TRUMPF

Whitepaper

ViP – VCSEL with integrated Photodiode

Smart VCSEL solution and key enabler for self-mixing interference technology

Contents

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Abstract

ViP stands for VCSEL with integrated Photodiode, indicating already that it features a photodiode embedded in the VCSEL resonator. This whitepaper will focus on specific VCSEL technology enabling stable polarized light emission and single-mode operation. Furthermore, it will present results on the integration of a monitoring photodiode into the resonator. VCSEL with integrated photodiode (ViPs) are part of the TRUMPF portfolio for more than 15 years and were specifically developed for high-volume, advanced sensing applications.
Especially the combination with self-mixing interference (SMI) is attractive, as the measurement principle is highly sensitive and almost free from any background noise caused by environmental light. Therefore, even sub-mW operation is sufficient for most applications. In this article applications ranging from high precision on the µm scale to high velocities up to 250 km/h will be presented. Another application that will be discussed is the detection of clean air quality as well as gaze gestures in near to eye applications enabled by the SMI technology. Excellent performance could be demonstrated in these diverse fields thus opening a great future for these devices.

Introduction ViP and SMI

ViP (VCSEL with integrated Photodiode) features a photodiode embedded in the VCSEL resonator. A single intra-cavity contact serves as VCSEL cathode as well as photodiode anode. The ultra-compact chip comes with two separately addressable mesas. In addition, good production capability and reliability make the device ideal for high-volume products.
Exploiting the principle of self-mixing interference (SMI), the ViP can be used in systems precisely measuring e.g., velocity, distance, quantitative particle concentration as a measure for air quality or fast eye-movements. The interferometric precision of velocity measurements enables demanding industrial applications like a new contactless encoder with high accuracy. ViP and the SMI principle make the detection almost insensitive for environmental background light. The functionality of the sensor has been demonstrated in bright sunlight and measuring speed over ground up to 250 km/h in automotive applications. ViP comes with low latency at low power, which makes it ideal for the detection of fast eye movements e.g. in VR/AR goggles. The miniature sensor fits into the frame of an AR/VR goggle and can detect eye-gestures. Another application example is an ultra-compact air quality detector measuring PM2.5 as well as ultra-fine particles. The system can be embedded in wearable consumer devices. With a size of a match head, it enables a precise, real-time, and personalized measurement.

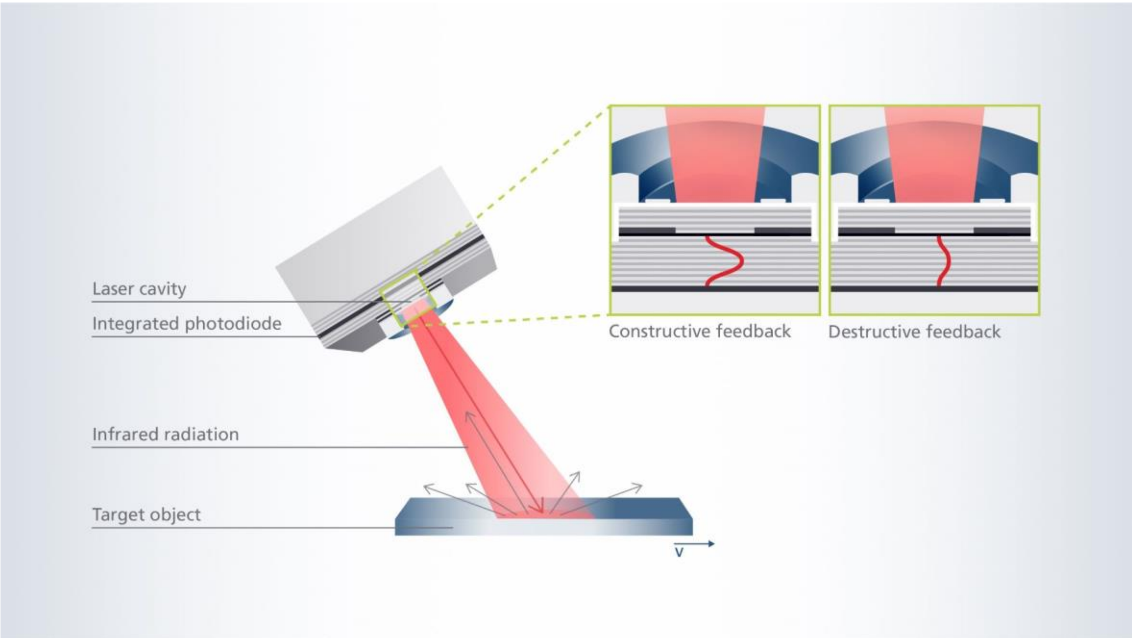

Figure 1: Graphic on the principle of SMI technology and its key enabler, the ViP

