Manual: Performance of wafer-fused VECSEL under high power operation

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Abstract

github.com/stefantkeller/VECSELsetup

Contents

1 Introduction

1.1 Installation

This is a Python library. If you don't have Python installed yet, I recommend you install "Anaconda" (http://continuum.io/downloads) for Python 2.7 (it's free!).

To install this library from github,

1. click on "Download ZIP",
2. extract the .zip
3. copy the folder to where ever you want it
4. adjust the Pythonpath

(at least, that's the proper way to do it). And, if you are familliar with git ... you know what to do.

If you don't care about "proper" and you simply want it to work (I don't know though what this breaks along the way...): after extracting the .zip, copy the folder to (something like; if you work with Anaconda as recommended above)

- Windows: C:\Anaconda\Lib\site-packages
- Mac: /Users/yourusername/anaconda/Lib/python2.7/site-packages

this path is already in the Pythonpath, and Python will find it.

For measurements (the stuff in meas/) you need pyvisa (https://pyvisa.readthedocs.org/en/master/).
For evaluation (the stuff in eval/) you need to also install errorvalues (https://github.com/stefantkeller/errorvalues).
Install it with the same procedure as listed above. If you intend to use the calibration in exp/eval/calibration.py as it is, this is going to write an automated report (tuck together some plots) as a pdf; ready for print. This relys on LaTeX(pdflatex) to be installed on your system.

If measurement and evaluation happens on two different computers (recommended) you probably install only those dependencies that you need. That's ok, the error handling in __init__.py catches ImportError's and ignores them. However, if nothing happens at all, you might want to check whether you have installed, what you're supposed to have installed (maybe everything is caught and subsequentially ignored?).

1.2 File hierarchy

The different folders have different purposes:

- meas, setup control to record measurements
- eval, scripts for evaluation of measurements
- exp, examples of working measurement routines (using meas), and evaluation (using eval)
- doc, documentation

1.3 Usage

Copy the files stored from the folder exp in your working directory. The example exp/meas/routine_measurement.py is the most exhaustive for setup control / recording measurements. While exp/eval/light_light.py highlights the evaluation part.

There is not graphical user interface (GUI), as one might know from LabView. Instead, with this library you have full controll over what the software does. But this comes with the price to actually having to read the lines of code – instead of looking at obscure icons.

There are only few lines of code to read, in order to understand what's going on; and those are accompanied with comments. So go ahead and read it. You best start with the example scripts in the folder exp.

These lines of code you can read with any text editor of your choosing. On Windows I recommend PyScripter (https://code.google.com/p/pyscripter/). It brings in some simple GUI features, so you can edit and launch your measurement routines easily.

2 Measurement Routine

The routine is written in Python. This brings in several advantages: First of all we can actually look through the code and comment on it, where clarification is needed. The Python syntax is simple enough – basically, English with peculiar grammar – so if you can read this documentation, you will understand the program just as well. LabView for example fails at exactly this point; it's very hard to maintain, and the different sections of the script are difficult to interpret (let alone the litteral spaghetti code). And lastly, with Python we don't depend on a third party license. Again, LabView and Matlab fail at this point.

2.1 The routine

You either look at the example given in "exp/eval/routine_measurement.py" and read it through, or you continue to read here. The following long text covers the same.

We choose a set of values corresponding to a) the current of the pump laser, and b) the temperatures of the heat sink. We specify further, a path where to store the results. And lastly, we choose on how often every power current is ought to be measured – repeated measurements in order to obtain the errorbars that inform us on the reliability of the results.

At each temperature, we set the power source to the requested currents, and read out the power meters. The results of each power meter is written in its own file. Each of these files starts with a header line, that contains the state of the relevant settings of the device in question. Consequentially, if we doubt the integrity of the measurements we can look at this header line and at least know what state the device has reported to be in. The information about the power source are also written to its own file, containing the set and actual current. Hence, at each temperature we generate one file for the power source, plus one for each power meter.

At the end of these measurements we write a line in a logfile: The set temperature, the actually reached temperature, the filenames of the files with the results of the different devices, along with a timestamp so we know which measurement took how long. The timestamp also allows us to connect certain effects to the time of the day it was measured. The approach with a logfile and the separate files of each device (whose names are automatically stored in the logfile), facilitates the analysis; all the information a analysis-script needs is specified in the logfile.

