APPLICATION **NOTE** \\ **Martin Finger, Frank Münchow, Armin Heinrichsdobler**

Testing Solutions for VCSELs

With High Resolution Array Spectroradiometer

The unique properties of vertical-cavity surface-emitting lasers (VCSELs) make them a workhorse for price-sensitive laser-based applications, e.g. in consumer electronics. In production, this demands mass-market-suitable, fast and highly reliable quality control of VCSELs. Instrument Systems provides test solutions for the comprehensive characterization and inspection of the temporal, electrical, spectral and spatial properties of such laser diodes in production as well as in the laboratory. For fast and reliable testing we offer a high-resolution array spectroradiometer (CAS). Together with an integrating sphere and an absolutely referenced photodiode it provides a highly precise and accurate measurement system for production. The all-new pulsed VCSEL tester PVT 110 extends the standard system configuration with fast-pulse driver electronics and a fast photodiode. This facilitates in-depth investigations of nanosecond-pulse driven VCSELs. The PVT 110 provides access to temporal electrical and optical key parameters such as pulse shape, duration and energy, as well as enabling full access to spectral information and LIV characterization with nanosecond pulses. Furthermore, the new VTC system allows for the analysis of a VCSEL array on single emitter level, e.g. to determine the radiant power and wavelength. The emission profile of the overall array from a larger distance can be determined by measuring with a light-permeable screen or a goniophotometer setup.

\\ 1. INTRODUCTION

Most of the research activities in vertical-cavity surface-emitting lasers (VCSELs), a special kind of semiconductor laser diode, started already as early as 1979. Since that time, VCSELs have become a mature technology, competing in many applications with edge-emitting laser diodes (EEL) and even replacing them in certain applications like short-range fiber optical communication. The emission of light, perpendicular to the epitaxial layers makes them very suitable for mass production as it enables optical testing and binning on the wafer level. Additionally, precise manufacturing process control made it possible to reduce the price for VCSELs below EELs. The lower price together with favorable properties like a symmetric beam profile, low power consumption and high modulation bandwidth lead to their wide spread use in applications as diverse as laser printers, optical mouses or optical data communication. In recent times, VCSELs and especially 2D VCSEL arrays appear also as an enabling technology for a wide range of emerging applications and markets in 3D sensing, such as

- Face & gesture recognition
- Autonomous driving
- Novel human-machine interfaces

Instrument Systems provides customizable solutions (hardware & software) for the characterization and quality control of the electro-optical properties of VCSELs in the lab as well as in production environments.

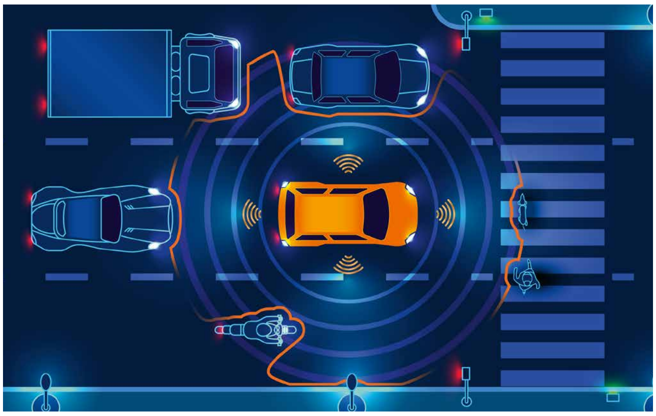

Fig. 1: Short-range LiDAR systems are investigated as a potential application for VCSELs.

\\ 2. VCSEL TESTING IN PRODUCTION LINES

Quality control of VCSELs and EELs in production lines requires the full optical characterization of a device-under-test (DUT) within milliseconds. For this, the combination of an integrating sphere (ISP) and a high-resolution array spectroradiometer (CAS) is the ideal system for fast and reliable tests of semiconductor laser diodes (Fig. 2), determining key characteristics like the centroid wavelength and the radiant power (Fig. 3). The high measurement speed requires that such spectral measurements are usually carried out with only a single, millisecond long optical pulse in the integration time window of the spectroradiometer.