VCSEL with stable polarization

The polarization of VCSEL output depends on crystal orientation, mechanical stress in the device and on optical anisotropy. The latter can be stabilized by a grating structure etched into the outcoupling facet. A sub-wavelength pitch of the grating significantly reduces losses by diffraction and scattering which are observed with a coarse grating. Here a grating pitch of around 140 nm and an etch depth around 70 nm are used. Mass production of such structures can be done using nanoimprint Lithography. Such gratings can be manufactured on single- or multimode VCSELs, on single emitters as well as on arrays.
Figure 2 shows, an electron microscope picture of the localized facet grating on a 10 µm aperture single-mode VCSEL. Figure 3 shows a small chip with two multi-mode emitters used in parallel to scale up the optical power. Wafer-prober measurement of the polarization angle for more than ten thousand single-mode chips shows, that the polarization stabilization works for all chips and the alignment accuracy can be within 5 degree. It should be noted that the slope efficiency of these single-mode devices is about 0.9 W/A at room temperature while multi-mode VCSELs reach 1 W/A. This is close to the performance without grating and indicates the advantage of the low loss approach using a sub-wavelength grating. By this technology VCSEL output can be polarized in one dedicated direction, while all other properties are preserved.
VCSELs with stable polarization direction traditionally have applications in spectroscopy. Polarized light is advantageous to tailor optics, especially in combination with optical meta-structures. Such flat optics in combination with VCSELs is ideally suited for ultra-compact applications in smartphones or AR/VR eye-glasses.

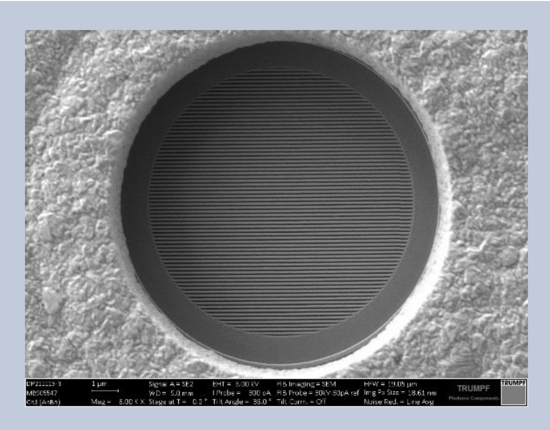

Figure 2:
SEM picture of localized facet grating

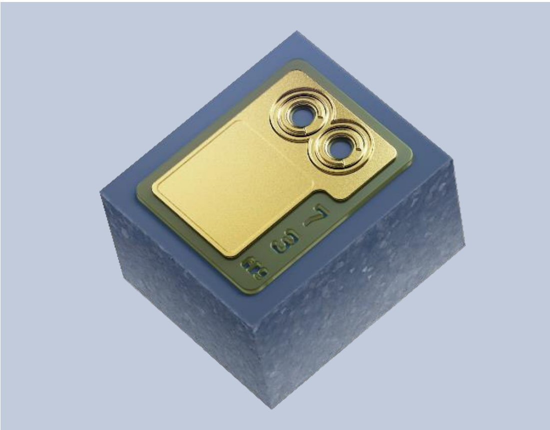

Figure 3:
Small VCSEL chip with two emitters,
both with polarization control

Technical details on ViP

TRUMPF manufactures ViP devices for over 15 years. The technology has demonstrated a good performance in consumer and industrial applications and has been significantly improved over the years. All devices described in the next sections have an emission wavelength of around 850 nm.

In a ViP device, the photodiode and intracavity contact are part of the resonator.

Figure 4 illustrates the concept of the vertical integration of a photodiode into the VCSEL resonator. The photodiode replaces one mirror pair below the active zone and is made of undoped GaAs. This is not only the most compact concept for the integration of a photodiode, but there are several specific advantages:

- The photodiode is placed around an antinode of the standing wave pattern of the laser radiation. Therefore, it is especially sensitive to the laser radiation and less sensitive to spontaneous emission or environmental light.
- The VCSEL resonator is a very narrow optical bandpass filter thus reducing environmental background light by orders of magnitude.

It should be noted that a single contact acts as the laser cathode as well as the photodiode anode.