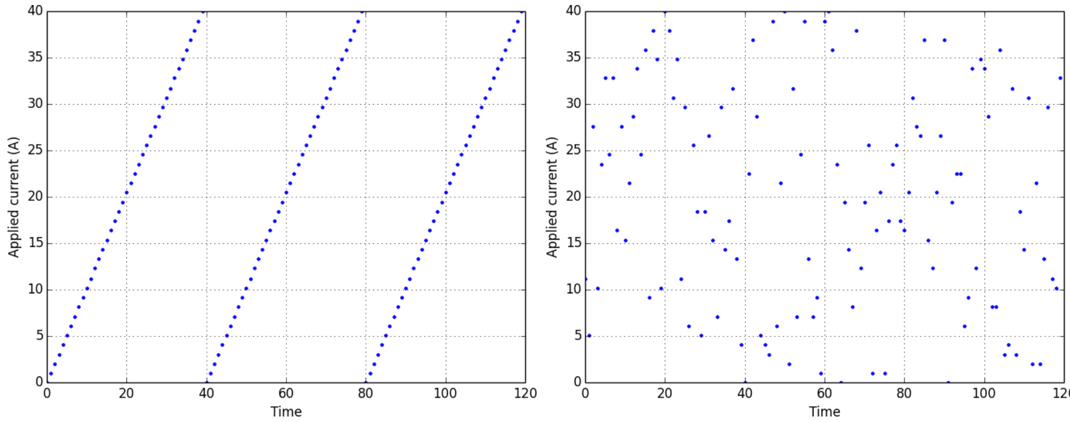

Figure 2.1: Two examples to apply various pump settings, with a repetition rate of 3. Left: A ramp. Right: Random sampling.

At each heat sink temperature we irradiate the sample with different pump powers. Each pump is repeated N times over all. The pump order is selected at random, as illustrated in Fig. 2.1. Thanks to the random sampling the measurement results are detached from the lab environment – most notably time-independent. The heat sink cannot control its temperature with absolute precision. Figure 2.2 illustrates this issue: It shows the actually present heat sink temperature for six set temperatures. In the left column the temperatures are plotted in chronological order. We can identify, the temperature drifts. The right column shows the same temperatures, but corresponding to the set pump. The repeated measurements see a spread of different temperatures but the temporal drifts can not be resolved.

In contrast, Fig. 2.3 shows the heat sink temperature during a measurement without the random pump selection. In this case, clearly, we cannot talk about a single heat sink temperature for all the pump settings for this specific set heat sink temperature. The resulting measurements are highly repeatable, but only given the same pump order. This pseudo-stability we exploit during the calibration process of the different beam samplers and detectors: During the calibration we don't care about reproducibility but solely about the repeatability of two consecutive measurements.

The power meter average each measurement point over 200 samples, of which each one sample takes approx. 3 ms [24].

The order of heat sink temperature is still a ramp: I expect the setting of a new temperature to be somewhat time consuming. Therefore, we want to make use of the previously set temperature. The measurement routine looks at the specified temperature range, picks the one closest to room temperature, and increases to every second entry. Once the highest temperature is reached, the residual temperatures are picked, in descending order, until the lowest temperature is reached. From there we heat back up to room temperature. This routine is illustrated in Fig. 2.4.

As mentioned already, we repeated the measurement of each pump setting N times. With this repetition we obtain a measure for how well we know the underlying true value. We are hence interested in the mean of these single measurements and the resulting unbiased standard error [25]

$$\Delta x = \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^{N} (x_i - \frac{1}{N} \sum_{i=1}^{N} x_i)^2}. \tag{2.1}$$

For the uncertainties attached to quantities obtained through fits, I use a so-called Jackknife [26] approach: In a nutshell, this method allows to estimate the influence of the