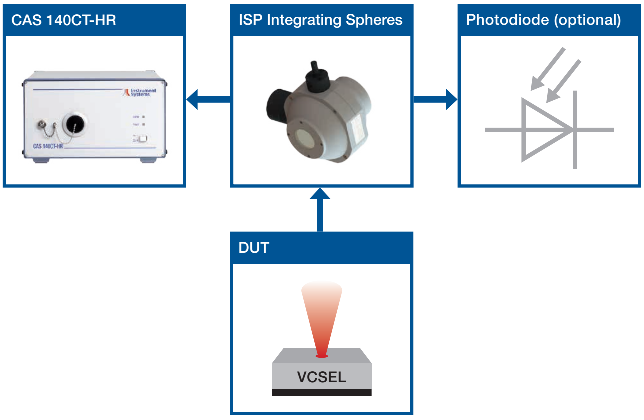

Fig. 2: High-resolution array spectroradiometers with integrating spheres allow for the fast and reliable spectral characterization of VCSELs. Optional photodiode sensors can further increase the precision of the radiant power measurement.

In such systems, the integrating sphere homogenizes the light field and the array spectroradiometer has to record the laser spectrum with the necessary accuracy and measurement speed. For light sources with a very narrow spectrum, the precision of the radiant power measurement can be further increased with an additional photodiode sensor attached to and calibrated with the ISP. It is recommended for high precision measurements to correct for deviations due to the wavelength-dependent reflectivity of the DUT and its surroundings with the self-absorption correction method. For this, it is necessary to choose an appropriate auxiliary light source with a suitable spectral power density distribution. The narrow spectral bandwidth of VCSELs – typically in the range of a nanometer – requires spectroradiometers with sub-nanometer spectral resolution. Instrument Systems offers with the CAS 140CT-HR, the CAS 120-HR and the CAS 100-HR three production grade high-resolution spectrometer platforms and additionally integrating spheres and suitable auxiliary light sources for semiconductor laser diode testing. This allows to provide customers a broad bandwidth of measurement solutions:

Key features

- High spectral resolution down to 0.12 nm
- PTB traceable measurements
- High sensitivity for high throughput (UPH)
- Short integration times down to
  9 ms with CAS 140CT-HR &
  4 ms with CAS 120-HR / CAS 100-HR
- Optional: ISP with photodiode sensor
- Optional: auxiliary light source for DUT specific self-absorption correction

Key results

- Optical spectrum
- Peak wavelength
- FWHM
- Radiant power

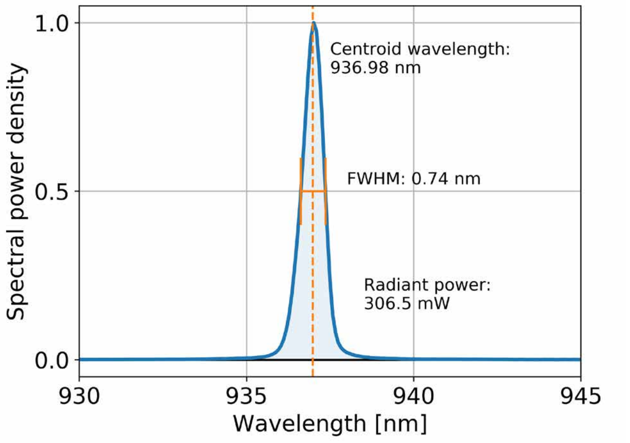

Fig. 3: Example spectrum of a 2D VCSEL array measured with a CAS 140CT-HR.

\\ 3. TIME-RESOLVED NANOSECOND PULSE TESTING IN THE LAB

More stringent requirements on measurement accuracy and the demand for an increased detection range with eye-safe laser sources for 3D sensing applications push the driving pulses for VCSELs towards shorter and shorter durations, while the required peak powers are increasing. Nowadays standard test procedures drive VCSELs with electrical pulses in the upper micro- or millisecond regime. However, novel test schemes require working with only nanosecond long pulses and many ampere peak currents. Instrument Systems covers this demand by offering with the PVT 110 an electro-optical test system for lab applications that enables working with driving pulse as short as only one nanosecond and providing up to 15 A peak currents. The PVT 110 makes the complete electro-optical characterization of VCSELs possible by following a multi-sensor approach (Fig. 4).