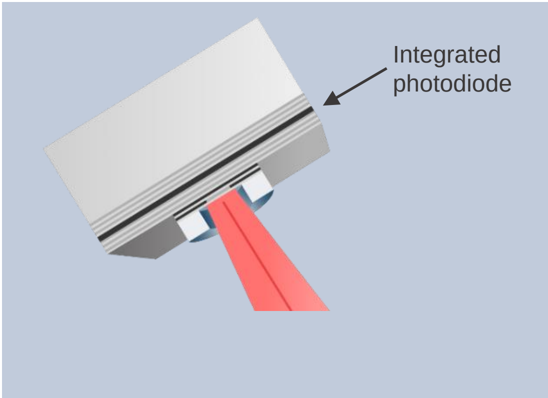

Figure 4:
Principle of ViP

Chip concept and realization

Figure 5 shows the lay-out and a SEM image of the very compact ViP chip with only 165 µm side length. The design combines two independent VCSEL mesas on top of a (larger) photodiode (surrounded by the white shape in the figure). The VCSEL anodes can be addressed individually, the cathodes share the same intracavity contact. The two mesas can be operated alternatively however share only one photodiode. The small spacing between the two optical apertures allows to focus them on the same target. This helps to establish redundancy and therefore a longer chip lifetime. As another option both mesas could be focused on different targets and an independent (alternating) measurement is enabled.

The polarization direction is stabilized as described above and indicated in figure 5 by the red arrows.

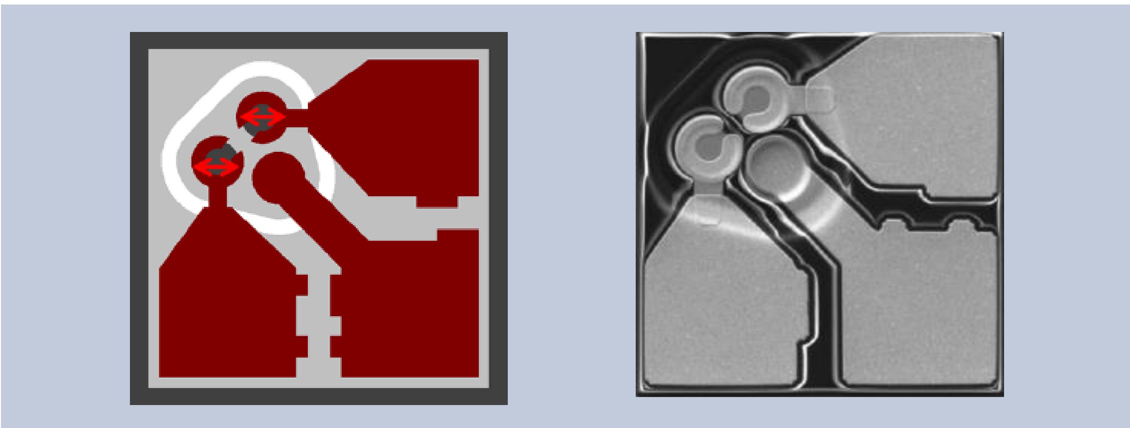

Figure 5:
ViP layout and SEM picture. The red arrows indicate the E-field direction of the transversal magnetic polarized output. Side length of the chip is 165 µm

Figure 6 shows on the left-hand the electro-optical characteristics of the ViP. The PD current is measured at a photodiode reverse voltage of -1V. The photodiode detects the laser emission as well as the spontaneous emission (sub-threshold) but with a lower sensitivity for the spontaneous than for the laser emission. This manifests in the kink in the photodiode curve at the laser threshold. It allows to detect the threshold current easily and without any external optical sensors. For the indicated current range the device stays within the boundaries of laser safety class 1.

The right-hand side of figure 6 shows spectral shift per current change (dλ/dI) and the side-mode suppression ratio (SMSR), both as a function of optical aperture diameter. The result of the measurement can be interpreted as single-mode emission up to an aperture diameter of 4 µm with multi-mode behavior coming in for larger diameters. For SMI applications, it is required, that ViP devices are single-mode and therefore below 4 µm aperture diameter.

