High Power Laser Diodes with Optical Feedback
Contribution to Doctoral Consortium

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1 RESEARCH PROBLEM

High power direct diode lasers, as they are used in material processing or photonic pumping applications, are sensitive to back reflected light, which is usually called “optical feedback”. This feedback is generated unintendedly by optical surfaces of laser processing tools like cutting heads or by the processed surface itself. In material cutting or welding processes copper or aluminum are highly reflective materials (Steen, 2010) and photonic crystals can be origin of unwanted radiation even at changed wavelength (Dowley, 1998). Inside the laser system the beam transformation or the fiber coupling unit generates optical feedback. In some applications optical feedback is actually desired as part of the design. Volume Bragg gratings (VBG) reduce the spectral width by utilization of feedback. However, there is a price to pay, when the reflected light reaches the emitter of the laser diodes it can result in spectral modulation, lifetime reduction or catastrophic optical (mirror) damage (COMD).

2 OUTLINE OF OBJECTIVES

To provide laser systems with reliable and stable operation in the presence of optical feedback, design guidelines have to be elaborated and evaluated.

To do this a measurement setup is developed to apply optical feedback to laser diodes, which is controlled in intensity and direction. Its influence on the electrical and optical properties of the laser diode is observed. Laser diode bars with different types of semiconductor material, structure and emitter count are investigated. Then the parameters with influence the probability of disturbance or device failure are identified. These parameters can rise or lower the risk of a COMD.

The influence of emitter position variation in fast-axis direction (smile) was evaluated. Optical components used for beam transformation, combination or fiber coupling have individual behavior to the generation of optical feedback.

The study is mostly application related as the used laser diodes and optical elements are commonly used components and optical layouts. This ensures that the gathered information lead to developments of protection strategies and devices for industrial laser diode systems against the threat of optical feedback.

3 STATE OF THE ART

Laser diodes are typically designed for stand-alone operation. For example the front facet reflectivity is optimized to achieve highest efficiency or highest brightness. However, the presence of optical elements is not taken into account, although they influence the internal resonator design. From the point of view of the laser diode manufacturer this point is comprehensible as the field of applications is wide it is difficult to optimize laser diodes to cover multiple optical scenarios.

For this reason the interaction between optical system and laser diodes were subject to extensively investigations (Ohtsubo, 2010). Especially single mode laser emitters with optical feedback got high attention. This is an effect of the commonly use of these types of laser diodes in the communication technology (Kaminow, 2013). In contrast, the information on broad area laser emitters and especially on laser bars are sparse. Also long term effects of optical feedback to the reliability of laser diodes are not yet understood.

4 METHODOLOGY

This chapter describes the measurement techniques and procedures to gather the information about laser device failure due to optical feedback.

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4.1 Laser Diodes

The used laser diodes are commercially available components. They are mounted p-side down on a passively cooled cooper heat sink. All laser diodes used in experiments are checked in advance. This includes visual inspection of front facet, recording of optical power to current and voltage (PIV) characteristics as well as spectral measurements and near and far field intensity distributions. The different types are listed in Table 1.

Table 1: Batches of test laser diodes.

Batch	Material	Wavelength	Emitter No.
A	AlGaAs	808 nm	19
B	InGaAs	980 nm	10
C	InGaAs	1010 nm	10

Laser diodes of batch A based on semiconductor material containing aluminum and are well known for susceptible behavior against optical feedback. Laser diodes with InGaAs semiconductor are more robust. Two versions with different wavelengths are tested (batch C and D).

4.2 Detection of Failure Threshold

The threshold of device failure has to be identified to derive design limits. Optical and electrical behavior is observed to gather indicators connected to defined feedback intensities.

4.2.1 Test Setup

The setup has to be suitable to measure and control the amount of optical feedback reflected towards the laser diode. The optical system has to be comparable to commonly used designs for laser systems.

In Figure 1 the basic layout of the test system is illustrated. The radiation of the laser diode is collimated by cylindrical lenses in fast- and slow-axis direction. An array of biconvex lenses rotates the beam of each emitter geometrically by 90 degrees to achieve a more symmetric beam parameter product. This component is part of the so called beam transformation system (BTS). Note, that the nomenclature of slow- and fast axis direction are now inverted. The collimated beam is transmitted through a polarization beam splitter and a quarter wave plate. After reflection at a mirror the beam passes the polarization optics again. Depending on the angle of the wave plate, a part of the beam is reflected at the beam splitter and hits on a power measurement head. The remaining radiation is transmitted towards the laser diode and focused via the collimation lenses back onto the emitter.

