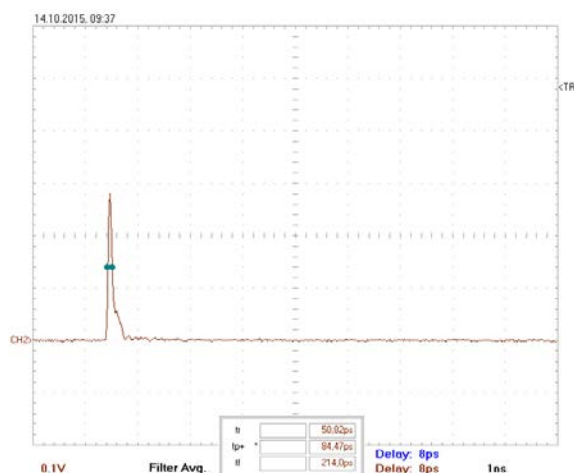


Figure 8: Measurement of optical power for very short pulse operation. The scale is 1ns/div. and the pulse length is about 85ps. A 25 mesa VCSEL array at 850nm has been used.

VCSEL, the rest by impedance. On the right hand of Figure 7 a 50% duty cycle operation at 200MHz is shown i.e. pulse duration about 2.5ns. The used pulse train is periodic while in practical applications a shift in phase and pulse length might be applied.

Figure 8 shows a measurement with a smaller array (25 mesas, chip size 0.25x0.25mm², emission at 850nm) and using a different driver IC. The maximum pulse power here is only 100mW and limited by the current supplied by the driver. Obviously the power from the VCSEL array at short pulses / low duty can be significantly higher than applied here. Mostly the short gain switching peak is used and the pulse duration is only 85ps. To our knowledge this is the first time that such short pulses have been achieved with a VCSEL array. Using such short pulses enable a single shot measurement technique [4] with cm-range accuracy. The used VCSEL can be further optimized towards maximum energy in the gain switching peak (see also references given in [4]).

3.3 VCSEL solutions for 3D scanning

In the competition with the sun a scanning solution needs several orders of magnitude less power than the illumination of a complete scene. The competition is obviously easier to win if the laser power is focused on one pixel at a time. The size of the beam is then determined by the desired resolution of the scanning system which can be e.g. 1° or even 0.1° in order

of about 1mm² with 451 individual VCSEL mesas with 8μm active diameter and a pitch of 40μm is bonded on top of a dedicated driver IC using a silver sintering process and sealed into an oQFN package. Such VCSEL chip delivers about 2W cw output and even higher power in pulsed operation.

For phased pulse trains a huge number of pulses is needed to illuminate the field of view, suppress the background and increase the accuracy by statistics. A duty cycle of 10-30% is commonly used and the VCSEL array is designed similarly to a cw source limited by the average heat removal. The required power level can be matched by the size of the VCSEL arrays.

Figure 7 (left and middle) shows a measurement of the optical output from the device shown in Figure 6 at two different current levels with 20ns pulses at 2% duty. Due to the low duty cycle of 2%, output is increasing with higher currents and thermal roll-over is not limiting the output power. The exact pulse shape is determined by the details of the impedance matching of laser, connections and driver, the driver itself and by laser properties. For the two different currents shown in Figure 7 the short peak at the beginning, the so called gain switching peak is determined by the

to detect small objects at large distances. Therefore for scanning solutions VCSELs requires special measures in order to collimate the beam.

This collimation can be done first with a micro-lens array with the same pitch as the VCSEL array i.e. one micro-lens per VCSEL. The divergence angle can be reduced by the factor $pitch/(active\ diameter)-1$ as has been described before [5]. For densely packed arrays the method is obviously limited but as a first stage of collimation nevertheless useful. The micro-lens arrays increases the typically low active area fill factor of the VCSEL array up to higher values in the lens plane. In a second step an additional lens can be used to focus all power from an array into the desired beam. Limited by the basic laws of optics (conservation of the optical extent, or Etendue) the waist of the collimated beam is larger than the size of the array by the same factor as the desired decrease in divergence.

