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Introduction

1.1 Motivation

High power diode lasers have helped to push laser technology to a new state of the art in modern industry. High power laser systems have many advantages over the lamp and gas discharge light sources in terms of optical power, electrical-to-optical conversion efficiency, and reliability [4]. Those advantages and ongoing performance scaling are mainly achieved by the substantial improvement in GaAs device technology and the epitaxial growth process of the III-V material system [4]. Due to the continuous improvement in diode laser technology and low-cost mass production, they have been widely used in direct diode applications for material processing, such as metal sheet cutting, soldering, drilling, and welding [4, 2]. In addition, diode lasers are a very effective pumping source due to their narrow spectral linewidth and, therefore, are widely used as pumps for solid-state laser systems. The pumping level of a solid-state laser (e.g., Yb: YAG) typically has a narrow absorption spectrum and this can be exactly matched with the diode laser emission linewidth.

The main goal of the GaAs-based broad-area high power diode laser development is to continuously increase the output power, efficiency, and beam quality. However, the output power is limited by saturation processes at high bias due to various non-linear

effects [8]. This doctoral thesis aims to improve power and conversion efficiency and to better understand the saturation mechanisms that limit output power. The chapter starts by providing a brief overview of the laser market and then compares the current state of the art of diode lasers for material processing application systems. Finally, the content of each chapter will be summarized.

Fig. 1.1 presents the overview of the annual sales revenue from 2017 to 2020 of the diode and non-diode lasers. In 2020, the total diode laser revenue reached US \$16.01B, which is 42% of the total laser market. The recently published report by financial consultant MC Kinsey and Company projects an annual growth rate for the laser market of about 10% through 2025, increasing from US \$16.01B in 2020 to US \$28B in 2025 [9]. In 2020, the Material processing and lithography sector showed the highest sales revenue, approx. 39% of the total sale, followed by the communication and scientific research and military, instrumentation and sensors, medical and aesthetic and entertainment, display, and printing, shown in the pie chart in Fig. 1.1.

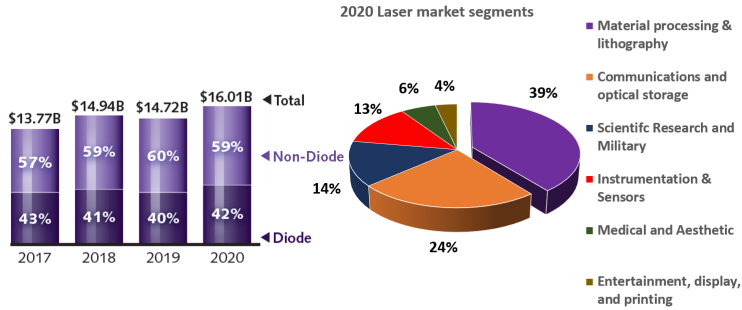


Figure 1.1: Laser focus world- Annual market review on sales and laser market segments. Published in 2021 [1]

The material processing market is divided into various applications, as illustrated in Fig. 1.2. Cutting, welding, and brazing account for approx. 51% of the total material processing related industrial laser application, with cutting being the dominant share [2]. These industrial applications require lasers with high power and high radiance (power

in a solid angle). To meet these requirements, diode-pumped solid-state laser systems, e.g., Yb: YAG-, fiber-, and disk lasers, are utilized due to their high beam quality. The demanding power and radiance requirements of these applications can be quantified using beam parameter product (BPP), which is defined as being the product of beam waist radius and half the divergence angle (further details in section 3.1.2). Fig. 1.2 (right side) illustrates the required range of BPP and optical output power for different laser applications in material processing. For example, for metal welding and cutting, the optical power level of approx. 1 kW optical power with a $BPP < 10$ mm.mrad is required as delivered by the diode.

In general, diode lasers are needed with low BPP and high power. However, it is challenging to maintain high optical power and lower BPP at the same time. The root cause of the increased BPP in broad area laser has already been studied in many earlier works [10, 11, 12]. This thesis aims, in contrast, to investigate the factors that limit power at high bias. Before delving into the investigation methods details, the following section provides an overview of the state of the art of high power broad area lasers.