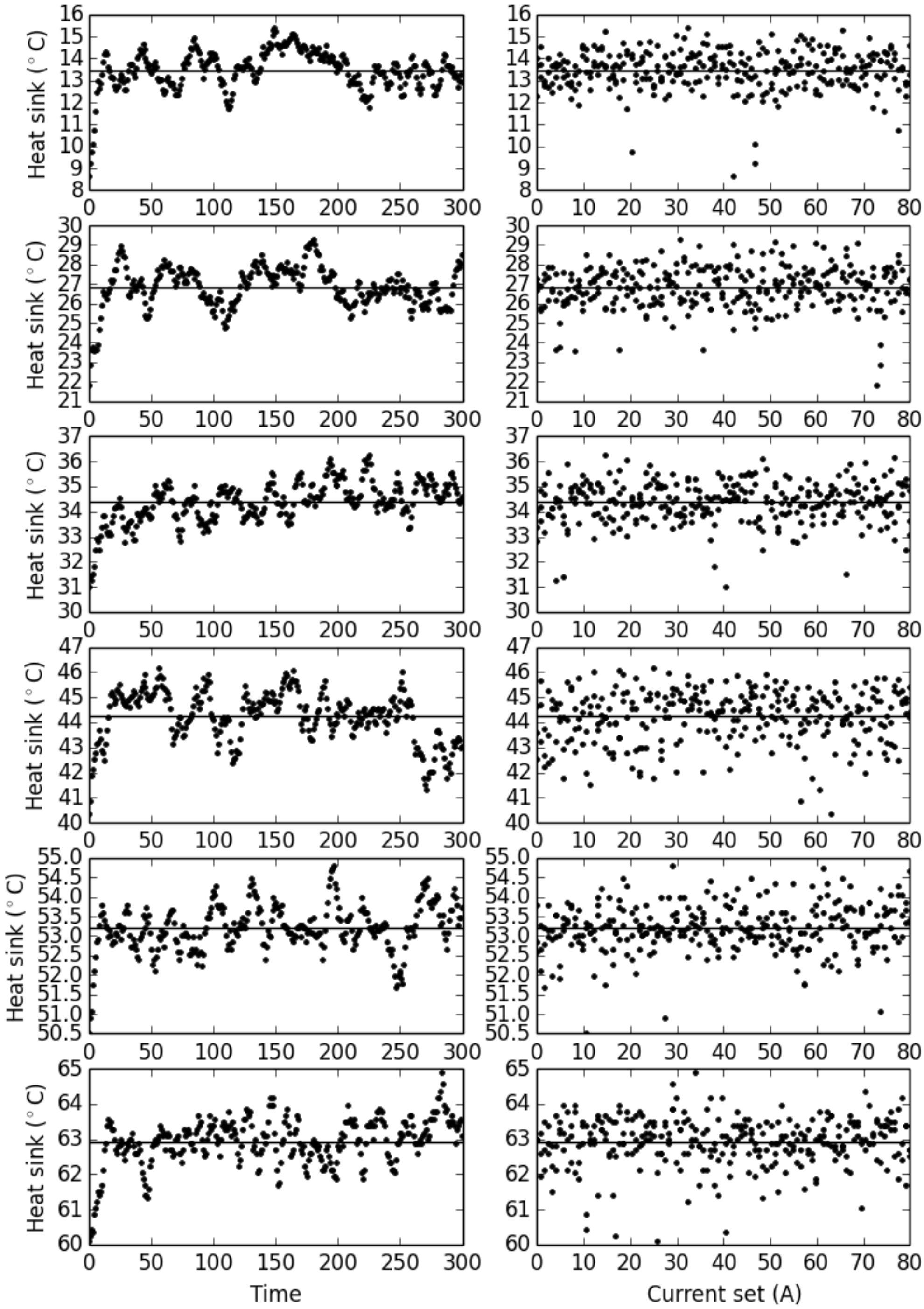

Figure 2.2: The heat sink temperature fluctuates over time (left). Thanks to the random sampling addressed in Fig. 2.1 the measurements don't see these drifts (right).