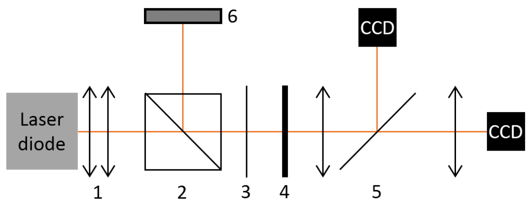

Figure 1: Measurement setup with variable feedback intensity and beam diagnostics. 1) collimation optics 2) polarization beam splitter 3) wave plate 4) feedback mirror 5) beam splitter 6) power measurement head.

Closely behind the BTS two slit blades are mounted to limit the transmitted radiation to a defined number of emitters. This allows determining the influence of optical feedback on a single or multiple emitters.

The electrical properties of the laser diode are monitored using a calibrated resistor together with a voltmeter. Photodiodes are used to measure the optical intensity. They are referenced to a commercial power measurement head. An optical imaging system is used to observe both, the near-field intensity distribution of the emitter facet and the far-field intensity distribution. A spectrometer takes the spectrum of the laser beam.

This measurement setup is automated as the quarter wave plate rotation is motorized and the measured data are collected by data loggers and software acquisition.

4.2.2 Procedure

The optical feedback beam is adjusted by manipulating the angle of the reflection mirror. The electrical and optical behavior of laser diodes with optical feedback is used to find the optimal alignment. Details to this behavior are given in chapter 5.1. Several steps are necessary to optimize the feedback injected into the laser emitter. First, the laser diode is operated without the feedback mirror and the centroid of the near-field intensity distribution is marked. After adding the feedback mirror the laser diode is operated below laser threshold. The mirror angle is varied along slow axis direction until the signal on the camera reaches its maximum. This step uses the threshold reduction effect due to optical feedback. In fast axis direction the mirror is tilted until the intensity distribution reaches the before marked position. Now the threshold reduction current value can be determined.

Due to temperature expansion a slight

readjustment is necessary at the working point. At high operation currents a lower feedback level has to be chosen to avoid damage to the laser diode. The spectrum is used as an indicator of maximal feedback injection, as the wavelength rises with higher feedback.

Depending on the test scenario the load of the laser diode starts minimal and is than raised until device failure. The load is controlled either by the feedback intensity or the operation current.

4.3 Long Term Tests

Industrial field experience has shown that optical feedback may lead to reduced lifetime of laser diodes. Devices with an initially stable operation condition may fail with time delay. This presumption is analysed by the following long term test.

4.3.1 Test Setup

Twenty-four devices of batch C are used in this long term test. Each was collimated in both axis and then applied to a reflective element. The transmitted radiation was absorbed by a beam dump. The devices were split up into four groups equipped with different feedback levels. The reflective elements were a 20 % VBG, a 10 % VBG and a plate with 8,2 % broadband feedback, respectively. One group was used as reference without optical feedback.

Every laser diode is monitored by a photodiode and the data recorded by a logger.

4.3.2 Procedure

All laser diodes are operated at their working point (I = 55 A). Optical output power and spectra of each laser diode are measured frequently and the emitters are inspected if a COD occurred. The test is cancelled when several laser diodes have damaged emitters.

5 RESULTS & ANALYSIS

5.1 General Behavior Due to Optical Feedback

This chapter shows the influence of optical feedback to the optical and electrical properties of laser diodes. These properties indicate how much of the feedback is coupled back into the emitter. Basing on this information the alignment of the feedback mirror is evaluated.

5.1.1 Results

The laser threshold current is reduced due to optical feedback. 808 nm bars (batch A) have a typical laser threshold of 7,15 A (standard deviation σ = 0,23 A) which is reduced to 4,56 A (σ = 0,38 A) with optical feedback. The laser threshold current of 980 nm bars of batch B without feedback is 4,38 A (σ = 0,21 A) and is reduced to 2,98 A (σ = 0,10 A) with feedback.

The wavelength of the emitted radiation shifts to longer wavelengths when the feedback intensity rises. In Figure 2 the wavelength depended of optical feedback at different operation currents is compared.

