Chapter 1

Introduction

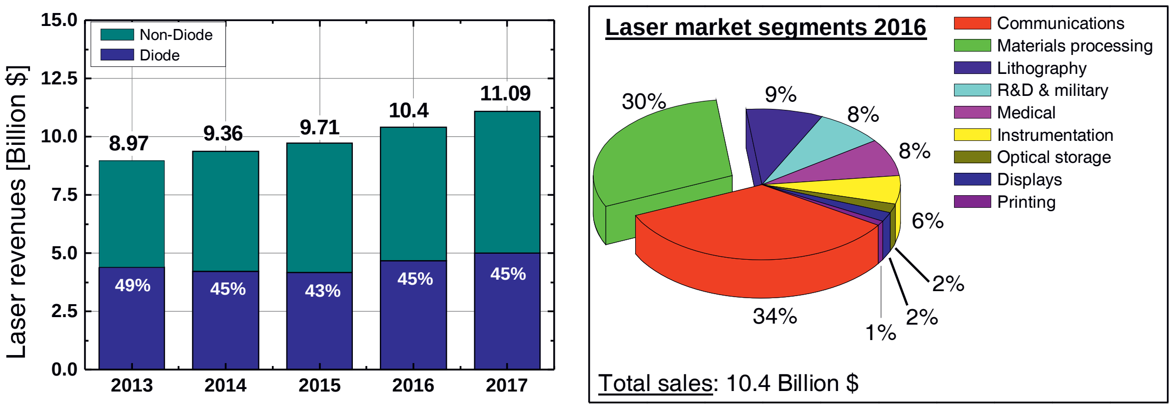
Throughout the last five decades, the semiconductor diode laser has developed into a technology of great importance to our modern society. In terms of performance, robustness and diversity, this field has experienced consistent progress, driven by academic and industrial research. Nowadays diode lasers find applications in fiber based telecommunications ('fast' internet connections), materials processing, surgery, gas- and ranging sensors and household electronics (e.g. blu ray player, laser printer). Moreover, their high reliability enables the use of diode lasers in places that are considered rather remote, e.g. in optical amplifiers in deep-sea cables, in communication units of satellites or in sensors of Mars exploration rovers.

The object of study in this doctoral thesis is the gallium-arsenide based, high power *broad area laser* (BAL), an opto-electronic device that had its advent in the early 1960s and has since developed into a key technology for laser based materials processing. Driven by an electric current, it produces laser emission in a wide range of available wavelengths $630\,\mathrm{nm} \leq \lambda \leq 1120\,\mathrm{nm}$, exhibiting long operational lifetime and high output powers at conversion efficiencies $> 60\%$. However, in terms of *beam quality*, the BAL performance is poor compared to competing laser systems such as the disk- or fiber lasers, limiting its usage in direct diode systems. Hence, motivated by a growing industry demand for efficient, high brightness laser sources, the focus in this work is placed on understanding the physical limitations to the BAL's beam quality.

This chapter starts with a motivation that includes an overview of the current laser market, followed by a comparison of state-of-the-art materials processing laser systems and a presentation of recent achievements in BAL performance. Afterwards, the methodology of this thesis will be presented and finally the contents of this thesis will be briefly summarized.

1.1 Motivation - High Power Diode Lasers in materials processing

Figure 1.1 illustrates the commercial relevance of diode lasers. In 2016, total diode laser revenues reached US \$ 4.68 billion, which is 45% of the entire laser market. Moreover, figure 1.1(a) shows that the laser market has been expanding at an average growth rate of 5% p.a. within the last 3 years and the market share for diode lasers is relatively stable at $\approx$ 45.5%. The origin of this strong industry demand for diode lasers lies in a variety of beneficial properties, most notably compactness, easy integration into electronic circuits, wavelength tunability and reliability.



(a) Laser sales and 2017 forecast.

(b) The laser marketplace in 2016.

Figure 1.1: Current status of the international laser market, data taken from [1]. Left: Total laser revenues in billion US \$ of the past 4 years and forecast for 2017 shows a growing market (average growth rate of 5% p.a. in the last 3 years). The share of diode lasers on the whole market is stable at $\approx$ 45.5% (4-year average). Right: Illustration of the laser market segments shows 34% of the laser revenues in 2016 belongs to the communications sector and another 30% to materials processing. All other laser industries share the remaining 36%.

The pie chart in figure 1.1(b) shows that among the laser market segments in 2016, materials processing is the second largest industry with 30% market share, closely following the communications sector (34%).