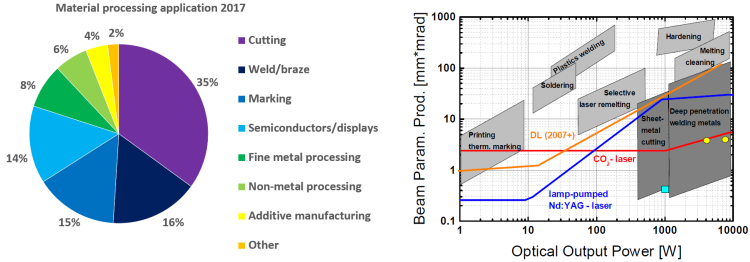


Figure 1.2: Left: market share of different industrial laser applications in material processing market. Right: the required power and beam parameter product, BPP for various applications [2]

1.2 Overview of state-of-the-art of broad area laser

A list of published single-emitter measurement results from established industries and research institutes is presented in Tab. 1.1. Since the main objective of this thesis is to optimize peak efficiency and to investigate the root cause of the power saturation at

high bias, a comparison of peak efficiency η_{peak} and peak saturation power P_{sat} (both marked in light gray color) of broad area diode laser will be beneficial.

η_{peak}	P_{opt} @ η_{peak}	P_{sat}	W	L	T_{HS}	λ	Reference
[%]	[W]	[W]	[μm]	[mm]	[$^{\circ}$]	[nm]	
70	4	17	90	4	-	940	Jenoptik 2012 [13]
67	5	22	100	4	25	915	Optoenergy 2017 [14]
72	6	18	100	4	25	975	IPG 2017 [15]
69	6	14	95	4	25	940	FBH 2019 [16]
64	5	13	100	4	25	940	Trumpf 2023 [17]
69	6	21	90	4	25	940	FBH 2023 [18]
85	7.5	-	200	1	-50	975	nLight 2006 [19]
74	8.8	-	200	4	-55	975	FBH 2013 [20]
74	9	25	220	4	25	976	Optoenergy 2020 [21]
66	12	28	220	5	25	976	Trumpf 2022 [22]
69	10.1	27	186	4	25	940	FBH 2023 [18]

Table 1.1: state of the art of published 915-975 nm single emitter results under continuous wave (CW) operation condition from research institutes and industries. Light gray column: values of interest for this thesis. W : stripe width, L : resonator length, T_{HS} : heat sink temperature, η_{peak} : peak conversion efficiency at maximum point, P_{opt} : optical power at peak conversion efficiency, P_{sat} : peak saturation power.

Optoenergy [14] reported a peak efficiency of 67% from a single emitter with a stripe width of 100 μm and a length of 4 mm, emitting at a wavelength of 915 nm. The single emitter utilizes an asymmetric vertical design with a confinement factor of 0.4%, effectively reducing optical loss and series resistance. This illustrates the importance of Extremely double asymmetric design (EDAS) like design.

In 2019, the Ferdinand-Braun-Institut (FBH) [16] published results for a similar device with a stripe width of 100 μm and a resonator length of 4 mm, achieving a peak efficiency of 69% using an extreme asymmetric vertical design by introducing an asymmetry near the quantum well. This particular vertical design features a high confinement factor Γ of 0.51% and higher barrier height ΔE , i.e. the energy difference between the first confined electron state in the QW and the band edge of the waveguide layer [23]. The higher barrier height prevents thermally activated carriers from escaping the QW, reducing leakage and resulting in low carrier loss and reduced thermal power saturation ($P_{\text{sat}} = 14$ W). Following [16, 24, 25], it is reported that the leakage caused

by thermally activated carrier escape from the QW can be eliminated by designing a vertical structure with an energy barrier of $\Delta E/k_{\text{B}}T > 10$, for $T = 25^\circ\text{C}$, where k_{B} is the Boltzmann constant.

Jenoptik [13] and IPG [15] also published notable results in terms of power conversion efficiency, with values of 70% and 72%, respectively. Additionally, they achieved high saturation power levels of 17 W and 18 W, respectively. The specific details of the vertical design employed by Jenoptik and IPG are not available in their respective papers. However, Jenoptik mentioned the use of a higher gain design with a modal gain prefactor $\Gamma G_0 = 11.6 \text{ cm}^{-1}$, where G_0 represents the material gain. The higher modal gain reduces the carrier density required to achieve threshold.