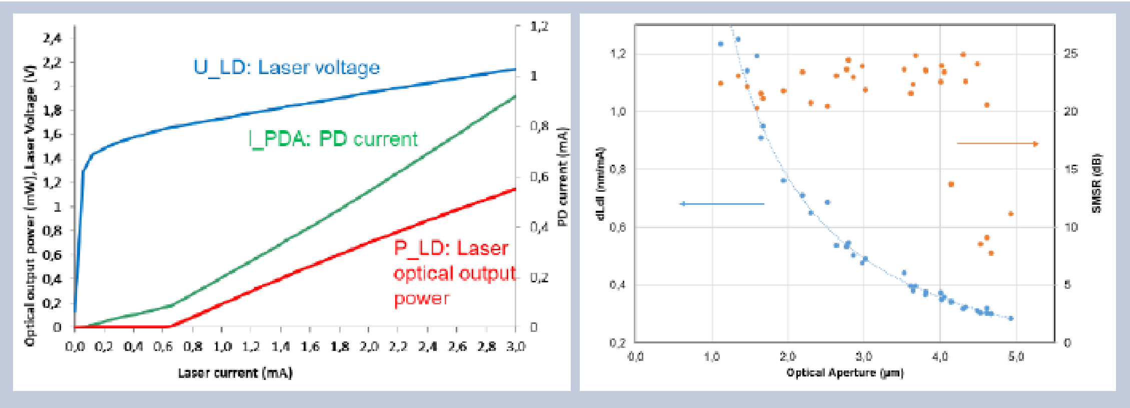

Figure 6: Left: Electro-optical characteristics of a ViP in cw-operation. Right: Spectral shift per current change and side-mode suppression ratio (SMSR) as a function of aperture diameter measured at a current of 2.4 mA

Reliability measurements

Laser output power and photodiode current results vs. stress time are shown in figure 7. Both quantities are stable within 10 % for more than 4.000 hrs. In fact, the major effect is a burn in in the first couple of hundred hours. Later, degradation is much slower and the ViP shows a stable behavior over many thousand hours. The complete ViP behaves similar to a normal (but very good) VCSEL at 850 nm. The design with a redundant mesa allows to double lifetime. Some of the applications described below require extremely low failure rates. A degradation of one mesa can be detected by the module ASIC based on the readout of the photodiode and the current can be switched to the neighboring mesa.

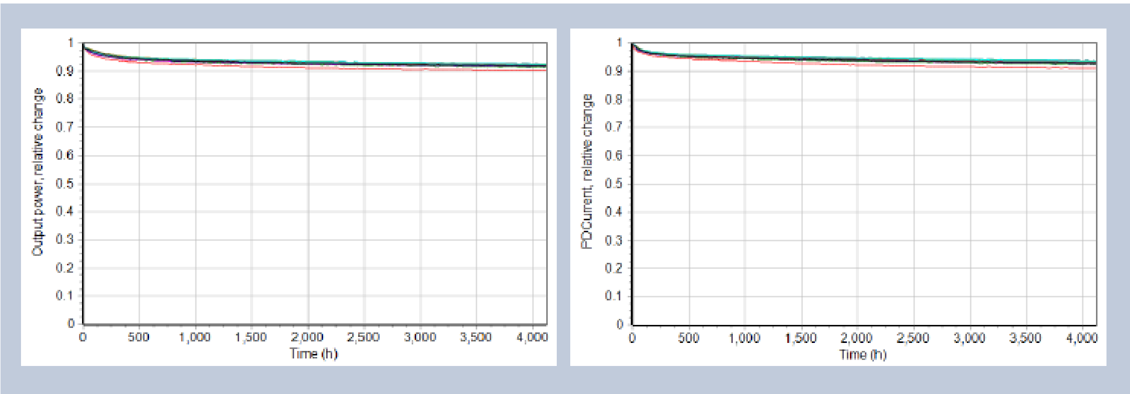

Figure 7: Reliability test at 2 mA stress current, T=65°C and a PD-bias voltage of -1.5 V. Left: Output power degradation vs. test duration. Right: Photodiode current degradation vs. test duration

Technology of self-mixing interference (SMI)

Self-mixing interference (SMI) means that scattered or reflected laser light re-enters the laser cavity and interferes with the standing wave. Depending on the phase of the feedback it can weaken or strengthen the laser amplitude which is monitored with a photodiode or via the laser voltage.
In order to maximize the feedback, the laser aperture is imaged on the target object with a lens.

Depending on the possible magnification and a numerical aperture (NA) large enough to capture the laser emission, the lens may need a decent size and distance. The method works best on a well-defined point, if lower SNR can be accepted it works over a depth range and in the vicinity of the focus point.