Figure 1.2 also shows that sheet metal cutting is the most widespread application in laser based materials processing, with a lion's share of 36% of the laser revenues in that field. Now, in materials processing in general, but especially in sheet metal cutting, the high power broad area laser has an important function as building block for the laser systems that are used here.

BALs show output powers in continuous wave (cw) mode of $P_{opt} > 20\,\mathrm{W}$ and peak power conversion efficiencies of $\eta_c \approx 70\%$. In addition, the assembly in a wafer fab allows low-cost mass production, enabling a significant reduction of the purchase price in terms of US \$

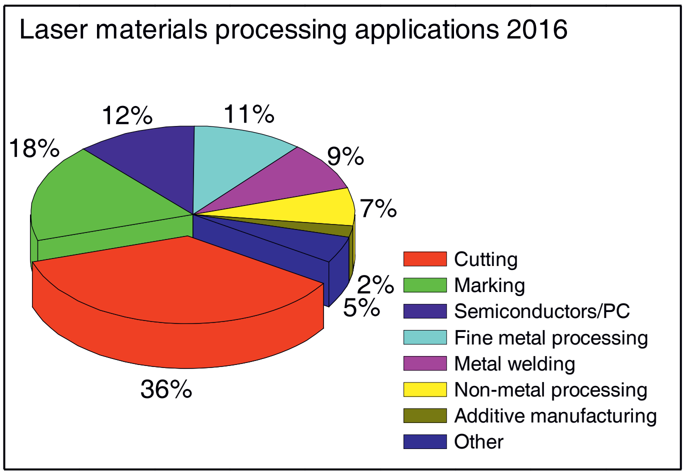


Figure 1.2: The materials processing field divided into relevant applications [1].

per watt of useful optical power (industry measure '\$/W'). This makes the BAL the ideal supplier of pump light for solid-state laser systems, e.g. Yb/Nd:YAG-, disk- and fiber lasers, which are used for deep penetration welding and sheet metal cutting. The latter two applications demand very high power densities of laser radiation, parameterized via the *radiance* $B = P_{opt}/\pi^2 \cdot BPP^2$. This is the formula for rotationally symmetric beams, the definition of B will be introduced in detail in section 2.1.4. For sufficient radiance B, high output powers in the kW-range and more importantly a low *beam parameter product* ('BPP' = beam waist radius $\times$ half divergence angle, cf. equation 2.7 in section 2.1.4) are needed.

Disk- and fiber lasers reach sufficient power densities for sheet metal cutting and, due to the efficient BAL pumping, their wall-plug efficiency ($\eta_{wp} \approx 30\%$) easily exceeds that of CO_2-lasers ($\eta_{wp} \approx 12\%$). However, since the energy delivered to the workpiece is converted in two steps, from electrical energy to pump light and then to 'high-beam-quality' (i.e. low BPP) light, the wall-plug efficiency of these systems is still low compared to *direct diode systems*. The latter reach wall-plug efficiencies $\eta_{wp} > 40\%$ [2] and power levels in the kW-range through beam combination of multiple BALs in fiber-coupled modules, using polarization- and wavelength multiplexing techniques. However, their radiance is too low for use in sheet metal cutting, due to their high beam parameter product.

This problem is illustrated in figure 1.3, where the required laser beam properties of common applications in materials processing are marked in a BPP vs. output power map. Here, the radiance increases from the top left corner to the bottom right corner.

The performance of diode laser systems is shown as an orange line and all accessible applications are depicted in light-grey. Today, direct diode systems with 8 kW optical output power and BPP of 7 mm mrad are commercially available (cf. table 1.1). However, as indicated by the slope of the orange line, high output powers can only be reached at the cost of high BPP. Hence, fiber lasers (1 kW at 0.37 mm mrad, blue rectangle) and disk lasers (8 kW at 4 mm mrad, yellow dots) still prevail in the lucrative markets for sheet metal cutting and deep welding.

The origin of the radiance deficit in direct diode systems is the lateral (slow-axis) beam quality of broad area lasers. In the lateral direction, the emission is multi-moded and far away from diffraction limited, such that the focus spot is too large to allow coupling into low-NA fibers.

The increased slow-axis BPP in broad area lasers reveals the motivation of this doctoral thesis. A more detailed understanding of the physical limitations and contributing effects to this problem is necessary. Hence, the main objective of this thesis is a root cause analysis that seeks to identify the most influential effects on the BALs beam parameter product. Ideally, the broadened knowledge from this investigation can be used to suggest sophisticated lateral laser designs that will improve the BALs beam quality without compromising output power, efficiency and reliability. This will enable a higher radiance for energy-efficient direct diode systems, which are in strong demand in the materials processing sector.