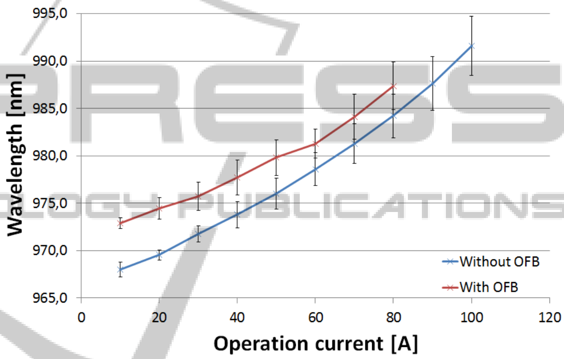

Figure 2: Central wavelength with and without optical feedback of laser diodes of batch B.

The operation voltage of the laser diode decreases with optical feedback intensity. As the emitters of the laser bar are parallel operated this effect occurs more intensive when all emitters are exposure to optical feedback. Depending on the intensity the operation voltage can be lowered to the values given in Table 2.

Table 2: Voltage reduction by optical feedback.

Batch	A	B & C
Voltage reduction	14 mV	8 mV

5.1.2 Discussion

The presented values are only given at a qualitative level of optical intensity. Future presentation will be able to give them in context of a quantitative feedback level injected into the laser diode emitters. This will be possible as a result of the calculations and beam simulations introduced in chapter 5.4.

The laser threshold current has a strong dependence to the intensity of optical feedback. It has a high suitability as a criterion of how well the feedback mirror is aligned. The physical background of laser threshold reduction can be explained by the Kobayashi-Lang rate equations, which are not subject of this survey (Kobayashi and Lang, 1980). It can be shown that the feedback mirror operates as an external resonator and has an influence of the electron-photon transition of the semiconductor.

The wavelength rises with higher amount of optical feedback. This effect can be caused by a raising temperature, which would affect a higher band gap of the electron transition. The semiconductor temperature rises due to absorption of the feedback radiation, which doesn´t fulfil the resonator condition.

Operation voltage reduction is observed with increased optical feedback. This effect might be also a result of the temperature change of the semiconductor bulk. There are several sources reporting of the temperature dependence of the semiconductor voltage. There are applications using this method as a thermal detector (Ryu, 2005).

For this work it is most important that a significant dependence of the optical feedback intensity to the laser threshold current, wavelength and operation voltage could be shown. Therefor these parameters can be used to evaluate the quality of the feedback beam alignment.

5.2 Detection of Failure Threshold

5.2.1 Results

Laser diodes of batch A are operated at nominal current of 50 A. The feedback intensity is raised until COD occurs. This measurement is performed for single emitters which are isolated with slit blades and whole bars. The mean value and standard deviation of this series are given in Table 3. The OFB power is calculated from the device optical output power reduced by the power ejected by the polarization optics.

Table 3: Optical feedback power at device failure of laser diodes of batch A.

	OFB power	Standard deviation
Isolated Emitter	1,3 W	0,15 W
Whole bar	0,8 W	0,09 W

When testing laser diodes of batch B raising the optical feedback intensity doesn´t compulsory lead to COD. Instead, the operation current is raised in 10 A steps until device failure. The test has been performed for isolated emitters, 3-emitter-packs and whole bars. The current values causing a COD are given in Table 4.

Table 4: Operation current at device failure of laser diodes of batch B.

	Current at COD	Standard deviation
Isolated Emitter	92 A	3 A
Neighbored emitter	70 A	2,8 A
Whole bar	60 A	2,7 A

During determination of device failure threshold also spectra of the laser beam are taken. Figure 4 **Error! Reference source not found.** shows the spectrum of an isolated emitter of batch A. The optical feedback power is varied. Two points are noticeable: First, at 0,4 W feedback power there is a significant change of the spectrum. Second, above 1,1 W the spectrum series ends; this is due to COD.

Simultaneously the near field distribution is captured. In Figure 3 two shots are compared: one at a feedback power below 1,1 W leading to the change in the spectrum and one above. The spots with the highest intensity moved and the size of the spot is larger. This shows that the near field distribution changed at the same moment as the spectrum.