The performance of broad-area lasers can be further enhanced by reducing the operating temperature and using wider stripe widths. The Ferdinand-Braun-Institut (FBH) reported [20] a peak efficiency of 74% at 8.8 W power level, measured at an operating heat sink temperature -55°C , from a single emitter with a $200 \text{ }\mu\text{m}$ stripe width and a 4 mm resonator length, using designs tailored for -55°C operation. The fit to pulsed measurements of unmounted bars with various resonator lengths at low current (measured up to $\sim 2 \text{ A}$) shows that η_{i} increases from 86% to 96% and modal gain prefactor increases from 6.4 cm^{-1} to 9 cm^{-1} when changing the operating heatsink temperature from 25°C to -55°C . The improvement in the modal gain prefactor at lower temperatures is briefly discussed in the section 2.2.8. The improvement in internal efficiency and modal gain prefactor leads to higher peak efficiency. However, voltage is found to be a further limiting factor for peak efficiency with a high resistance tied to the QW, consistent with earlier studies [19].

Optoenergy [21] demonstrated a remarkable improvement in efficiency by using a stripe width of $220 \text{ }\mu\text{m}$ at operating heatsink temperature, $T_{\text{HS}} = 25^\circ\text{C}$. A Wider stripe width allows for a larger active area for current flow, reducing series and thermal resistance and resulting in higher power and efficiency under high-bias conditions. Their devices exhibited a peak conversion efficiency η_{peak} of 74% at a power level of 9 W and a saturation power level of 25 W. Trumpf [22] also reported results with wider stripe width, achieving output power levels up to 28 W without any saturation. The most recent results from the Ferdinand-Braun-Institut [18] demonstrated a peak efficiency η_{peak} of 69% and a saturation power P_{sat} of 27 W using a resonator length of 4 mm and a stripe width of $186 \text{ }\mu\text{m}$. These results were achieved by employing an extremely asymmetric vertical design.

To summarize, the highly vertically asymmetric design, with high $10k_{\text{B}}T$ barriers and confinement $\Gamma \sim 0.4\ldots 0.5\%$ delivers peak efficiency $\eta_{\text{E}} \sim 70\% \pm 3\ldots 4\%$ [14, 16]. The best peak saturation power P_{sat} remains $\sim 18\ldots 22$ W from $100\text{ }\mu\text{m}$ stripe width devices [15, 18, 14]. Wider stripes enable high powers, reaching up to 28 W. Low temperature artificially increases the modal gain prefactor ΓG_0 , leading to increased peak η_{E} , upto to 85% [19, 20]. Nevertheless, voltage increases significantly, which is suggested to be associated with the QW [20]. Higher gain vertical designs with confinement up to $\Gamma \sim 0.8\%$ increase the power due to the overall lower carrier density at 25°C [16, 14].

The main limiting factors to increase the power and peak efficiency are found to be the voltage, threshold current, and slope. The main component contributing to the overall voltage includes the voltage drop resulting from the band gap, defects, bulk resistance, and effects associated with the Quantum well (QW) [24, 26]. The threshold current is influenced by lateral leakage, spontaneous emission, and non-radiative recombination rate [26, 27]. The slope is affected by optical losses and internal efficiency. The optical losses originate from the bulk layers and QW, while the internal efficiency is dependent on factors such as leakage, carrier loss, and non-stimulated recombination (spontaneous emission, Auger, Shockley-Red-Hall recombination) [16, 26]. Power saturates at high bias due to thermal or non-thermal effects. The power saturation can be described by the impact and consequences of the increased number of carrier density in the quantum well. The active zone temperature of a diode laser increases with high bias in continuous wave (CW) operation, leading to reduced gain. Therefore, high carrier density in the quantum well is needed to reach the threshold, increasing the threshold current density. The increased carrier density accelerates the rates of the spontaneous emission and non-radiative recombination process in quantum well as well as the carrier leakage and as a result, the laser exhibits thermal power saturation [28, 16]. The thermal contribution on power saturation mechanisms can be determined by characteristic temperatures T_0 and T_1 . In addition to those loss processes, high bias introduces various non-linear effects - two-photon absorption losses, longitudinal spatial hole burning, and additional bias-driven leakage. Bias-driven leakage is due to the carrier accumulation outside of the QW at high bias. The band edge bends due to the high voltage drop across the low mobility p-side. Therefore, the difference between the conduction band edge and the quasi-Fermi level of electrons reduces, leading to enhanced electron accumulation at the p-side. This accumulation of carriers results in the higher carrier and photon loss [29, 30, 31, 32]. Those thermal