In order to gain a more detailed picture of the current status of industrial laser systems and BAL performance, a state-of-the-art overview will be presented in the following section.

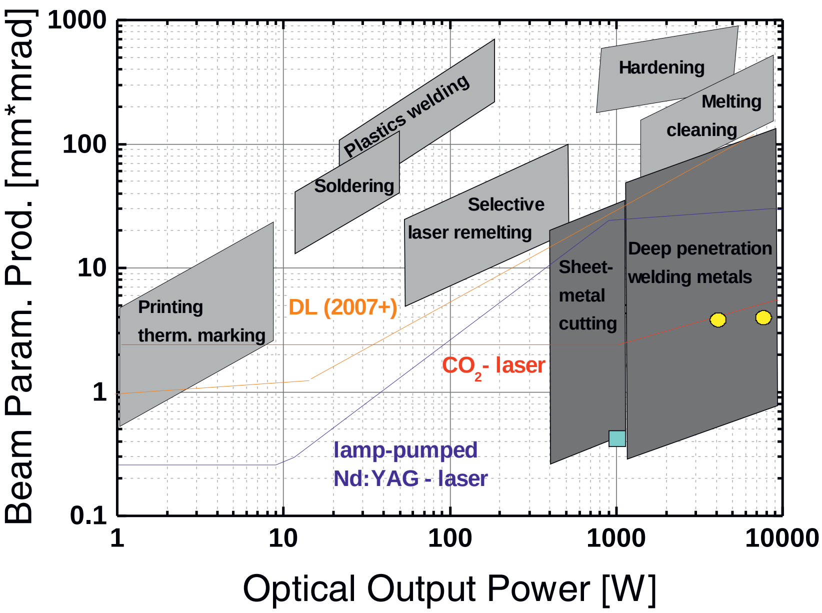


Figure 1.3: Materials processing laser 'roadmap', adapted from [3]. Beam parameter product (BPP) plotted versus optical output power in double-logarithmic scale. The laser source radiance B increases at higher powers and reduced BPP. Relevant laser applications and performance of different laser species are noted. Today the highest radiance is achieved by disk lasers (Trumpf 'TruDisk' series, yellow dots) and fiber lasers (IPG 'YLR-1000WC', blue rectangle).

A list of commercially available laser systems for materials processing is shown in table 1.1, ordered in descending values of linear radiance $B_{lin} = P_{opt}/BPP$. As already illustrated in figure 1.3, direct diode systems - though very efficient - exhibit inferior beam quality, i.e. they reach high output powers only at cost of a high beam parameter product. Hence, most of these systems occur at the end of the list. At the top, however, fiber-, CO_2- and disk lasers show a linear radiance $B_{lin} \geq 2\,\mathrm{kW\,mm^{-1}\,mrad^{-1}}$.

$\mathbf{B_{lin}}$ [*]	$\mathbf{P_{opt}}$ [kW]	**BPP** [mm mrad]	$\boldsymbol{\lambda}$ [µm]	$\boldsymbol{\eta_c}$	**type**	**vendor/product**
2.7	1	0.37	1.07	0.31**	Yb fiber	IPG YLR-1000WC
2.3	8	3.5	10.6	-	CO_2	Rofin DC series
2	16	8	1.03	>0.3	Yb:YAG disk	Trumpf TruDisk 16002
1.6	10	6.2	10.6	0.15	CO_2	Trumpf TruFlow 10000
1.1	8	7	0.97	-	direct diode	Teradiode
1	8	8	1.07	0.4	Yb fiber	IPG YLS-CUT
0.18	11	60	0.9-1.07	0.36**	direct diode	Laserline LDF series
0.15	1.5	10	0.976	0.33**	direct diode	IPG DLR-976-1500
0.13	4	30	0.92-1.04	0.42	direct diode	Trumpf TruDiode4006

Table 1.1: Commercially available industry laser systems for materials processing, listed in descending linear radiance $B_{lin} = P_{opt}/BPP$, measured in (*) $\mathrm{kW\,mm^{-1}\,mrad^{-1}}$. Data taken from online product catalogs (03/2017).(**) efficiency calculated based on noted power consumption. (-) Data not available.