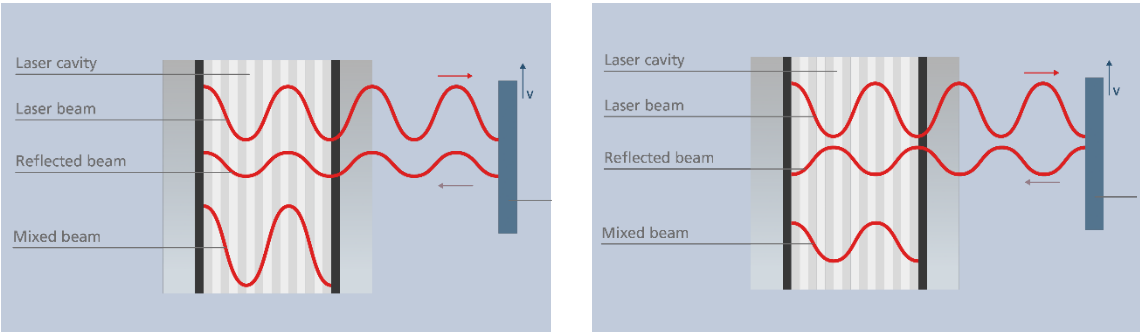

Figure 8 and 9: Left: Constructive feedback, the laser amplitude is strengthened within the laser cavity. Right: Destructive feedback, the laser amplitude is weakened

Velocity measurement

If the light gets scattered back by a moving object with velocity v, the feedback radiation has a frequency shifted by the Doppler effect. The laser amplitude will be modulated with a beat frequency, which is a measure for the target's velocity.
The left graph in figure 10 shows an ideal SMI amplitude signal. The graph on the right shows the signal Fourier-transformed into the frequency domain, which allows to identify the Doppler frequency and therefore to measure velocity accurately.

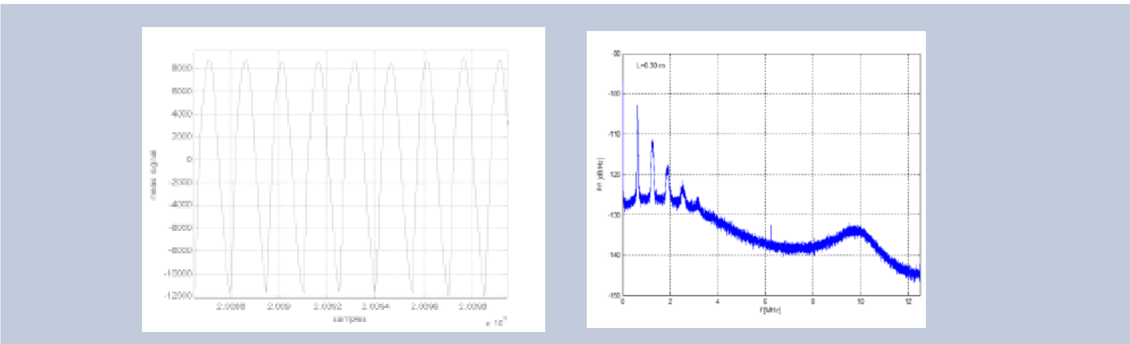

Figure 10: Left: Ideal SMI amplitude signal Right: Frequency domain of the middle signal showing Doppler peaks with >20dB SNR plus higher harmonics

Distance measurement

A simple trick helps to measure the distance between the laser and reflecting object accordingly: Modulating the laser current with a triangle-function leads to a modulated internal temperature of the laser and therefore a modulated wavelength. The wavelength shift of the feedback is the larger, the more distant an object is. The beat frequency then depends on the distance.

Unique properties of SMI technology over other sensors

SMI measurements offer outstanding accuracy at the 0.1% level over a wide range of velocities (10^{-4} …10^{2} m/s). SMI competes here at par with laboratory class instruments but is 1000 x smaller and lower in cost. Such accuracy is realized in a remote, touchless measurement and works on almost any surface. SMI technology is insensitive to environmental light, not originating from the laser sensor itself. It should be noted again that the SMI laser system design stays below the eye safe limits.

Due to coherence length of the VCSEL, the ideal working range for SMI sensing technology is up to 1 meter.
SMI is the superior technology if it can build on its strengths like robustness, accuracy, low power consumption and compactness to measure speed and user input signals. In the following section applications are described which build on SMI advantages and have demonstrated excellent results.

Applications for SMI

Figure 11 shows an overview of some SMI applications grouped by the measured signal. The combination of velocity and distance sensing enables versatile user interfaces. A highly accurate laser mouse has been produced for more than a decade. Equivalent to a mouse a finger touch and scroll interface can be designed. New types of "massless" microphones and vibrometers are possible. The following sections give four examples of applications: high accuracy, wide speed range, particle measurement and eye tracking. This illustrates the versatility of the technology and the possibility to adapt hardware and algorithms to the requirements of a specific application.

