VCSEL in interferometry: a comparison to edge-emitting diode lasers regarding their applicability in speckle-interferometry

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Speckle-Interferometry (SI) is a powerful tool for fast, robust and non-contact measurements of displacement, vibration, roughness or shape. One of the key components in SI is the light source. Typical light sources are gas lasers, which meet all requirements like high intensity, homogeneous beam profile, and high degree of coherence. Due to large size, temperature control and high costs these types of laser can often not be used as an illumination source in SI-systems. Next to standard edge-emitting diode lasers, vertical cavity surface emitting lasers (VCSEL) are a promising alternative light source in SI. In this work, standard edge-emitting lasers are compared to VCSELs regarding the applicability in interferometric applications.

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1. Introduction

There are different requirements for a light source in interferometric applications: (1) the emitted light has to be highly coherent; (2) the output power has to be above a certain limit to guarantee a good illumination of the specimen depending on the used camera chip; (3) the beam profile has to be as homogeneous as possible; (4) the light source has to feature a high wavelength stability.

Most gas lasers (e.g. argon ion laser, helium neon laser, etc.) meet all of the above requirements. Due to large size, temperature control and high costs these types of lasers can often not be used as an illumination source.

Standard edge-emitting diode lasers are smaller and cost-effective light sources, although they cannot satisfy all requirements as well as gas lasers. This often leads to a decrease of resolution, due to low intensity, poor beam quality or instability in wavelength.

Vertical cavity surface emitting lasers (VCSEL) are a promising light source for SI: they are small, have a homogeneous beam profile and a low wavelength dependency on temperature. Furthermore, the operation current is very low compared to standard diode lasers (< 10 mA).

VCSELs are often used in applications like optical fiber communication [1], spectroscopy [2] or optical clock [3]. Due to their good optical properties, they are a promising alternative light source in interferometric applications like Speckle-Interferometry.

The structure of a VCSEL can be seen in Fig. 1. In contrast to an edge-emitter, the light is emitted perpendicularly to the wafer.

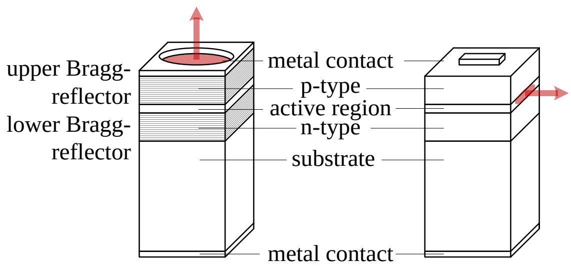

Fig. 1. Schematic diagram of a VCSEL (left) and an edge-emitting diode laser (right). In case of the VCSEL, Bragg reflectors have been inserted into the p-type and n-type region. Here, the light is emitted perpendicularly to the wafer and features a circular beam profile. The edge-emitter features an illumination direction parallel to the wafer with an elliptic beam profile.

2. Measurements

In this chapter, the different measurements for the characterisation of exemplary VCSELs are described and first results are shown. The used semiconductor lasers are all emitting in the red visible spectrum.

Spectrum and coherence: All measurements concerning spectral properties of VCSELs and diode lasers under test have been performed with the spectrometer *Oceanoptics HR2000* with a spectral range of 644.14 nm < λ < 699.86 nm and a spectral resolution of $\Delta\lambda = 0.03$ nm.

Fig. 2 shows the spectrum of a VCSEL and an edge-emitting diode laser.