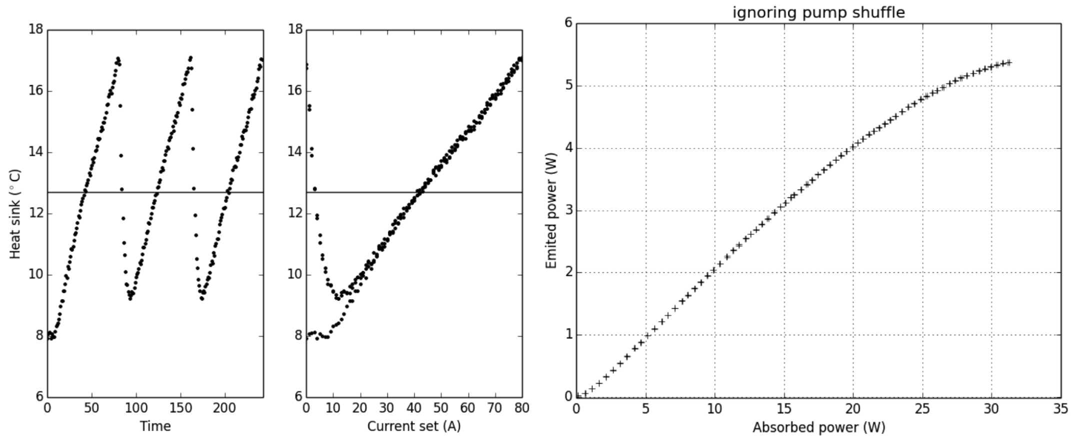

Figure 2.3: In contrast to Fig. 2.2, when we ignore the random pump sampling highlighted in Fig. 2.1, the temperature seen by the single pump settings differ strongly from the average heat sink temperature (left). The resulting LL-characteristic has very little noise on its data points (right). But these small error bars dismiss the fact that the underlying points were measured under very different conditions; eroding the significance of this low noise.

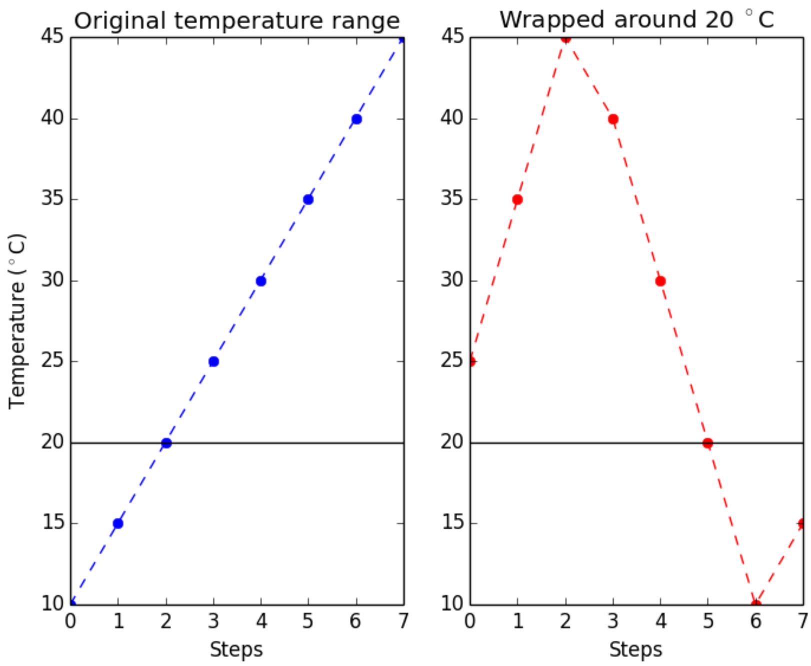

Figure 2.4: An example of how a given temperature range is wrapped around the room temperature (here assumed to be 20 °C).

single measurement points on the fit parameters without working through the covariance matrix of the fit. The resulting error value is directly related with the unbiased standard error (2.1), used for the rest of the report.

2.2 Safety precautions

The goal of this script is to automate as much as possible. Ideally, we want to install a new VECSEL, align the output coupler, press start, and return some time later to a complete data set for this specific VECSEL under test. For this we need to be sure our measurement routine handles potential errors appropriately.

For this we must not rely on software. Instead, we have to implement the safety precautions on hardware side. In software we can try to mitigate potential problems through proper error handling. I don't know how this would be done in LabView. In Matlab and Python this is performed through so-called try/catch and try/except handles, respectively. With it I have implemented that if anything goes wrong software side, the power source is shut down (This order itself is so low-level, that it *should* always work.). For example, one of the devices could send an unexpected answer, the heat sink doesn't reach its requested temperature within reasonable time, etc. For the unlikely event that even the power source shut down doesn't work, we have to implement the safety precautions on hardware side.

Our power source has two ways to be shut down: We can disable the current, or we can set the current to zero. In order to disable the current, we first have to ask the power source, whether the current is currently applied. If it is, we toggle it like a light-switch to shut off. However, querying the current state is error-prone. Hence, if an error is caught we leave the shutter to be in what ever state it is and only set the current to zero. Potentially it is still applied. But the light output at 0 A is barely detectable – but there still *is* a leak flow of photons. Writing to the power source should not cause any new problems, so simply writing 0 A should go through.