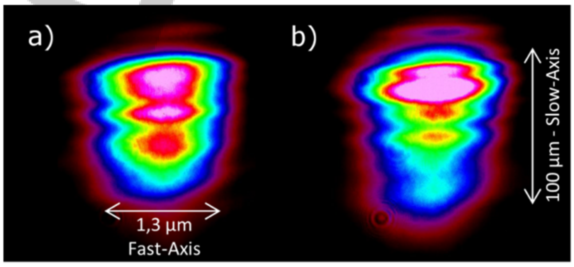

Figure 3: Near field distribution a) before and b) after change in spectrum.

In the next step the spectrum of a whole bar (batch A) is observed. The feedback is applied to all emitters at the same time. The contribution of the different emitters to the spectrum and their variation due to optical feedback is illustrated in Figure 5.

After finishing the COD threshold measurement the laser diodes are examined with a light microscope. Figure 6 shows a typical front facet of a laser diode with COMD. The blue-green colored part represents semiconductor. In the bottom part of the figure the heat sink is visible. As the device was operated in LED operation mode the violet stripe represents the remaining radiation generated by the emitter.

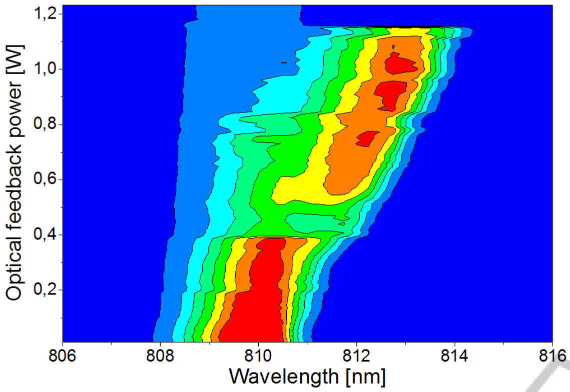

Figure 4: Spectrum shift by feedback intensity variation in case of an isolated emitter.

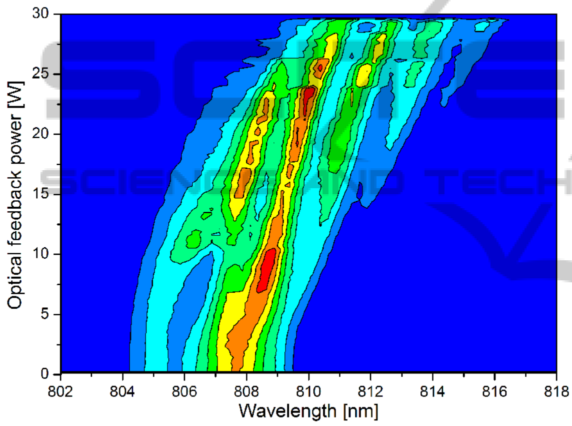

Figure 5: Spectrum of whole bar of batch A with varied optical feedback intensity.

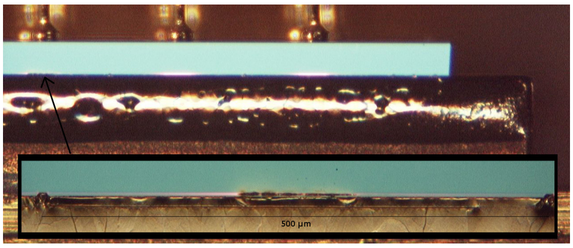

Figure 6: Light-microscope picture of facet with COMD. The violet area is radiation from LED operation mode of the laser diode.

5.2.2 Discussion

The measurements prove the expectation that devices of batch A are less robust against optical feedback than devices of batch B. The value named OFB power is the power generally reflected towards the emitter. It is not equal to the power injected into the emitter because losses at optical elements have to be taken in account. This value will be calculated in future.

The failure threshold is higher in case of an isolated emitter compared with several emitters with optical feedback. First, this can be due to a higher thermal load of the semiconductor when several emitters are applied of optical feedback. The radiation is partly absorbed in the bulk material and heats up. The higher temperature can increase the risk of COD.

Second, the emitters are subject of direct radiation from other emitters. All emitters are collimated by the same FAC lens, but each emitter has its own lens array element of the beam transformer (compare Figure 7). The beam has a remaining divergence after collimation and the beam expands by propagation. The returning beam can be larger than the lens array aperture. The part of the beam which doesn´t fit through its array element is then coupled to the beam path of the neighbored emitter. On this way it is finally coupled into that emitter. That means that an emitter of a laser bar has a higher optical load due to the optical feedback of its neighbored emitters.