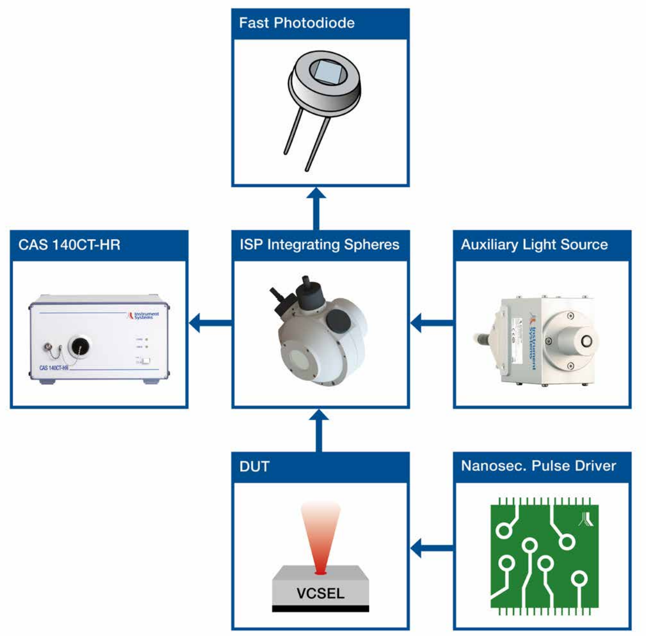

Fig. 4: PVT 110: High spectral resolution VCSEL inspection combined with time-resolved short-pulse testing.

This system integrates additional to a high-resolution CAS for the spectral characterization, a fast photodiode to measure time-resolved the optical nanosecond pulse train generated by the semiconductor laser. Simultaneously, the VCSEL driver PCB developed by Instrument Systems enables driving the VCSEL with high peak currents of up to 15 A as well as the measurement of the electrical driving pulses. This permits directly observing differences between the driving and the detected pulses. Figure 5 shows the averaged raw signal of 1000 pulses, each with a duration of 100 ns. The gray shaded area marks the standard deviation. Sophisticated algorithms are applied to these signals, for example to deal with electrical backreflections that cause oscillations when the driving pulse is switched off. In order to determine accurately the peak power of the optical pulse, it is necessary to measure the spatially averaged temporal pulse shape. For this reason, the characteristic gain-switching spike cannot be seen in Fig. 5, since it appears only for a very short time in the center of the beam profile.

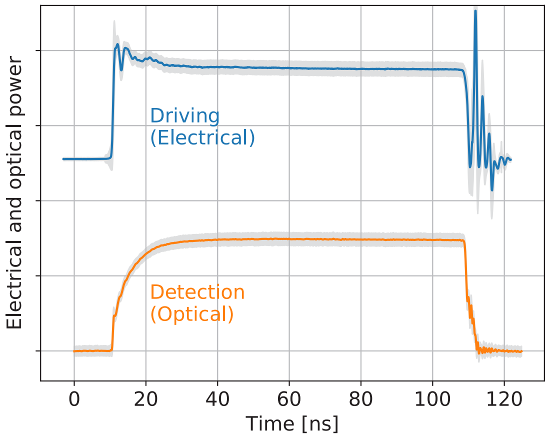

Fig. 5: Average electrical driving pulse and corresponding optical signal of 100 ns pulses with a duty cycle of 1 %. The curves are averages of 1000 pulses and the gray area represents the standard deviations at each data point.

The pulse driver electronics enables generating highly customizable pulse trains. Fig. 6 shows an example in which millisecond long sections of nanosecond pulses are interrupted by millisecond long breaks to avoid extensive heating of the DUT. The durations of the sections, breaks and pulses can be freely adjusted within a broad range. For example, pulse durations from nanoseconds up to microseconds are possible. This high flexibility permits finding the optimal driving pulse pattern for the intended application.

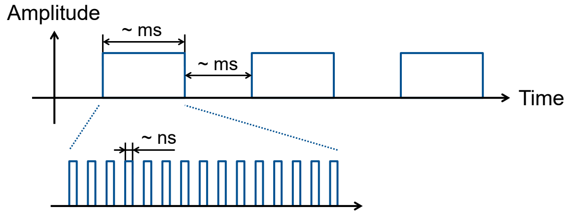

Fig. 6: Schematic of a possible driving pulse train with millisecond-long sections of nanosecond pulses.

An essential characterisation for laser diodes is to measure the so-called LIV curves. This means the relation how the optical power (L) depends on driving current (I) and voltage (V). These dependencies make it possible to derive many key characteristics of the DUT, like threshold current or slope efficiency. Figure 7 shows exemplary the LI dependence of a VCSEL measured with 100 ns driving pulses. This behavior is largely independent of the pulse length. In contrast, the IV characteristic depends for nanosecond pulses strongly on the exact pulse duration and approaches only a steady state for longer pulses (Fig. 8). This underlines the necessity of characterizing VCSELs precisely with the nanosecond pulse pattern to be implemented in the future application. Further investigations have shown that for fixed pulse duration, the observed IV-characteristic is in a first approximation independent of the duty cycle.