On the hardware side, the "laser on" light in front of the lab is controlled by a logic tied to the power source: As soon as the power source applies a certain specified voltage the laser warning turns on. During the measurements this safety sign therefore is always on.

As a second safety precaution I supply a script that allows us to test modifications on the measurement routine with fake devices. In order to connect the measurement routine with the measurement devices we have to specify a protocol. In the new script we do this by selecting an external file that contains the initiation details. By specifying the fake protocol we can modify the routine without the real devices. This separation in code is, for one, good practice, and secondly convenient if we cannot use one of the devices due to a revision or whatever. To be detached from the physical devices was not possible with the old script – which is one of the reasons why it was possible to toggle the power source shutter while setting the wavelength of the power meter.

3 Calibration

Figure 3.1 shows a photograph of the setup. Before we can use it to characterize samples, we have to characterize the setup first. Following the beam path, we start with the lens system indicated as pump. This input beam is targeted at the sample. Part of this pump beam is sampled by a beam sampler (BS), a glas plate with high damage threshold and anti reflective coating on one side. This sampled light is directed towards a detector. The pump light is reflected off the sample, collimated by a lens, and again sampled as for the input. The lasing output passes the output coupler (OC), a collimating lens, and another

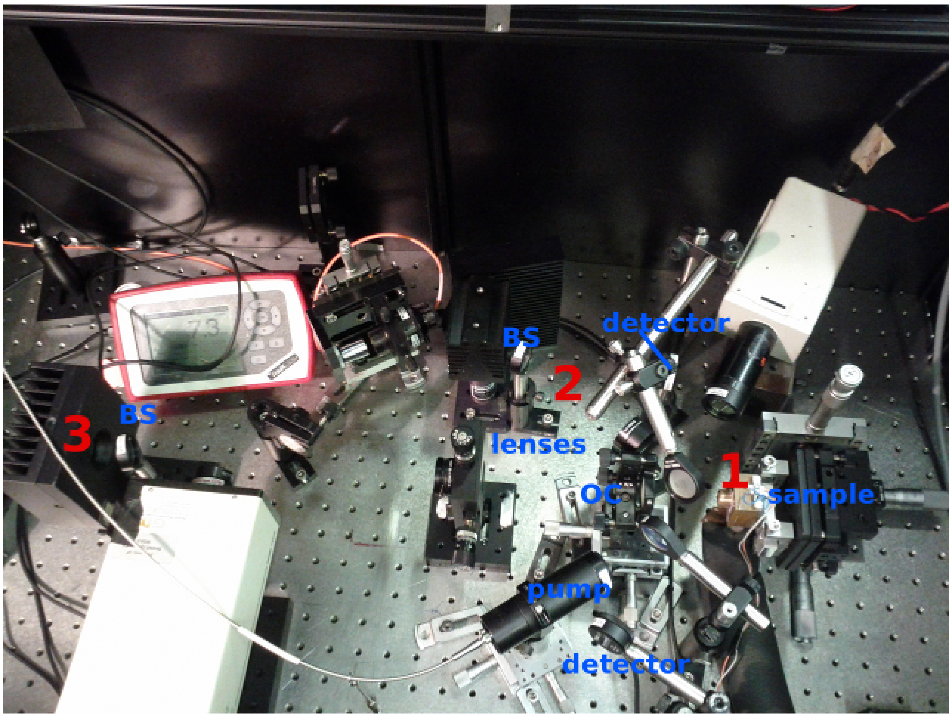

Figure 3.1: In order to calibrate the setup we have to measure the actually present power at the indicated positions 1–3.

beam sampler (coated for the emission wavelength). This beam sampler we eventually use to record the spectrum of the emission.

In order to calibrate this setup we need to know how to correlate the readings of the single detectors with the actually present powers. For this we place the thermal power meter at the four indicated positions. With the thermal power meter we can validate the setup up to 40 W, in principle.

Position 1 requires to remove the sample. We're interested in the correlation between the readings of the detector after the beam sampler and the measurements at the sample position. From this same measurement we can also extract a look-up-table what current setting of the pump laser corresponds to what output power.