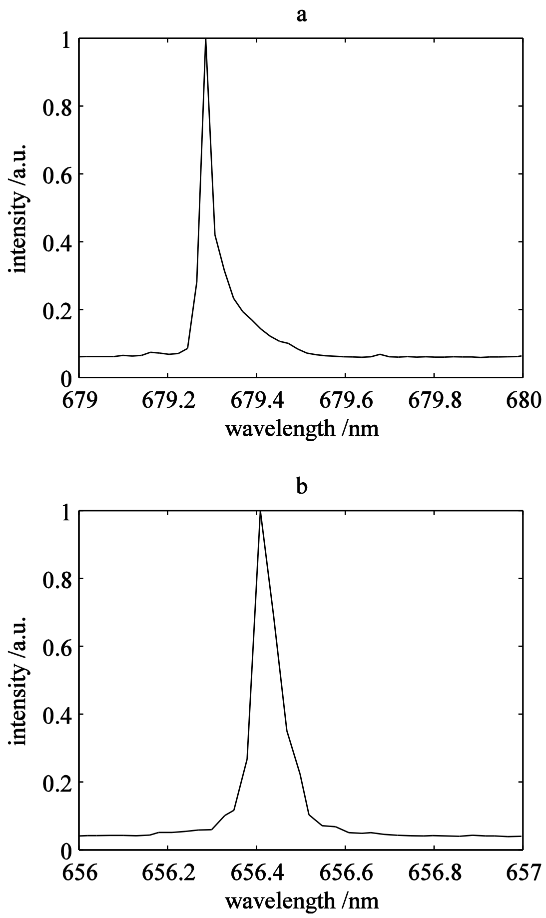

Fig. 2. Spectrum of an exemplary VCSEL (a) and an edge-emitting diode laser (b). In both cases the data has been acquired with an Oceanoptics HR2000 spectrometer and has been normalized to one.

An estimation of coherence length can be obtained by applying equation (1) on both spectra [4].

$$l_c = \frac{\bar{\lambda}^2}{\Delta\lambda}, \qquad (1)$$

where $\bar{\lambda}$ is the peak wavelength and $\Delta\lambda$ is the spectral line width. To determine $\Delta\lambda$, the FWHM of a Gaussian fit has been calculated. In case of the VCSEL, the estimated coherence length is 10.1 mm, in case of the edge-emitting diode laser it is 4.4 mm

Beam profile: Next to an adequate coherence length, the applicability in SI is also depending on a homogeneous illumination.

Here, edge-emitting diode lasers suffer from their beam direction parallel to the wafer. The resulting elliptic beam profile is a major disadvantage of edge-emitters in contrast to VCSELs.

There are different methods to overcome this problem: one solution is a broad-minded designed beam enlargement. Another method is the use of aspheric lenses to reshape the beam profile. A third solution is the use of an aperture or optical fibre: the emitted light is coupled into a single mode fibre on the one side and collimated on the other side leading to a circular beam profile without astigmatism. All named approaches are either expensive due to special optical elements or involve heavy loss of intensity.

An important advantage of VCSEL (with respect to interferometric applications) is the low divergence and the circular profile the emitted beam. This allows the use of cheaper standard optical elements to collimate or focus the beam.

In order to compare the profile of a VCSEL and an edge-emitting diode laser, the intensity distribution of both has been captured using a CCD-Camera. Fig. 3 shows the beam profile of an exemplary edge-emitting diode laser and a VCSEL. It is obvious that in case of the edge-emitting diode the beam diverges more in one of the transversal directions than in case of the VCSEL.

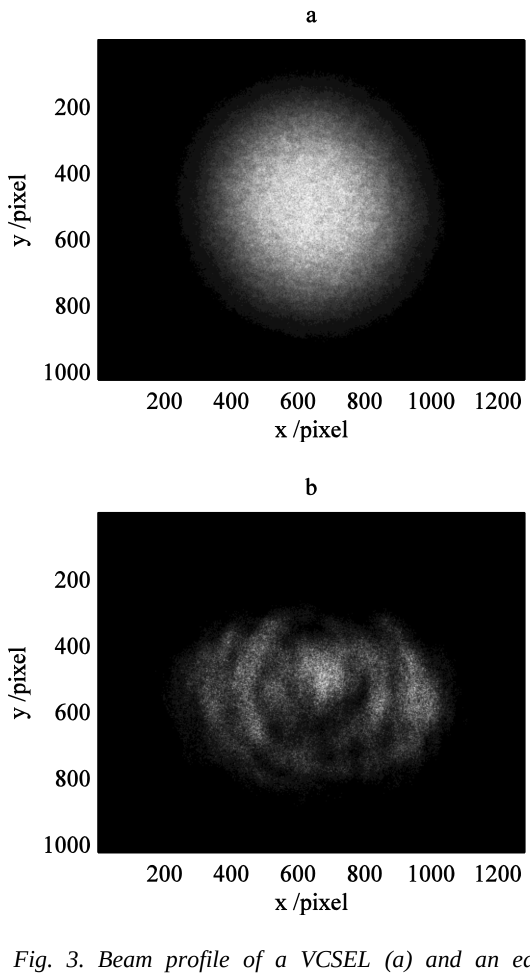

Fig. 3. Beam profile of a VCSEL (a) and an edge-emitting diode laser (b), both normalized to a maximal intensity value of one. In case of the VCSEL, the profile is circular, whereas in case of the edge - emitter, the profile is elliptic.

Here, the VCSEL has a homogeneous and circular beam profile, whereas the edge-emitting diode laser features the typical elliptic intensity distribution. To determine the degree of elliptic profile, in both cases the FWHM of a Gaussian fit along the x and y axes has been calculated. In case of the VCSEL, the ratio

$FWHM_x/FWHM_y$ is 0.98, in case of the edge-emitting diode laser it is 3.0.