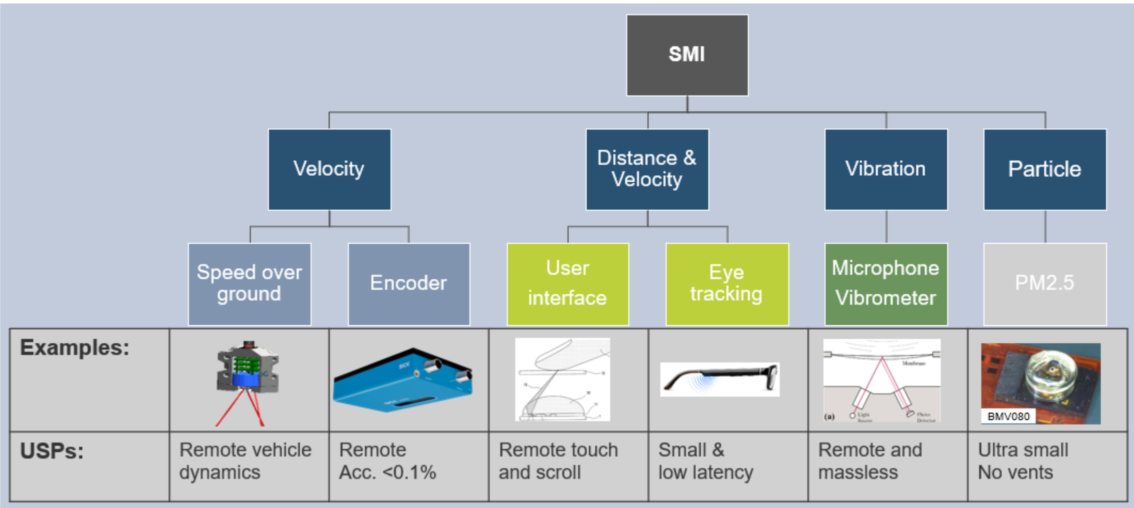

Figure 11: Application landscape for SMI systems incl. exemplary embodiments and their uniqueness

Encoders

Rotary encoders are used in the industry to measure the movement of e.g., a tool or a workpiece. However, on delicate materials a touchless measurement principle is desired. Complementary to the interpretation of the signal from a moving object via the Doppler frequency given above, the signal can as well be described as interference fringes modulating the laser power. Those fringes can be counted, and the displacement can be calculated. This works well for small and slow movements; the accuracy is very high. In typical experiments an accuracy of better than 0.1% has been realized. Figure 12 shows a commercial encoder product using the SMI approach based on two ViPs. The use of two ViPs with opposite inclination helps to compensate the error from the unknown angle towards the surface and to mitigate the influence of speckles. The product is used in industrial applications for a contactless and highly accurate measurement of speed and displacement. It works on all sorts of scattering surfaces such as tire, textile, cardboard, food and with any background light at a working distance of 50 mm.

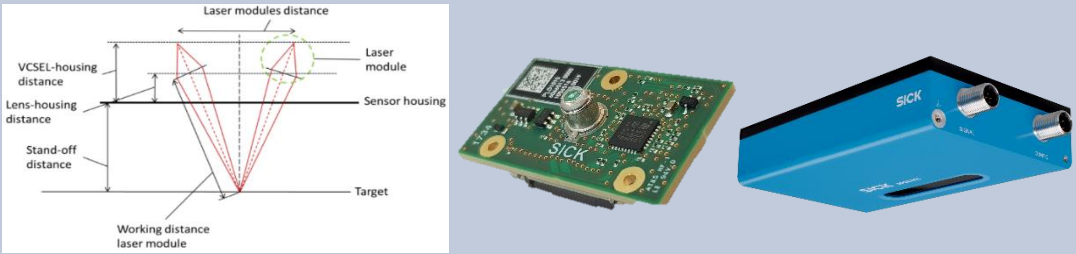

Figure 12: Left: Configuration of the two SMI sensors in an encoder
Middle: VCSEL in TO can with lens and circuitry. Module manufactured by TRUMPF
Right: Final encoder product SPEETEC from SICK

Speed over ground

Velocity measurements in automotive applications are most often based on wheel speed measurements. Those fail if the underground is slippery (snow, gravel) or if the car is sliding sideways to the wheel direction. Furthermore, brake control uses the individual wheel speeds to adjust the braking force and needs to reserve a good part of the budget for steering. A better knowledge of the real “speed over ground” helps to reduce breaking distance and improve control of the car in difficult driving conditions.