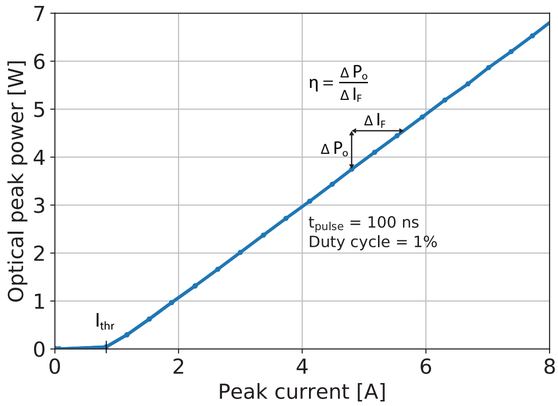

Fig. 7: Dependence of the optical peak power on driving current for 100 ns pulses with 1% duty cycle. Threshold current and slope efficiency are marked in the figure.

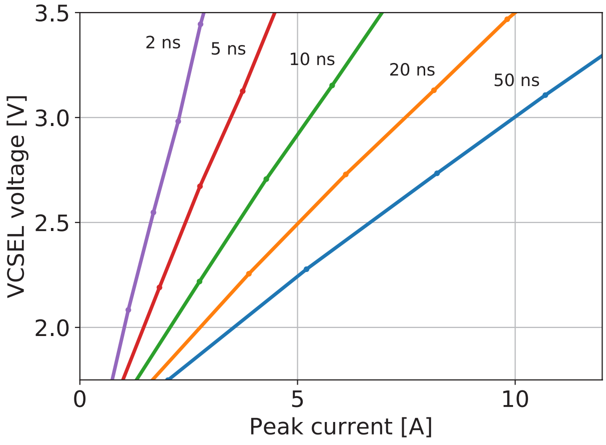

Fig. 8: Peak current of VCSEL driving pulses depending on the driving voltage and pulse duration for a fixed duty cycle of 1%.

It is well-known that VCSELs are temperature sensitive devices. The spectrum of a VCSEL changes due to the temperature dependence of the refractive index and the thermal expansion of the resonator material. Fig. 9 shows exemplary the spectral change and the shift of the peak wavelength, when the operating temperature of the DUT is varied from 20 °C to 60 °C. Such measurements are important for characterization as well as for further studies to make VCSEL more robust to temperature variations.

Nanosecond-driven VCSELs seem to open up very promising applications in mass markets, like consumer electronics. However, in-depth characterization in the laboratory and continuous quality control in production lines is essential to ensure the intended operation and reduce failure-rates. The laboratory measurement system PVT 110 for time-resolved electro-optical short pulse testing of VCSELs from Instruments Systems provides customers with:

Key features

- High spectral resolution down to 0.12 nm
- Pulse duration down to 1 ns
- Peak currents up to 15 A per pulse
- Pulse trains with up to 100 MHz repetition rate
- Time-resolved electro-optical characterization
- IV & LIV sweeps
- Temperature control of DUT
- Flexible pulse train definitions

Key results

- LIV characteristic
- Full spectral information of DUT
  (e.g. peak wavelength, radiant power, bandwidth …)
- Individual pulse shapes, durations & energies
- Pulse peak power & current