Since the main objective of this thesis is the broad area laser, a look at the current status of BAL performance in the 9xx nm wavelength range is worthwhile. Here, two lists are presented: The first (cf. table 1.2) shows an overview of commercially available broad area lasers and laser bars, respectively. The second list (cf. table 1.3) shows the latest research results in the high brightness diode laser field. It should be noted that both lists do not claim completeness. In addition, the supply of information is quite different among research groups and diode laser vendors. Hence, not all parameters are available for all of the listed devices.

In comparison to the B_{lin}-values for direct diode systems listed in table 1.1, the radiance of single emitters is reduced by approximately two orders of magnitude. The radiance up-scaling in direct diode systems is usually done by dense and coarse wavelength beam combining (WBC) as well as polarization multiplexing. The latter ideally increases the radiance by a factor of x2, while WBC scales the radiance with the number of wavelength channels N_λ and an efficiency factor f_{WBC} [4]. However, since the BAL is the basic element

$\mathbf{B_{lin}}$ [*]	$\mathbf{P_{opt}}$ [W]	$\mathbf{BPP_{lat}}$ [mm mrad]	**w** [µm]	$\mathbf{\Theta}$ [°]	$\boldsymbol{\eta_c}$	**comment**	**vendor**
3.5	11	3.14	90	8	>0.55	FWHM, 975 nm	II-VI
2.6	8**	3.05	100	7	0.65	95% p.c., 980 nm	Osram OS
1.4	4.2**	3.05	100	7	0.62	95% p.c., 938 nm	JDL
1.3	4.2**	3.14	90	8	-	FWHM, 975 nm	coherent

Table 1.2: Commercially available 9xx nm broad area emitters and laser bars, listed in descending linear radiance $B_{lin} = P_{opt}/BPP_{lat}$, measured in (*) $\mathrm{W\,mm^{-1}\,mrad^{-1}}$. Data taken from online product catalogs (03/2017).(**) Power per emitter in laser bar. (-) Data not available.

of a direct diode system, the overall radiance is increased with improved BAL radiance. The brightest commercially available diode laser emitters reach 2-3.5 $\mathrm{W\,mm^{-1}\,mrad^{-1}}$. In terms of conversion efficiency, these emitters reach values $\eta_c > 60\%$, indicating that a considerable amount of useful output power is lost in direct diode beam combining systems where $\eta_c \approx 40\%$.

$\mathbf{B_{lin}}$ [*]	$\mathbf{P_{opt}}$ [W]	$\mathbf{BPP_{lat}}$ [mm mrad]	**w** [µm]	$\mathbf{\Theta}$ [°]	$\boldsymbol{\eta_c}$	**comment**	**reference**
4.8	-	-	-	-	-	press release	OSRAM [5]
4.4	11	2.5	90	7	0.45	960 nm AWL-BAL	this work
4.3	13	3	-	7	0.63	9xx nm	nLight [6]
3.5	7	2	90	7	0.53	95% p.c., 969 nm	this work, [7]
3.2	8	2.5	-	-	-	9xx nm	Eckstein [8]
3.15	10.4**	3.3	100	7	0.69	95% p.c., 976 nm	OSRAM [9]
2.8	11**	4	90	10.2	0.69	95% p.c., 915 nm	JDL [10]

Table 1.3: Recent development in 9xx nm BALs/laser bars, listed in descending linear radiance $B_{lin} = P_{opt}/BPP_{lat}$, measured in (*) $\mathrm{W\,mm^{-1}\,mrad^{-1}}$. (**) Power per emitter in laser bar. (-) Data not available.

The results of recent research activities are presented in table 1.3, showing a considerable increase in BAL radiance compared to commercially available standards. The last two entries are results from 5-emitter minibars, showing very high conversion efficiencies of $\eta_c = 69\%$. Two results were obtained in the course of this doctoral thesis. First, deeply implanted $w = 90\,\mu\mathrm{m}$ BALs with suppressed lateral carrier accumulation show a linear radiance of $B_{lin} = 3.5\,\mathrm{W\,mm^{-1}\,mrad^{-1}}$ at $P_{opt} = 7\,\mathrm{W}$ (cf. section 3.4). Secondly, BALs with a lateral mode filter ('*anti-waveguide*' layer, AWL) reach $B_{lin} = 4.4\,\mathrm{W\,mm^{-1}\,mrad^{-1}}$ at $P_{opt} = 11\,\mathrm{W}$ (cf. section 4.2). However, both improvements compromise the power conversion efficiency, leaving space for optimization.