On position 2 we measure the beam power present after the collimating lens. This we relate with the readings of the detector after the beam sampler gathered during the measurements of position 3 and 4. As I realized after the measurement I should have removed the lens as well – we want the reference value to correspond to the power before beam sampler and lens. In order to calibrate the reflection detector we combine the results from two different measurements. Between these two measurements we don't change any of the elements within the beam path. Non the less, calibrating the reflection detector relies on the repeatability of the operation. To keep track of this repeatability we measure each pump setting multiple times – 3 times for the presented data, each within a random order, see section 2.

The measurements taken at position 3 (with the lens removed, reading out the output directly after the output coupler) and position 3 (the real position of the power meter during regular operation) allow us to infer from the results obtained at position 4 to the undistorted output power.

References

[1] A. C. Tropper, S. Hoogland, *Review, Extended cavity surface-emitting semiconductor lasers*, Progress in Quantum Electronics 30, 1–43, (2006)

[2] A. Rantamäki et al., *High-power flip-chip semiconductor disk laser in the 1.3 μm wavelength band*, Optics Letters, Vol. 39, No. 16, (2014)

[3] A. J. Kemp et al., *Thermal Management in 2.3-μm Semiconductor Disk Lasers: A Finite Element Analysis*, IEEE Journal of Quantum Electronics, Vol. 44, No. 2, (2008)

[4] A. Chernikov et al., *Influence of the spatial pump distribution on the performance of high power vertical-external-cavity surface-emitting lasers*, Appl. Phys. Lett., vol. 97, no. 19, pp. 191110-1-191110-3, 2010

[5] S. Calvez et al., *Semiconductor disk lasers for the generation of visible and ultraviolet radiation*, Laser & Photon. Rev. 3, No. 5, 407–434 (2009)

[6] A. Sirbu et al., *High performance wafer-fused semiconductor disk lasers emitting in the 1300 nm waveband*, Optics Express, Vol. 22, Issue 24, pp. 29398-29403 (2014)

[7] G. Baili et al., *Experimental demonstration of a tunable dual-frequency semiconductor laser free of relaxation oscillations*, Optics Letters, Vol. 34, No. 21, (2009)

[8] M. Lukowski et al., *Widely Tunable High-Power Two-Color VECSELs for New Wavelength Generation*, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 21, No. 1, (2015)

[9] R. G. Bedford et al., *Power-limiting mechanisms in VECSELs* in Proc. Enabling Photon. Technol. Defense Security Aerospace Appl., (2005)

[10] A. Sirbu et al., *Wafer-fused VECSELs emitting in the 1310 nm waveband*, Proc. SPIE 8966, 8966OG-1-8 (2014)

[11] J. Hader et al., *VECSEL optimization using microscopic many-body physics*, IEEE J. Sel. Top. Quantum. Electron. 17, 1753 (2011)

[12] A. J. Kemp et al., *Thermal Management in Vertical-External-Cavity Surface-Emitting Lasers: Finite-Element Analysis of a Heatspreader Approach*, IEEE Journal of Quantum Electronics, Vol. 41, No. 2, (2005)

[13] B. Heinen et al., *106 W continuous-wave output power from vertical-external-cavity surface-emitting laser*, Electron. Lett. 48, 516 (2012)

[14] S. L. Vetter, S. C. Calvez, *Thermal Management of Near-Infrared Semiconductor Disk Lasers With AlGaAs Mirrors and Lattice (Mis)Matched Active Regions*, IEEE Journal of Quantum Electronics, Vol. 48, No. 3, (2012)

[15] M. Devautour et al., *Thermal Management for High-Power Single-Frequency Tunable Diode-Pumped VECSEL Emitting in the Near- and Mid-IR*, IEEE J. of Sel. Topics in Quant. El., Vol. 19, No. 4, (2013)

[16] B. Heinen et al., *On the Measurement of the Thermal Resistance of Vertical-External-Cavity Surface-Emitting Lasers (VECSELs)*, IEEE J. Quantum Electron. 48, 934 (2012)

[17] S. Giet et al., *Comparison of thermal management techniques for semiconductor disk lasers*, Proc. of SPIE Vol. 6871, 687115, (2008)

[18] J. Hader et al., *On the measurement of the thermal impedance in vertical-external-cavity surface-emitting lasers* Journal of Applied Physics 113, 153102 (2013)

[19] H. Lindberg et al., *Thermal Management of Optically Pumped Long-Wavelength InP-Based Semiconductor Disk Lasers*, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 11, No. 5, (2005)