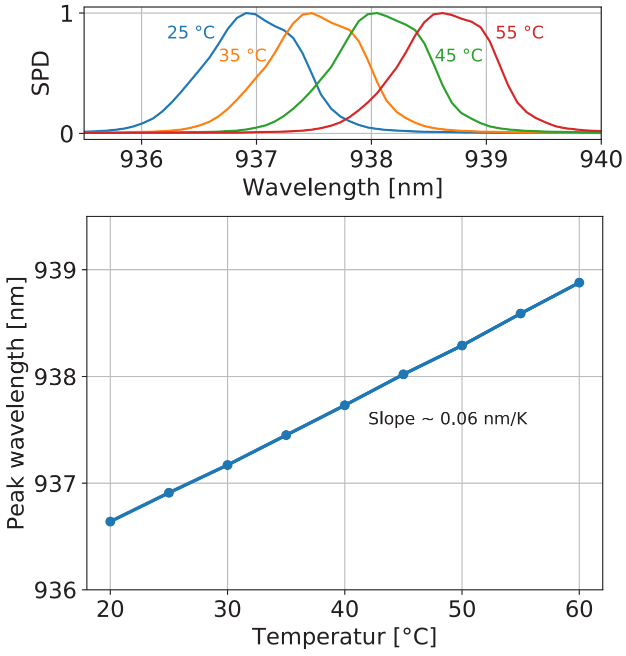

Fig. 9: Top: Normalized VCSEL spectra at different temperatures (SPD: Spectral power density). Bottom: Temperature dependent shift of the VCSEL's peak wavelength.

\\ 4. SPATIALLY RESOLVED SINGLE EMITTER MEASUREMENTS

Identifying the functionality and quality of a VCSEL array on single emitter level is an important task in production environments and can be carried out by the VTC system (VCSEL Testing Camera, see Fig. 10). This specially designed system consists of a camera and microscope optics and permits measuring the spatial distribution of the light from a VCSEL array with a single shot image. The information enables the analysis of each single emitter in terms of absolute power within a very short time-frame, enabling e.g. defect detection even in production. The system is optionally equipped with a translation stage moving only the optical parts without the need of repositioning the DUT during the measurement. It allows stitching for large DUTs and precise positioning with an uncertainty smaller than 2 µm. An additional CAS-HR spectrometer enables an analysis of the spectrum for each single emitter on the array. Fig. 11 shows a typical image of such a measurement.

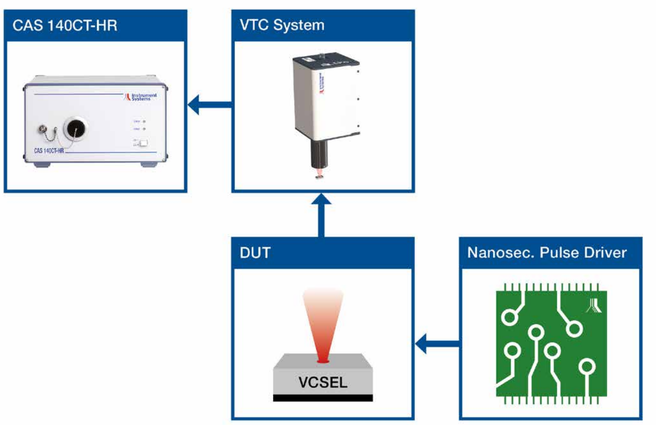

Fig. 10: The VTC system consists of the camera with microscope optics and a port for connecting a CAS spectrometer. Optionally, the Pulse Driver can be used for driving the DUT.

The camera system is flat-field corrected and comes with an absolute calibration traceable to national standards. The optical resolution is around 2.2 µm and the Field-of-View is 1 mm x 1 mm.

The VTC allows to measure a series of images of the VCSEL array in order to get all optical parameters of the array: position in x and y, focus position, absolute power, numerical aperture, waist and M^2 value. Together with a CAS spectroradiometer, the spectrum of each individual emitter can be characterized including peak and centroid wavelength (see figure 11 for an example).

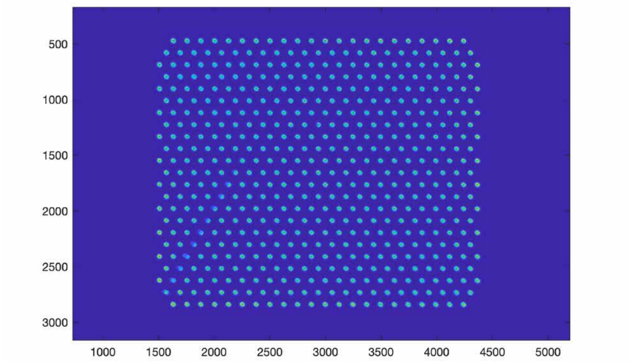

Fig. 11: 2D image of sample VCSEL, imaged with VTC system.