Wavelength stability: During interferometric measurements, the stability of the illumination spectrum is a major issue: wavelength shifting, side modes and mode hopping due to changes in temperature must be avoided during measurements.

The diode lasers have been characterized in previous work. Here, the laser temperature and the laser current have been adjusted while observing the emitted spectrum. The result of this investigation is a stability map, where stable operating points of the edge-emitters could be determined. Similar measurements presented in [5] have been performed in this work regarding VCSELs: Fig. 4 shows the relation between wavelength and laser temperature and current, respectively.

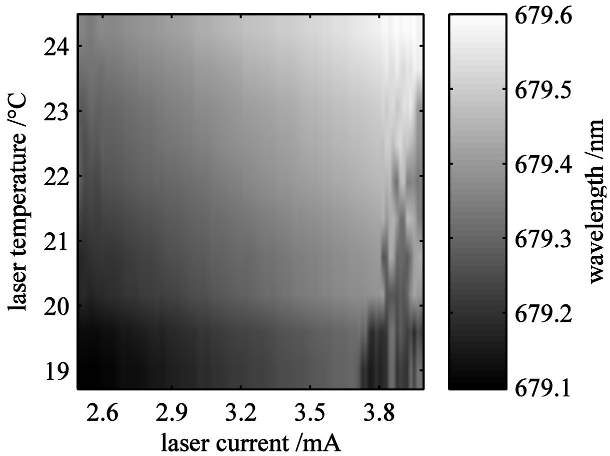

Fig. 4. wavelength map of an exemplary VCSEL. Temperature has been tuned from 19 °C to 24 °C using a Peltier-element mounted next to the VCSEL. Most operation points offer a very good wavelength stability (mode hopping can be observed for I > 3.8 mA).

The VCSEL in the case of Fig. 4 has a wavelength temperature variation $\Delta\lambda/\Delta T$ = 0.05 nm/K. The value of the edge-emitter under test is $\Delta\lambda/\Delta T$ = 0.25 nm/K. Both values are typical for each laser type. Due to very low laser current (I < 4 mA), the VCSEL showed no measurable self heating (ΔT < 0.1 K) after mounting it to a passive heat sink.

VCSEL arrays: Another interesting aspect of VCSELs originates from the optical path perpendicular to the wafer surface:

VCSELs can be easily manufactured in 2D arrays on a wafer. The single elements in such an array can either be produced equally or they can be built with different properties like different emitting wavelengths. Every single VCSELs in such an array can be controlled individually.

There are some applications where this fact can be very useful. The simplest example of use of such a VCSEL array is a coherent illumination source with increased intensity. A second possible application of VCSEL arrays with elements with different emitting wavelengths is Speckle-Interferometry. Here, the two wavelength technique is a well-known approach to acquire the shape of an object under test. Two interferograms are needed, each acquired with another illumination wavelength. Subtracting both interferograms leads to a phase image, where the distance on contour fringe to another is given by the synthetic wavelength Λ:

$$\Lambda = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2| \cos\alpha}, \qquad (2)$$

where λ_1 and λ_2 are the illuminating wavelengths and α is the angle of observation. There are different approaches to acquire interferograms with different wavelengths: in [6] both wavelengths are illuminating the object at the same time. A camera-system consisting of two cameras with filters separates both interferograms from each other. A second is presented in [5]: a rotating mirror is selecting one wavelength after another.

Both setups offer good measurement results but they have in common that additional elements need to be introduced to the setup to obtain different interferograms. One single VCSEL array with at least two elements with different wavelengths can be used as an adequate light source instead and increase the resolution of such a setup if the emitting wavelengths are chosen suitable [7].

3. Conclusions

We demonstrated that vertical cavity surface emitting lasers have several advantages compared to standard edge-emitting lasers regarding interferometric applications: first they have a homogeneous and circular beam profile. Secondly they feature a lower wavelength temperature variation compared to edge-emitting lasers. The current-temperature characterisation of a VCSEL showed a broad area (see Fig. 4) with stable operation points. Due to low laser current, no self heating could be observed after mounting the VCSEL to a passive heat sink.

The main disadvantage of commercially available VCSELs is the lower output intensity. While the typical cw-output power of VCSEL is 0.5 mW – 5 mW, high-power VCSELs may be fabricated, either by increasing the emitting aperture size of a single device [8] or by combining several elements into arrays. (Of course mono mode VCSELs can only be produced with small aperture sizes.)

Future work will compare both types of lasers adapted for applications in shape and roughness measurement using SI.

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