A more capable solution for a VCSEL with low divergence angle is a VECSEL where the much longer cavity enforces single mode operation at large active diameters and high power levels. VECSELs have been described frequently in the past [6,7,8]. Divergence angles as low as 0.15° can be realized and the brightness can exceed $10\text{MW}/\text{cm}^2/\text{sr}$.

Beside these additional requirements to the VCSEL source there is the need for a compact scanner preferably combined with a large optical aperture. The challenge in the development of scanning systems is certainly high; however there are almost no alternatives for long reach outdoor systems.

3.4 Wafer-level micro-lenses

A discrete assembly of micro-lens arrays on posts and above top-emitting VCSEL array chips [9] needs 6 axis adjustment plus time to cure the glue which could sum up to minutes per array. It is therefore highly desirable to enable wafer scale micro-lens arrays i.e. making thousands at a time.

A new process based on on-wafer replication of micro-lenses in a polymer layer has been investigated to produce full VCSEL wafers with integrated micro-lenses on top and is described in [10].

Figure 9 shows a 3" VCSEL wafer with polymer micro-lenses produced on wafer level. The micro-lens facets are on top of an about $120\mu\text{m}$ high pedestal and cover the front side of the chip. Figure 10 shows that almost perfectly perpendicular side-walls in the polymer were obtained. For illustrative purposes the top left array has not been covered with micro-lenses.

We conclude that the process of on wafer integrated polymer micro-lenses is feasible and shows a good performance. The chip with on wafer micro-lenses is compatible with all further production steps and the brightness of such a chip is ten times higher than without micro-lenses.

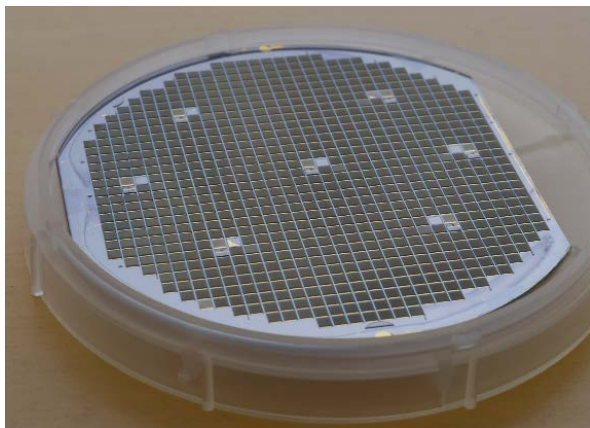


Figure 9: 3" wafer with polymer micro-lenses produced on wafer.

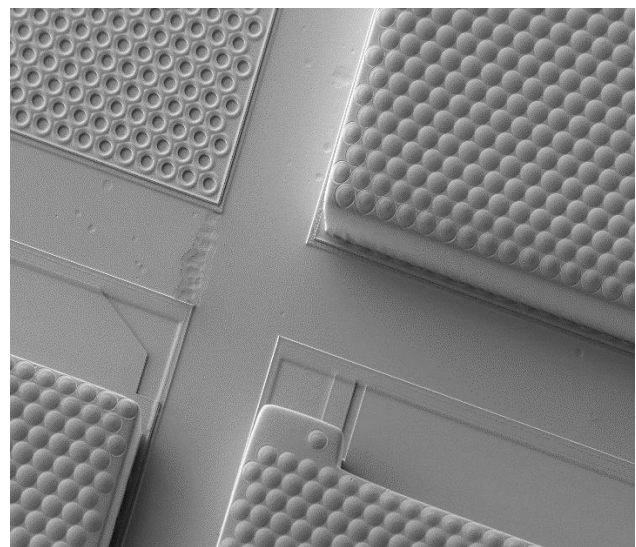


Figure 10: SEM photo of a wafer with VCSEL arrays and integrated micro-lenses. The top left array has no lenses for comparison.

4. SELF MIXING INTERFERENCE

Optical feedback interferometry or self-mixing is a well-known sensing principle for velocity and distance measurements. For a thorough treatment giving a theoretical background and an overview of this field we refer to the literature [11,12].