SMI allows a remote measurement of the real speed above the (road) surface. It is not affected by strong sunlight on snow and it even works with fog and spray water (having a different velocity and being easily filtered out). The car has two axes of movement and three axes of rotation but an SMI system with three independent sensors is sufficient to disentangle all information and to give a real speed over ground vector as well as slip angle if we use a few trivial boundary conditions.

In all tests SMI performed at least as well as a state-of-the-art commercial system used for R&D in the car industry. Test rides have been done on frozen lakes in winter, up to 250 km/h on highways and in racing cars. SMI was able to work under all these conditions. This activity is certainly the most extreme test of SMI ever done.

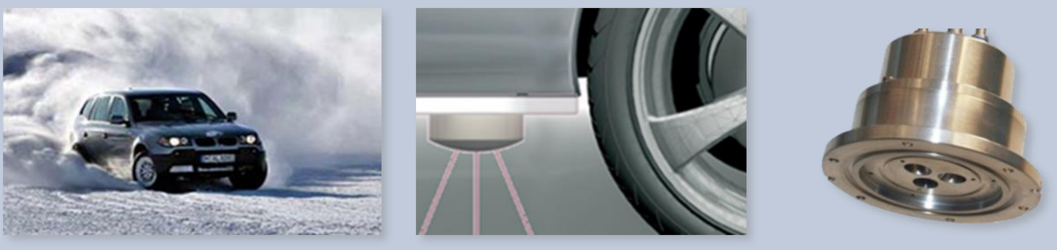

Figure 13: Potentially unsafe driving condition during a test. 3-axes SMI system underneath the car for perfect velocity and slip angle measurement

PM2.5 particle measurement

Particulate matter in the air is a serious health risk causing strokes, heart disease and lung cancer. The biggest impact is from particles which are smaller than 2.5 µm (PM2.5). While average outdoor values for cities are reported in the daily news, local or indoor values may deviate strongly over time. A personal measuring device could help to adapt your preferred running time and route or to switch on the air cleaner in your room. Up to now sensors have been too large for mobile devices. VIP and SMI enable a sensor which can be easily integrated into consumer products e.g., wearables.

Traditional particle detectors control and enforce an air flow by a built-in fan. Size, the need for venting holes and ventilation noise are not appreciated in consumer products. Bosch particle sensor BMV080, developed in close cooperation with Bosch Sensortec and TRUMPF, can measure particle speed and concentration, if they are just passing near the detection focus. Figure 14 shows this principle.

The particle sensor BMV080 contains three ViPs pointing into different directions yielding the vectorial average velocity. The sensor module can be underneath the cover glass like a smartphone display. No openings in the housing are required. The measurement focus is a few mm outside the device (see figure 15).

Figure 16 shows a photograph of the Bosch Sensortec BMV080 sensor with three ViPs, ASIC and lens integrated. A ray-tracing simulation of the single freeform lens illustrates the focusing of all three beams. The total volume is 3x3x3 mm³, certainly the world's smallest particle detector.

The module is robust against sunlight, water and scratches on the cover-glass.

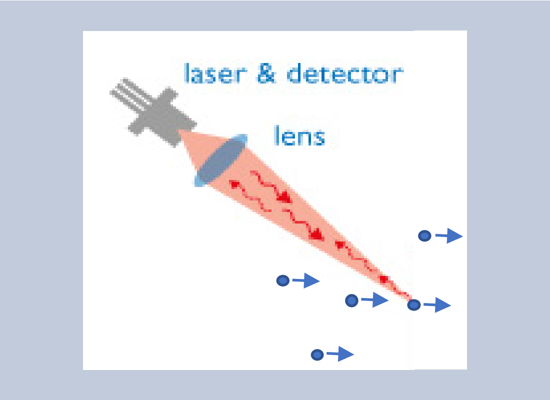

Figure 14: Principle of a SMI-signal, measuring a particle passing the laser focus

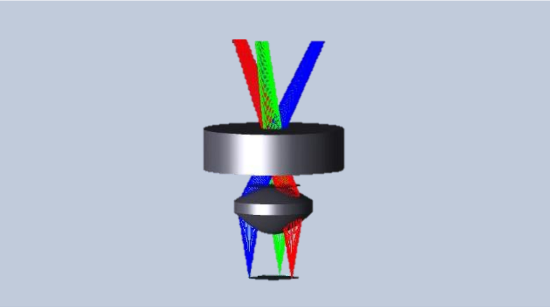

Figure 15: Ray-tracing simulation of the lens shaping three laser beams

Figure 16: Miniature PM2.5 module with three VCSELs, optics and ASIC (BMV080 from Bosch Sensortec)