and bias-driven saturation effects increase the laser threshold, decrease the slope and efficiency, and limit the power at high bias. Furthermore, series resistance increases with increasing barrier height of quantum well at low temperature, limiting the efficiency, and the actual reason is not clear so far but can be explained by inefficient carrier transport into quantum well [20]. The limitations of carrier transport in the QWs due to the capture and escape processes have been well-established [33, 34]. Their consequences have primarily been explored in relation to modulation properties [35, 36, 37, 38] and power-current characteristics [39]. However, the impact of capture-escape on the series resistance has not been addressed yet.

Based on the above discussion, it can be argued that modal gain and carrier transport mechanisms play an important role in understanding power saturation mechanisms. In this thesis work, further study is conducted to comprehend the impact of high modal gain on power saturation. Some parts of the results regarding the impact of the high modal gain on the threshold and longitudinal effects have already been presented in Boni et al., *27th International Semiconductor Laser Conference (ISLC)*, 2021 [40]. Moreover, a comprehensive investigation is carried out to understand the impact of QW on series resistance and power. Some findings regarding the impact of capture time on series resistance and power saturation have been previously published in Boni et al., *Semiconductor Science and Technology* 35(8), pp. 085032, 2020 and Boni et al., *Physica Scripta* 98(3), pp. 035017, 2023 [41], respectively.

1.3 Method and structure of this thesis

The method employed in this work is as follows. First, based on the available knowledge, the best compromise in the vertical design and lateral design is determined to achieve high efficiency and high beam quality. Then, a list of potential effects is identified for detailed investigation. After that, simulation and experimental tasks are designed to isolate those effects as much as possible to understand their impact on the desired output parameter. While isolating the effects in simulation can be easily confirmed, however, in experiments, it is quite challenging. The acquired knowledge from the simulation is then applied to the vertical designs, which are subsequently epitaxially grown, followed by a cost-effective and fast short-loop process. This process verifies whether the simulation expectations align with experimental results and assesses the growth quality. The short loop measurement process and techniques are described in

section 2.4. Any disagreements between the experiment and simulation results are addressed through further analysis and the initiation of new simulation tasks. It is important to note that some disagreements may be justified by limitations inherent in the simulation model (not all effects included) and measurement accuracy. If the short loop process yields positive results, an unprocessed copy of the wafer undergoes a full process, followed by passivation, facet coating, and mounting. The resulting devices are then characterized in detail under various operating conditions. This entire procedure constitutes an iteration, and in the context of this thesis, four iterations have been performed.

The structure of this thesis is organized as follows. Chapter 2 provides a theoretical background of broad-area lasers. It encompasses a mathematical framework, including the simulation model, to facilitate an understanding of the simulation results. The most important parameters that affect the laser output performance and need to be optimized are introduced. Finally, the measurement process and characterization techniques are presented.

Chapter 3 involves the vertical design improvement for higher power and efficiency by focusing on modal gain variation. The first part of the chapter introduces two low modal gain vertical designs, one symmetric and the other asymmetric, as examples of best design practice, as orientation, and investigates their effects on power saturation and beam quality. The second part presents a series of asymmetric vertical designs with varying modal gain to diagnose power saturation mechanisms. The diagnosis of the results is focused on: the high modal gain designs and their impact on threshold current and their sensitivity to reflectivity and longitudinal effects, their impact on temperature sensitivity and the thermal power saturation, and loss mechanisms. In the end, a summary with the most important findings is presented.

Chapter 4 contains the diagnosis and analysis of carrier transport-capture effects on power and efficiency. The first part investigates the impact on series resistance through detailed simulation of a series of devices that are designed for this diagnosis. The impact of capture effects on series resistance is explored by studying how series resistance varies with injection current, temperature, and barrier height, allowing an effective capture time to be determined. The second part of this chapter focuses on the impact of capture effects on power, identifying a new form of bias-induced power saturation. The objective here is to understand the optical and carrier losses associated with capture effects, which ultimately limit the output power at high bias.

Finally, Chapter 5 summarizes the most important findings and observations presented throughout this thesis. Additionally, an outlook is provided for further advancements in improving the power and efficiency of broad-area lasers.