The main advantage from a cost-perspective point of view of self-mixing over other configurations of interferometry is that several functions are provided by the laser. The laser is not only the source of coherent light, but also an active filter due to its narrow optical bandwidth. Moreover, the active medium of the laser cavity acts as an amplifier and finally as an optical mixer. This makes the laser sensitive to extremely small fractions of feedback.

4.1 Velocity measurement

If the laser is aimed at a scattering object (see Figure 11), a small portion of the scattered light reflects back into the cavity where it mixes with the strong laser field.

When the movement of the object has a component along the direction of the laser beam, the phase of the reflected light continuously shifts with respect to the original laser light, resulting in a periodic variation of the feedback into the laser cavity at a frequency equal to the Doppler frequency. Thus the feedback from this moving object generates a changing interference signal inside the laser cavity with this Doppler frequency, and hence the laser output power is modulated with a frequency, from which the velocity of the scattering object can be derived.

Depending on the angle of observation and the speed of the object a signal is measured which shows in the frequency domain a clear spectrum (Figure 12) with the Doppler peak and some higher harmonics. Note the strong signal to noise (SNR) of more than 20dB for a measurement performed at 30cm distance to a black object with here only 0.07% reflectivity. Rather high velocity as discussed below for “speed over ground” can yield similar signals if a more orthogonal incidence on the object is used. In the speed-over-ground experiments described below velocities up to 250km/h have been accurately measured.

If the object is farther away or the reflectivity of the object is reduced the signal height is reduced, too. A measurement of SNR for 2% and 0.07% feedback as a function of distance is shown in Figure 13. At least in the lab environment where these measurements have been performed, SMI works for a distance of almost 2m. In practical applications and e.g. adverse conditions additional safety margins on SNR may be needed. In laboratory experiments partially obstructed lenses as well as e.g. dense water vapor between laser and object have been tested. SNR decreases in these situations but as long as sufficient signal is detected the velocity measurement is correct. It should be noted that SNR is measured together with the frequency of the Doppler peak and can be used as a figure of confidence.

4.2 Signed velocity and distance

In the manner described above, one can only determine the magnitude of the velocity and not yet the direction. In a semiconductor laser, a current modulation also leads to a shift in

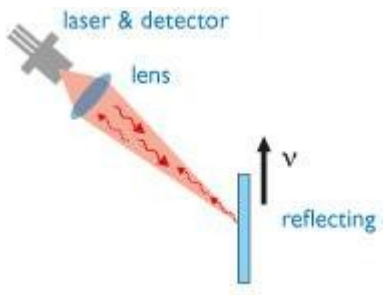


Figure 11: Coherent laser light aimed at a moving surface is scattered back partially in the

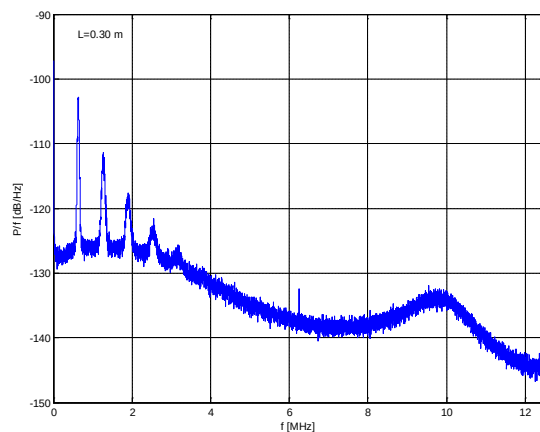


Figure 12: Frequency domain measurement of the SMI signal at constant speed on a black wheel moving at constant speed from a distance of 30cm.