Key features

- Single shot solution for evaluating spatial distribution of a VCSEL
- 1 mm x 1mm Field-of-View, stitching possible
- 0.35 µm pixel size
- Translation stage optional, no movement of DUT needed
- Traceable absolute calibration
- Fully compatible with LumiSuite software

Key results per emitter

- Absolute power
- Peak wavelength
- Numerical aperture
- Waist

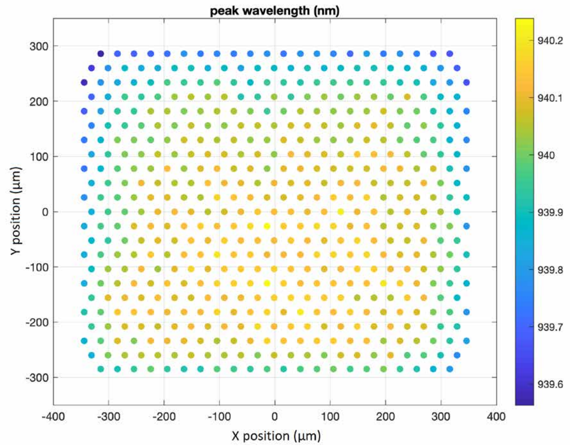

Fig. 12: Measured peak wavelength of a sample VCSEL using a CAS-HR and VTC system.

\\ 5. ANGULAR-RESOLVED MEASUREMENT IN FAR-FIELD

5.1 VCSEL far-field system

Characterizing the angular-resolved emission of the VCSEL array in the far field is another highly relevant application. On the one hand, far-field measurements give information on the divergence of the emitted beam, which is an important parameter in many VCSEL applications. On the other hand, identifying the emitted intensity profile from a distance is crucial for eye safety reasons and needs exact examinations. Instrument Systems offers different solutions for characterizing this emission profile, e.g. the VCSEL Far-Field System (based on a light-permeable screen) for price-sensitive applications and various goniophotometer solutions for highest accuracy and flexibility.

The cost-efficient far field system shown in Fig. 13 uses a light-permeable screen to measure the intensity distribution of the emitted light. Fig. 13 shows the sketch of the setup: The DUT irradiates the screen and the transmission of the screen is imaged by a camera system. This setup allows to measure the angular distribution of the emission of the VCSEL array. The camera exhibits a radiometric calibration traceable to the PTB.

Key features

- Cost-effective solution for measuring angular distribution of a VCSEL array
- For one-shot solution
- Traceable, absolute calibrated

Key results

- Absolute radiometric measurement
- Angular distribution of the VCSEL
- Opening angle and numerical aperture
- Emission profile, e.g. intensity peaks and valleys
- Height of intensity peaks as well as distance between them

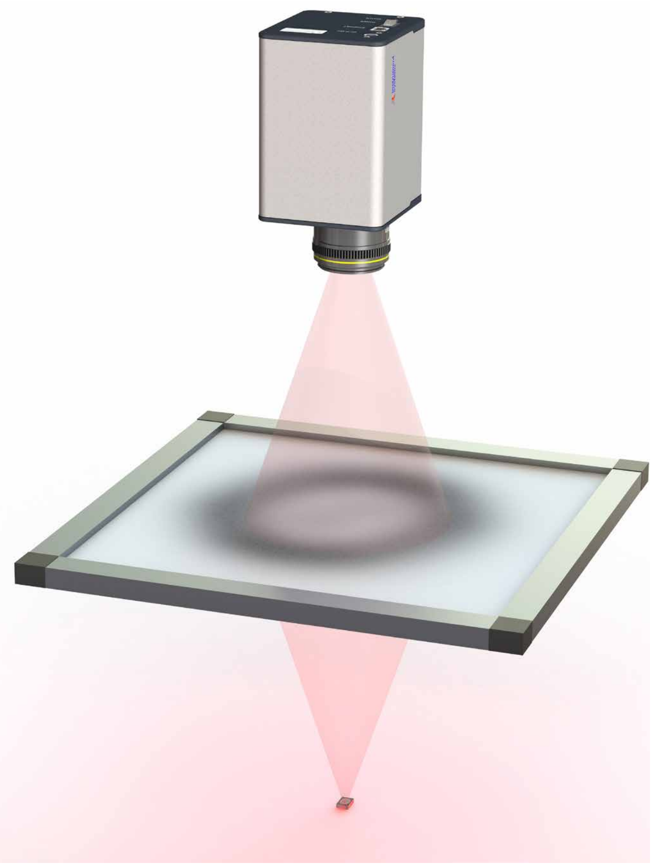

Fig. 13: The DUT irradiates the screen which is imaged by a camera system.