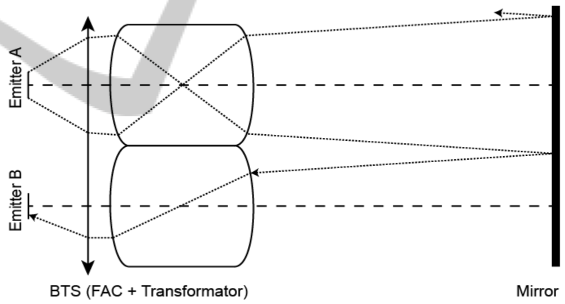

Figure 7: The beam emitter from Emitter A expands due to its remaining divergence. After reflection the beam can hit on the transformator array segment of the emitter B.

The laser diode has several optical properties. It could be shown that these correspond to each other. Changes in the spectrum lead to changes in the near field distribution. Intensity peaks in the near field distribution are observed to be the origin of COD. The position of these intensity peaks might be at the same position of the defects visible on the front facet investigated by light microscopy after COD.

5.3 Long Term Behaviour

5.3.1 Test Results

Optical feedback has the ability to damage a laser diode instantly. This damage threshold can be determined as shown before. When a laser diode is operated below this damage threshold this doesn´t correspond to a stable operation mode. The COD can occur time-delayed.

To demonstrate this behaviour each one emitter per test procedure is isolated. The optical feedback intensity is variable and set to a value below instant COD threshold. The time to COD is measured and the mean values are shown in Figure 8. At feedback levels close to the instant COD threshold the emitter lifetime is very short and lasts between several hours to several days. When the optical feedback intensity is lowered further the lifetime is significantly higher. The measurement point with the longest lifetime before COD was at half the instant COD threshold and ran for about 700 hours.

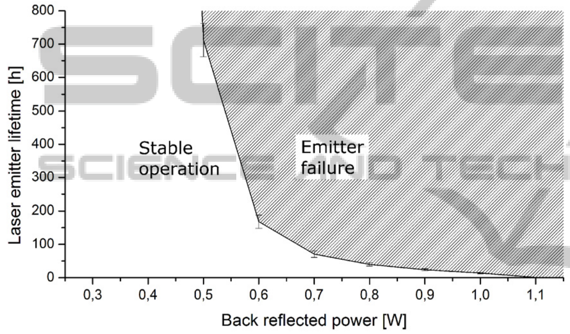

Figure 8: Runtime until device failure dependent on optical feedback intensity. In this chart measurement series of laser diode batch A are presented.

Another scenario operates with a far lower feedback, which is instead applied for a longer time period. This scenario has been examined by a long term test using laser diodes of batch C. Figure 9 shows the optical power of five of 28 during the whole test. At these five devices a COD of one emitter occurred. Three of the failure laser diodes were equipped with a 20 % VBG, while two had a 8,2 % broad band feedback. The first device failure happened after 2700 hours of operation, the test has been cancelled after 3700 hours.

One of the laser diodes has been inspected by spectroscopic methods in advance. In cooperation with the team around Dr. Tomm of the Max Born Institute Berlin the bar was observed by laser beam induced current (LBIC) procedure. This can show defects present inside or on the surface of the semiconductor (Fang, 1992). One emitter of a bar indicated defects inside the bulk material. During the test exactly this emitter failure.

5.3.2 Discussion

In further steps an appropriate model is developed to describe this behaviour. The “Weibull”-distribution might be suitable to fit the measurement results. It is commonly used for reliability analysis and description of failure probability (Ohring, 1998). Moreover there are studies about lifetime reduction of laser diode systems, which are subject to other stress factors, like cooling temperature or operation current increase. If device failure behaves similar in both cases, optical feedback and other stress factors, the same physical reason for COD might be responsible.

The long term test shows that even feedback rates of commonly used optical elements can reduce the lifetime of laser diodes drastically. It is not yet shown why two laser diodes with lower feedback had COD. There might be a difference between narrow and broad band feedback.

An interesting result is that the emitter with defects showed COD during he test. It can be an indication that device failure occurs preferable at emitters with existing defect cells. To provide more data another test run with laser diodes inspected by the LBIC procedure is currently in preparation.