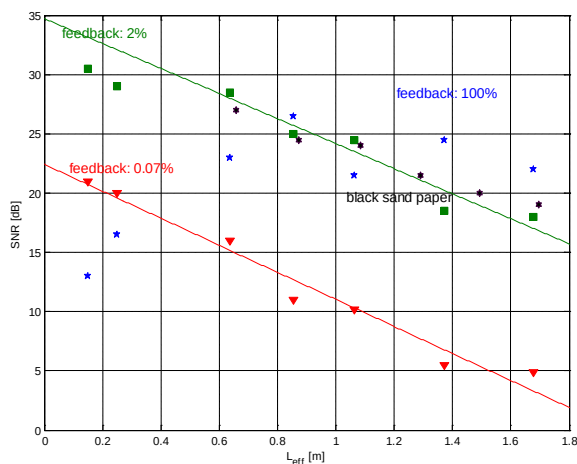


Figure 13: SNR as function of distance and feedback.

the wavelength of the emitted light. A decrease in wavelength has a similar effect as a scattering object moving away from the source, whereas an increase in wavelength mimics an object moving towards the source. If a triangular modulation of the laser current is used, the wavelength will decrease and increase periodically, mimicking periodical movements away from and towards the source. This method can measure signed velocity as well as distance simultaneously. A detailed description also for distance measurement of moving objects can be found in [13].

4.3 VCSEL with integrated Photodiode

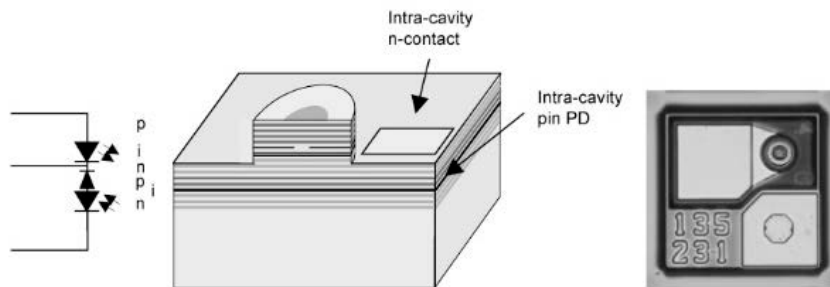


Figure 14: Schematic of a VCSEL with integrated intra-cavity photodiode and according top view picture of a processed die with a small footprint of 200x200µm²

Vertical cavity surface emitting lasers are ideal light sources for self-mixing interferometry from both an economic as well as functional point of view. Due to its extremely short cavity length of the order of the wavelength, a VCSEL operates in a single longitudinal mode, which avoids signal distortions due to mode beatings. It has low power consumption and the circular output beam allows simpler optics than for side-emitting lasers. Philips has developed an integrated device, which combines laser and photodiode

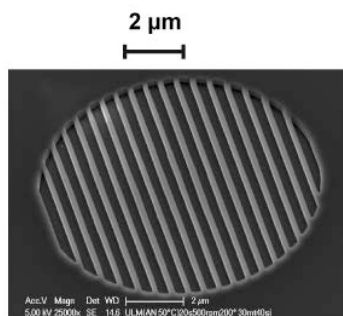


Figure 15: Photograph of the surface grating on top of the mesa.

in one monolithic device:

An advanced approach for an integrated photodiode (PD) to a VCSEL structure is placing the PD inside the cavity without additional contact or spacer layer, actually integrated into the bottom DBR which now consists of a first part of 16 n-DBR layer pairs and 2 p-doped DBR pairs followed by the 100 nm thick absorbing GaAs layer, which is placed symmetrically around an antinode of the standing wave pattern in order to get maximum responsivity and maximum contrast of stimulated versus spontaneous emission [14]. The bottom reflector is completed by additional 22 pairs of n-doped DBR layer pairs. The intra-cavity contact in the central n-doped DBR part is used as both, VCSEL cathode and monitor anode. The additional pn-junction between VCSEL cathode and PD anode is not shortened, but driven in forward direction and thus just adding an additional voltage drop to the monitor diode bias voltage. For use in self-mixing

interference sensors, it is beneficial to use single-transverse-mode VCSEL's. The resulting 3 terminal device comprises a p-i-n-p-i-n structure as shown in Figure 14. The according top-view photograph of a real device is shown on the right hand side. Electro-optical performance data have been published earlier [13]. The polarization is stabilized using an approach that makes use of a shallow etched surface grating (Figure 15)[15].