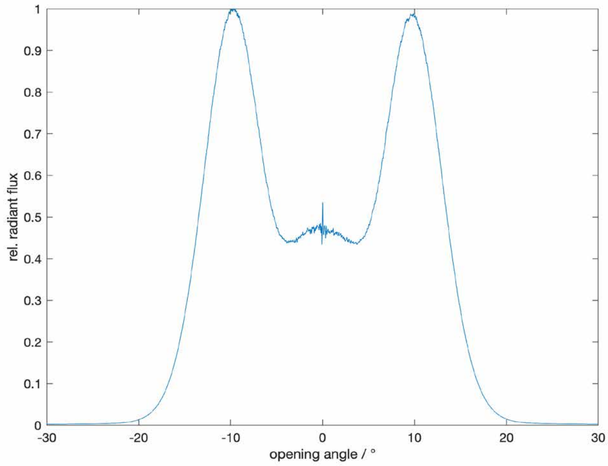

Fig. 14: The angular distribution of a sample VCSEL measured with the transmission screen.

5.2 Goniophotometer

In order to characterize the angular-dependency of the light emitted by the VCSEL in even more detail, goniophotometer measurements can be carried out, e.g. with Instrument System's LEDGON or LGS series. With these systems, the spatial emission pattern can be analyzed over the complete forward hemisphere with a very high angular accuracy of 0.1° for the LEDGON and 0.01° for the LGS 350 system. This is especially important for narrow emission devices such as VCSELs.

Fig. 15 shows a typical 3D emission profile of a VCSEL device measured in a goniometer setup . Clearly visible is the characteristic donut-like profile of the emission pattern, which can be analyzed both in 2D and in 3D. The goniophotometer solutions of Instrument Systems offer the possibility to characterize the emission pattern of a single emitter as well as for a complete VCSEL ensemble. Furthermore, analysis can be executed in both continuous wave or pulsed operation mode.

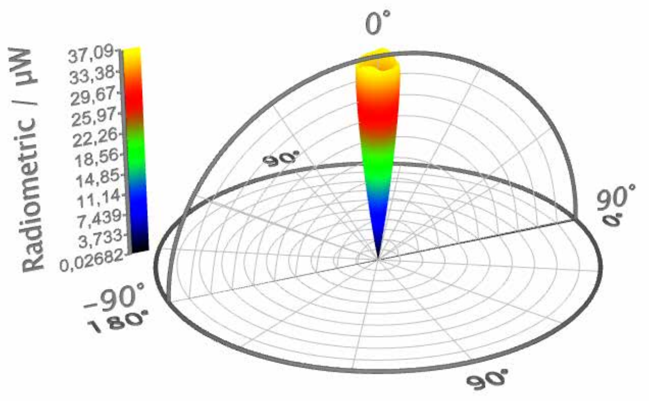

Fig. 15: 3D emission pattern of a sample VCSEL.

\\ 6. OUTLOOK: FAST AND HIGHLY PRECISE VCSEL TESTING FOR PRODUCTION

Increasing demands on quality control and compliance (especially eye and skin safety) require reliable as well as extremely fast and precise VCSEL testing solutions. Relevant quantities such as absolute power, wavelength, single emitter defects, numerical aperture, and beam uniformity have to be measured with a very high accuracy to avoid safety issues. Instrument Systems provides a comprehensive, yet modular solution adapted to your individual needs. In the future many applications make it necessary to transfer laboratory-proven tests for VCSELs to production lines. Especially for security-relevant components like LiDAR systems (in the field of autonomous driving) or in consumer electronics, manufacturers will have to ensure that each VCSEL responds correctly to the driving signals in the final device. This requires not only testing the complete VCSEL array but also each single emitter. Temporally and spatially resolved optical testing with predefined driving pulse patterns in production can make this feasible. Here, the development of production grade contacting for driving the DUTs with high-frequency nanosecond pulses, which have bandwidths in the gigahertz range, is considered to be one of the major challenges. Also, ever-increasing array sizes and/or NA values pose high demands on the measurement devices. Instrument Systems is working on transferring our measurement solutions from well-proven laboratory systems to VCSEL tests in production and can support customers in this field with our longstanding optical metrology experience in mass production of light-emitting semiconductors.

Instrument Systems
KONICA MINOLTA Group

Instrument Systems GmbH
Kastenbauerstr. 2
81677 Munich, Germany
ph: +49 (0)89 45 49 43-58
fax: +49 (0)89 45 49 43-11
sales@instrumentsystems.com
www.instrumentsystems.com

We bring quality to light.

an_vcsel-testing-solutions_en_V3.0