5.4 Describing Model

5.4.1 Optical System Modelling

The amount of optical feedback reaching the laser diodes facet can be calculated. Therefore the

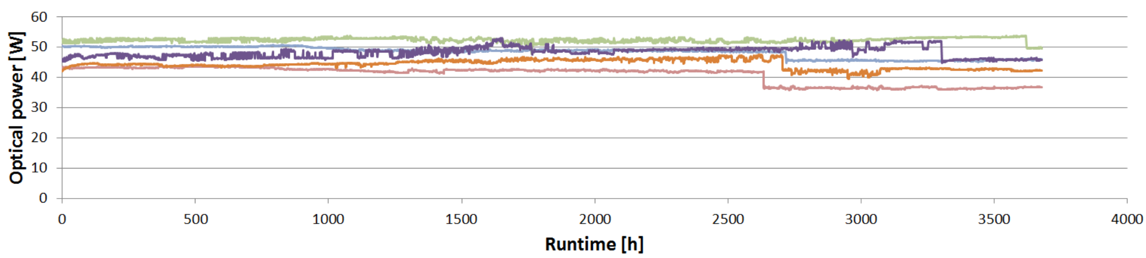

Figure 9: Optical power trends of five laser diodes operated in the long term test. Three with 20 % VBG and two with 8,2 % broad band feedback. The drop in each trend indicates the moment of emitter failure.

components of a laser diode system have to be described individually. The optical components shown in Figure 10 are typical for high power laser diode systems. However, VBG and fiber coupling are optional and depend on the application needs.

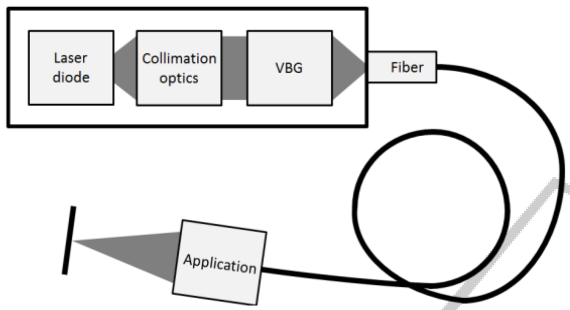

Figure 10: Typical elements of an optical system relevant for amount of optical feedback.

The optical elements can be divided into three main groups and their belonging beam paths are drafted in Figure 11. a) Collimation optics. The divergent laser beam and hits on the fast axis collimation (FAC) lens. Commonly the first flat surface has a distance of only 70 to 150 µm to the emitter. The light is reflected divergent and only a small part is reflected into the emitter. b) Selective optics. The beam is collimated and hits a plane surface, where it is partly reflected. As the reflected beam is collimated it can be transmitted over long distances inside the optical system. c) Focusing optics. The beam is focused on the plane surface of an optical element like a light guiding fiber. This case is interesting, when observing a multi emitter bar. Each emitter beam path is mirrored and reversed and ends finally at an emitter opposite of the original one. Here a strong coupling between each two emitters can be observed.

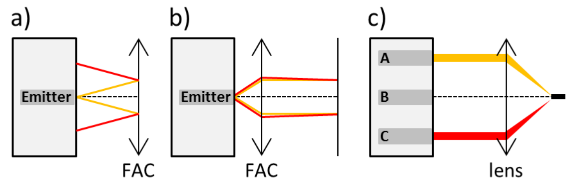

Figure 11: Three groups of optical elements contributing to the amount of optical feedback: a) collimation optics, b) selective optics and c) focusing optics. Yellow lines represent forward beams, red illustrates reflected beams.

The optical power reaching the laser diodes facet P_{OFB} is calculated by the emitter output power $P_{out}$the reflectance R of the reflective element and the transmission efficiency η of the optical system.

$$\mathrm{P}_{OFB} = \mathrm{P}_{out}\, R\, \eta \tag{1}$$

While P_{out} and R can be measured η has to be calculated. η describes how much of the angular and the spatial intensity distribution of a laser diode emitter is transmitted through the optical system. As the intensity distribution of an emitter is not homogenous it is approximated by a super Gaussian distribution.

$$\eta = \int I_o\, e^{-2\left|\frac{x}{\sigma}\right|^{2\,SG}}\, dx \tag{2}$$

This is valid for spatial and angular distribution by picking according parameters. σ represents the half width or angle of radiation at 1/e² intensity, respectively. The SG value is used to fit the Gaussian distribution to the measured intensity distribution. I_o is used to set the result to 1, when the integral over the whole range is calculated.