4.4 Philips "Twin-Eye Laser" product for computer input devices

A specific module is commercially available for the use in e.g. computer input devices like mice. One of the unique features of the Philips Twin-Eye integrated laser self-mixing interference sensor is its very small form factor of less than 0.2 cubic centimeters (see Figure 16). It employs two VCSEL's to measure the velocity in x- and y-direction and the height above the surface, as described above. The integrated photo diode measures the fluctuations in laser power and the photocurrent is injected into an application-specific integrated circuit (ASIC). The ASIC converts this signal into a digital signal and applies a fast Fourier transformation (FFT) to determine the undulation frequency and thus the speed relative to a scattering surface. It also allows automatic current saving mechanisms for battery powered applications and guarantees eye-safety without any manual adjustment of the laser current.

On top of the package a lens is placed that is made of material resistant to soldering processes. The lens has two inner spheres, which share the outer sphere. The VCSEL's are placed off-axis with respect to the inner spheres such that the two beams exit the lens with an angle of 90° with respect to each other and an angle of 30° with respect to the surface normal.

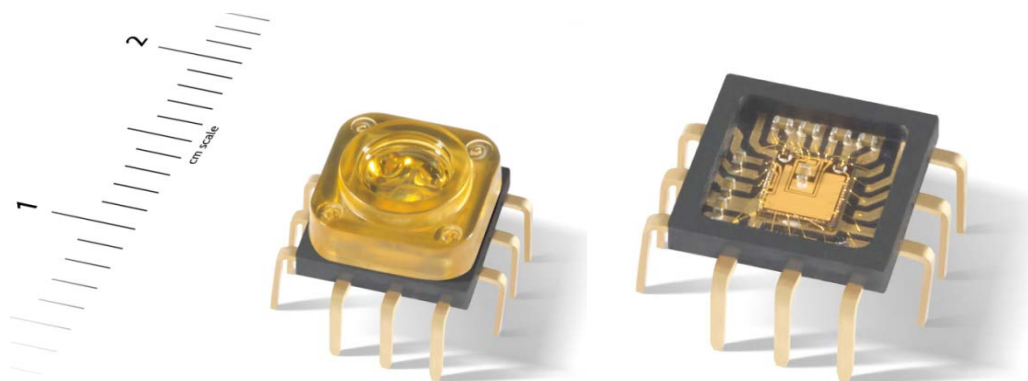


Figure 16: The Philips Twin-Eye laser sensor on scale (left) and enlarged inside of system-in-package sensor (right)

As the sensor aims at application into e.g. computer mice, the focal point is designed a few millimeters above the lens. As a result, the sensor is only sensitive to surfaces in its vicinity. This is, however, not a fundamental limit.

The ASIC includes control systems to give a predictable resolution as a function of speed, in a regime from 0.1mm/s to 4 m/s. The resolution stays very high and constant, even for relatively high velocities. Unlike pattern recognition based optical mice the SMI based laser sensor does not require an excessively increasing computing speed for higher velocities.

4.5 High precision SMI measurements

Industrial sensors measuring length and movements of objects are used in many markets and applications, e.g. cable manufacturing, extrusion, steel and paper processing and other production equipment. Typical sensors like encoders, wheel encoder assemblies, cameras and interferometers employ mechanical, magnetic and optical technologies. However, for many industrial applications they have insufficient performance on relevant surfaces or are too costly. Furthermore, most sensors are used in so-called „indirect“ systems, in which the actual object movement and/or speed is measured indirectly via encoder-based systems. Thus actual speed accuracies are limited and misalignment and mechanical wear necessitate regular calibrations by the user.

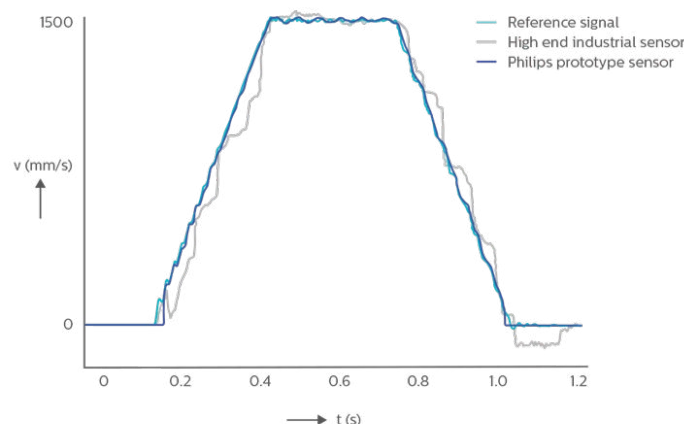


Figure 17: Measurement of aluminum cable speed: SMI-VCSEL based sensor (dark blue line) compared to reference (light blue line) and high-end industrial sensor (grey line).