Eye-tracking

Velocity eye-tracking is a well-known technique to analyze the behavior/ mood/ interest of a test person in front of a scenery or a computer screen. In augmented reality (AR) applications the information, which object the user is looking at, helps to improve 3D experience and to avoid visual discomfort. Furthermore, it can be used as user input, triggering actions by staring at an object or blinking. Recently AR goggles for consumer applications are introduced, increasing the need for lightweight, compact and affordable sensors.

Typically, eye-tracking is based on imaging techniques. Data-rate and signal processing result in a trade-off between low latency and energy consumption. Especially during fast saccades, it would be beneficially to directly measure the speed of the eye-movement. Due to the Doppler-effect, SMI technology can sense the speed-vector of the rotating eye at the point of the interaction with the laser. When using the triangle modulation technique, speed readings are updated with the modulation frequency of the triangle which is typically between 5 kHz and 50 kHz. For this reason, SMI allows naturally for very-low latency measurements (<1ms). Another advantage of the SMI sensing principle is that it can be miniaturized due to the ViP in combination with optics and ASIC, offering an integrated and very compact solution. The laser is always class 1, for eye-safety. Such a solution is ideal for near to eye applications with limited available space. Prospects, limitations and the benefit of multiple sensors are currently investigated. In close cooperation with Bosch Sensortec the laboratory set-up illustrated in figure 17 has been used to measure the eye velocity and distance for some voluntary eye gestures. A detailed data analysis concludes that SMI and the ViP based sensor are well suited for this type of eye gesture recognition

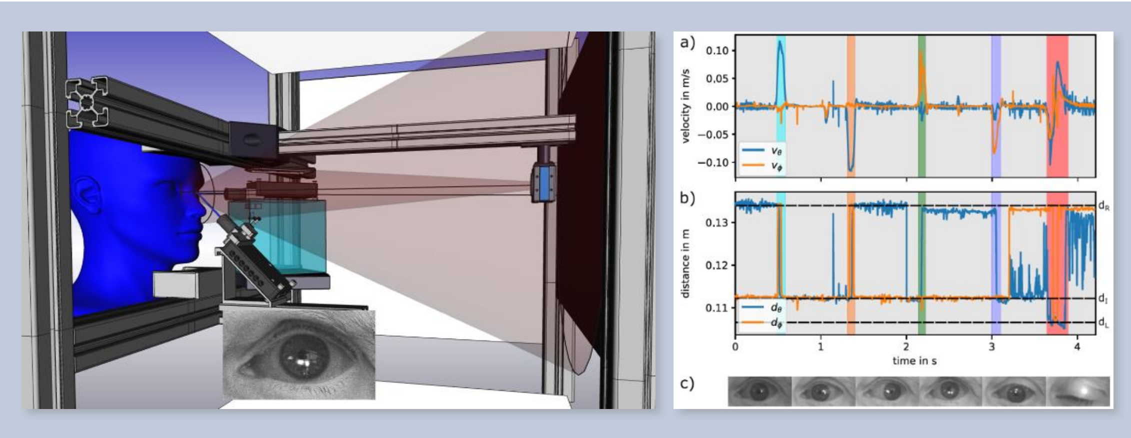

Figure 17:
Left: Laboratory set-up to measure eye movement with SMI and at the same time with a camera
Right: Measurements on voluntary eye gestures. Velocity and distance are derived from SMI data, the pictures are taken by the camera and indicate the eye gesture performed by the user

Conclusion and outlook

VCSELs with integrated polarization gratings and with integrated photodiode are adding new functionality while preserving the compactness and robustness of the VCSEL. The ViP component has been optimized for SMI based measurements, which combine interferometric accuracy with robustness. Miniature sensors have shown their benefits in diverse applications demonstrating accuracy, low and high speed, sensitivity to miniature particles and to eye-movements.
Based on the demonstrated benefits and the ability for high volume production the concepts of VIP and SMI are ideal for future consumer electronics products. More versatile user interaction and new measurables will be found in future wearables. Next steps in VIP development may comprise the on-chip integration of optics and new wavelengths.

Acknowledgement
We would like to thank our cooperation partners at Sick AG and Bosch Sensortec GmbH for many years of fruitful cooperation and for bringing SMI and ViP into exciting products.

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