The constraints of the integral depend on the individual optical component. Depending on the number of variables equation 2 has to be integrated in both spatial and both angular directions.

FAC Reflection (Figure 11a): Beams emitted from the facet from one point are reflected back into the active region by fulfilling these upper and lower angular constraints:

$$\alpha_{FA\,u,\;FA\,l} = \frac{\tan^{-1}\left(\pm\frac{h_E}{2} - y_E\right)}{2\,d_{BFL}} \tag{3}$$

By changing emitter height h_E to width w_E and emitting point position y_E to x_E the integration constraints in slow axis direction are given. Additionally this has to be integrated spatially in x and y direction.

FAC aperture (Figure 11b): Due to remaining divergence the beam size increases after collimation. When reflected through the optical system it can be cut of at the aperture of the optical elements. Especially the FAC lens has typically a small aperture A. The integration constraints of equation 2 are given by the distance d between FAC lens and reflective element and focal length f:

$$\alpha_{FA\,u,\;FA\,l} = \tan^{-1}\frac{\pm\frac{A}{2} - y_E + 2\,d\,\tan\frac{y_E}{f_{FAC}}}{f_{FAC}} \tag{4}$$

In this case only the fast axis direction has influence to the transmission efficiency and has to be integrated angular and spatial.

Smile: Induced through mechanical stress by soldering a laser chip onto a heat sink the center of an emitter has an offset Δy to the optical axis. The angular distribution is not relevant in this case. Here the spatial integration constraints are modified.

$$y_{u,l} = \pm y_E + \Delta y \tag{5}$$

On this way the influence of all optical components to the total amount of optical feedback reaching the emitter can be described.

5.4.2 Validation & Discussion

For validation these equations were calculated with the parameters of typically optical components and simulated with the optical design software ZEMAX.

Figure 12 shows the results of the equation 2 with the constraints of equation 3 compared with the simulation of light reflected at the FAC lens surface.

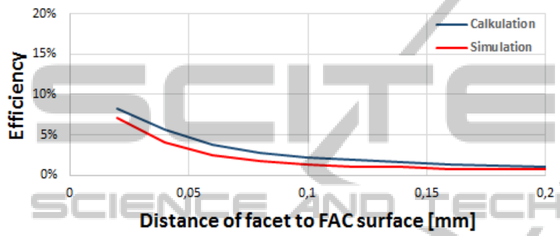

Figure 12: Efficiency of the transmission of the reflected beam through the FAC lens aperture.

This has also been done for equations 2 and 4 describing the beam cut off due to exceed of lens aperture. Several FAC lens types are used. The comparison of calculated and simulated values is plotted in Figure 13.

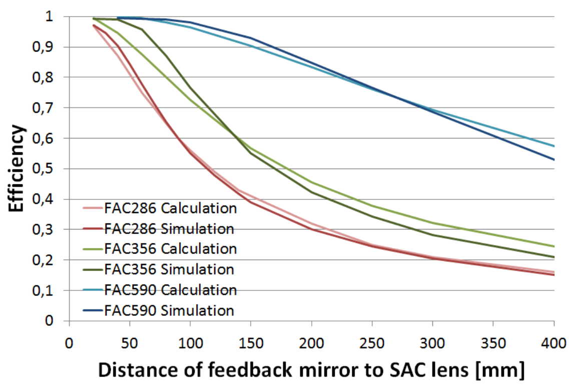

Figure 13: Efficiency of the transmission of the reflected beam through the FAC lens aperture.

Both figures show a good agreement of calculation and simulation.

In a future step measurement data will be added to these plots.

6 STAGE OF THE RESEARCH

The experimental work of this research project has proceeded to final stage. Measurement series with different devices are completed. Defect threshold of isolated bars and multiple emitters are determined. Additionally a long term test in cooperation with the MBI Berlin is in preparation. In the next stage the observed effects of optical feedback to the laser diode properties are compared and described by physical theory. To calculate the optical power injected into the laser diode emitters a comprehensive optical model will be elaborated. This will finally describe the coupling efficiency of the reflected light. Within the next months parts of the presented work will be published in peer-reviewed journals.

Based on the results of this work LIMO will be capable to integrate protection devices into laser diode systems. For this purpose knowledge of the damage threshold of the used laser diodes, influence of the optical components and application are necessary. This information will be derived from the next stage research and lead to a reliable operation of high power laser diode systems.

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