First results including surfaces with reflectivity changes from black to white and varying height profile of 3mm show relative accuracies better than 0.1% at speeds of up to 20m/s and working distance of a few mm up to 0.5 m.

Other functionalities that were successfully evaluated are detection of e.g. standstill, movement direction, object edge, slip and paper jam. Specific requirements to the VCSEL for industrial sensing are high thermal load at 100% duty cycle, extended lifetime and temperature range. High speed and displacement accuracies of better than 0.1% also require tight control of VCSEL characteristic such as wavelength and wavelength change with drive current.

Philips is currently developing products for industrial sensor applications based on its Laser Doppler technology. The laser sensors measure true object speed and displacement, outperforming currently available sensors in speed and displacement accuracy. Direct contactless speed and/or length measurement can be performed on virtually all surfaces, including rough cables and sensitive surfaces such as fabrics.



Figure 18: Picture of the experimental three axes test system which has been mounted below a car.

4.6 Speed over ground sensing

Accurate speed measurement in a contactless manner is of key importance in many markets. Automotive safety-related systems, like ABS and ESP, require precise determination of vehicle speed [16]. For these systems, measurement of true car speed relative to ground instead of only wheel speed would be a major breakthrough. Philips Photonics is developing Speed-Over-Ground (SpOG) sensors that are small and cost-efficient enough for use in passenger cars. The sensor is based on Laser Doppler Self Mixing Interference as described above but employs 3 independent lasers in order to get synchronous 3-axes measurements. In practical experiments it turned out that a 2 axes measurement is less accurate as the vertical movement of a car is significant and a 3 axes measurement is needed to correct for those. An accuracy of better than 1% for the velocity and better than 0.5° for the slip angle has been demonstrated. SpOG has been positively evaluated in practical tests to work on all road surfaces and under all automotive conditions (e.g. rain, fog, snow). Experimental drives on snow and in bright sunlight have been mastered without any problem as the SMI effect is only sensitive to coherent laser light.

A laboratory style test system is shown in Figure 18 which has been mounted underneath a car and is robust enough to withstand rain and snow conditions. At the current stage of development, data processing is performed by an FPGA system inside the car. The later system development has to replace this by a specific ASIC and integrate the system further in order to match the requirements in standard

passenger cars. The system is only slightly more complex than the Twin-Eye sensor however needs cm-size lens diameter to realize a distinct SNR at a distance of up to 50cm.

Concrete benefits in the car application are braking distance reduction, slip control, side-wind correction and parking assistance. Additional benefits as e.g. tire monitoring can be realized if this measurement is combined with traditional wheel sensors.

5. CONCLUSIONS

VCSELs find new applications in illumination and sensing of objects and velocities in 3D space. The contactless and low power measurement with high accuracy is a fundamental advantage of light based measurements. VCSELs bring the additional advantage of compactness and robustness making them a unique technology for all these sensing applications. The self-mixing effect further allows interferometric accuracy and is completely independent from environmental light.

The market for 3D sensing is showing an enormous growth because such functions are needed in every car, every smartphone and other IoT devices. Required VCSEL quantities will be 10-100 times higher than in the traditional VCSEL applications. With a need of potentially many billion VCSELs this industry may develop far beyond the current level and become more LED like.

6. ACKNOWLEDGEMENT

We would like to acknowledge the fruitful cooperation with the company iC-Haus [3] and especially with R. Burkard, H. Flocke, U. Malzahn, G. Pandza and H. Reh. The measurements shown in Figure 7 and Figure 8 are their result and property.

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