[20] H. Q. Le et al., *Scalable high-power optically pumped GaAs laser* App. Phy. Lett. 58, pp. 1967–1969, (1991)

[21] V.-M. Korpijärvi et al., *11 W single gain-chip dilute nitride disk laser emitting around 1180 nm*, Optics Express, Vol. 18, No. 25, (2010)

[22] W. Nakwaski and M. Osinski, *Thermal resistance of top-surface-emitting vertical-cavity semiconductor lasers and monolithic two-dimensional arrays* Electronics Letters, 28(6), 72-574, (1992)

[23] Thorlabs, *Achromatic Doublets*, http://www.thorlabs.de/NewGroupPage9.cfm?ObjectGroup_ID=259

[24] Thorlabs, *Power meter operation manual*, http://www.thorlabs.de/thorcat/19500/PM100USB-Manual.pdf

[25] R. J. Barlow, *Statistics – A guide to the use of statistical methods in the physical sciences*, The Manchester Physics Series, Wiley, (1999)

[26] B. Efron, G. Gong, *A Leisurely Look at the Bootstrap, the Jackknife and Cross-Validation*, The American Statistician, Vol 37, No 1 (Feb 1983), pp. 36-48

[27] C. Hessenius et al., *Lateral lasing and ASE reduction in VECSELs*, in Proc. Vertical External Cavity Surface Emitting Lasers, San Francisco, CA, 2011, pp. 791909-1-791909-8

[28] A. Chernikov et al., *Heat management in high-power vertical-external-cavity surface-emitting lasers*, IEEE J. Sel. Topics Quantum Electron., vol. 17, no. 6, pp. 1772-1778, Nov.-Dec. 2011

[29] J. D. Mansell et al., *Gaussian to Super-Gaussian Intensity Profile Conversion with Refractive Micro-Optics*, online http://www.mansellassociates.com/CLEOTalk.pdf, (2000)

[30] P. W. Epperlein, *Micro-temperature measurements on semiconductor laser mirrors by reflectance modulation: a newly developed technique for laser characterization*, Jpn. J. Appl. Phys. 32, 5514-5522, (1993)

[31] K. Pierscinski et al., *Investigation of thermal management in optically pumped, antimonide VECSELs*, Microelectron. J., vol. 40, no. 3, pp. 558-561, (2009)

[32] G. Tessier et al., *Quantitative thermal imaging by synchronous thermoreflectance with optimized illumination wavelengths*, Appl. Phys. Lett. 78, 2267-071106, (2001)

[33] Springer Materials, *The Landolt-Börnstein Database*, online http://www.springermaterials.com

[34] U. Keller, *Lecture Quantum Electronics*, ETH Zurich, (2012)

[35] Edmund optics, *Understanding Spatial Filters*, online http://www.edmundoptics.de/technical-resources-center/lasers/understanding-spatial-filters

[36] Newport, *Spatial Filters*, online http://www.newport.com/Spatial-Filters/144910/1033/content.aspx

[37] Thorlabs, *Principles of Spatial Filters*, http://www.thorlabs.de/NewGroupPage9.cfm?ObjectGroup_ID=997

[38] M. Osinski et al., *Effective thermal conductivity analysis of 1.55 μm InGaAsP/InP vertical-cavity top-surface-emitting microlasers*, Electron. Lett., vol. 29, issue 11, (1993)

[39] Electronic Archive, *New Semiconductor Materials, Characteristics and Properties*, online http://www.ioffe.ru/SVA/NSM/

[40] J. Piprek et al., *Thermal Conductivity Reduction in GaAs-AlAs Distributed Bragg Reflectors*, IEEE Photonics Technology Letters, VOL. 10, NO. 1, (1998)

[41] A. Rantamäki et al., *High power semiconductor disk laser with a semiconductor-dielectric-metal compound mirror*, Appl. Phys. Lett. 104, (2014)

[42] J. Piprek et al., *What Limits the Maximum Output Power of Long-Wavelength AlGaInAs/InP Laser Diodes?*, IEEE Journal of Quantum Electronics, VOL. 38, NO. 9, (2002)

[43] E. F. Schubert, *Materials - Refractive index and extinction coefficient*, online http://homepages.rpi.edu/ schubert/Educational-resources/Materials-Refractive-index-and-extinction-coefficient.pdf, Rensselaer Polytechnic Institute, NY USA