1.2 Method - Root cause analysis

The usual way to expand the knowledge on an object of study is a stepwise progress that contains the creation of a (simplified) model of the interaction of physical parameters, the implementation of this model in simulations and the subsequent comparison of predicted outcomes to measurements. However, in broad area lasers a complex interaction of the many internal parameters (refractive index, temperature, carrier density, gain, electric field, material strain etc.) exacerbates thorough device simulation, such that different models can lead to consistency with the measured data and no clear answer on the limiting effects can be given. Hence, the focus is shifted to experimental methods that aim for increased device performance (PDCA-cycling) and on understanding of the underlying effects (root-cause-analysis).

The main progress in diode laser technology is based on a simple iteration-cycle:

- **P**lan: Develop laser design on basis of present knowledge
- **D**o: Device fabrication in wafer fab (lithography, etching etc.)
- **C**heck: Characterization of multiple emitters in parameter-matrices
- **A**ct: Feedback to laser design and fabrication chain.

This PDCA-cycle is industry standard and appropriate to improve existing technologies by repeating the iterations until a performance goal is reached. However, in the well established diode laser technology, where the learning curve saturates, the PDCA-cycle is often insufficient to reach the desired performance. Due to the complex and comprehensive fabrication process many potential influences arise. Hence, it is more and more difficult to achieve reproducibility and to correlate incremental changes in laser performance to specific design measures.

Furthermore, a PDCA cycle does not necessarily yield results that provide more *understanding* of the underlying effects. But for a further technology improvement, this understanding is crucial! It makes it possible to estimate fundamental limits of important laser properties and enables the development of more accurate simulation-tools. In this way, new strategies for improved laser designs can be deduced that - ideally - exceed the progress made with PDCA-cycling.

Hence, in this thesis an alternative approach is adopted: the *root cause analysis*. Therein, based on the available knowledge, a list of potentially important effects is generated. Then an experiment is designed, such that each effect is isolated (if possible) in order to assess its contribution to the figure of interest. In this thesis, the BALs are designed to differ in only one property that is suspected to influence the lateral beam quality. In this way, 'diagnostic' series of laser devices are produced that give insights into the relative contributions of different limiting effects.

It should be noted that PDCA-cycling and root cause analysis are not competing strategies. On the contrary: they complement each other, so that progress in laser device performance can be reached faster. The root cause analysis answers the question '*What should we focus on?*', addressing device physics to identify limiting effects, while PDCA-cycling is inevitable to get the 'fine-tuning' of the relevant parameters, i.e. reaching the best performance based on the known limits.

1.3 Structure of this work

This doctoral thesis is divided into four main chapters that contain the following information:

In chapter 2, the theoretical background for the understanding of the results is provided. A brief introduction to the topic is followed by a revision of the basic characteristics of modern high power broad area lasers. The figures of *beam quality* and *radiance* are introduced and the problem of slow-axis beam quality degradation is outlined. Furthermore the most important techniques used are explained briefly, including the simulation of lateral modes in a thermal waveguide and the processing technique of ion implantation. Finally the measurement equipment and its accuracy will be presented.

The above mentioned root cause analysis is the core of this thesis and is presented in chapter 3, starting with a listing of all effects that are anticipated to influence the BAL's lateral beam quality. Next, a simple empirical model of BPP growth with the (local) active zone temperature is introduced, enabling the comparison of BALs with different thermal resistance and conversion efficiency. The following three main sections contain the results of diagnostic studies on BALs that focus on: the vertical design and its correlation to the thermal lens, process- and packaging induced effects on the BPP and the degree of polarization and the influence of the lateral carrier/gain profile. At the end of chapter 3, the most important findings are summarized and strategies for improved lateral beam quality are proposed.

Chapter 4 contains further results of experiments that are explicitly aimed at reducing the number of lateral modes. While in chapter 3 the BAL stripe width is fixed at $w = 90\,\mu\text{m}$, the first section in chapter 4 assesses changes in the behavior of BALs as function of stripe width. Here, the focus is on output power, efficiency, lateral beam quality and radiance as a function of injection stripe width. In the second section, the results of a lateral mode filter approach are presented. The so-called '*anti-waveguide*' generates high losses for modes with large lateral extent via a neighboring waveguide structure that is congruent to the central vertical laser waveguide but possesses a thin layer with strong optical absorption.

Finally, chapter 5 contains a summary of the most important observations in this thesis and a discussion of their generic validity. Furthermore, an outlook on possible further efforts for radiance enhancement in broad area lasers will be given.