1 Introduction

The history of modern diode lasers traces back to the inference of the existence of a stimulated recombination process in 1916, that was needed to reproduce Planck's law of radiation [1]. Despite of the awareness that a population inversion in a solid state crystal would enable **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation (LASER), the experimental proof of concept was realized for the first time in 1954 in the microwave range [2]. The power levels were in the nano-Watt range, but with a previously unseen spectral purity. Technical developments based on this discovery led in the year 1960 to the first laser, a flash-lamp pumped solid-state ruby crystal that emitted in the visible wavelength range [3].

Only two years later in the year 1962, the first coherent laser emission from a GaAs-based diode laser was reported [4]. The invention of the double-heterostructure [5] enabled the first **C**ontinuous **W**ave (CW)-driven diode laser to be developed in 1969 [6], operated at room-temperature. In this approach, effective carrier confinement is achieved in an active region that is formed by a low energy band gap material, such as GaAs. A wider band gap material, such as AlGaAs, is embedding the active layer to form optical waveguide and cladding layers to confine the optical wave. Furthermore, strained quantum wells as active regions were introduced [7] to further reduce laser threshold, improve carrier confinement and extent the usable wavelength range. The high commercial potential of laser emission lead to subsequent improvements of laser performance, efficiency, tunability, modulability, material quality, reliability and suitability for mass production. Nowadays, laser technology is a key component of our every day life. For example many industrial branches include lasers in their production chain, where they are used for cutting, welding, brazing, marking, hardening/repairing or 3D metal printing. Lasers are also used for data processing, data storage, material characterization, skin and eye treatment, **LI**ght **D**etection **A**nd **R**anging (LIDAR), sensors, spectroscopy, fundamental research, entertainment and lighting, lithography, micro processing and military defense applications. The steadily increasing demand implies strong industrial competition and a constant extension of the application range. This work focuses on high power diode lasers for material processing applications, specifically, for use as optical pumps for Yb:YAG based thin-disk lasers and therefore operate at a wavelength around 935 nm.

Since ever higher power levels are sought by industry and a high wall-plug efficiency of a laser machine tool for low operation costs (€/Watt) is one of the most important purchase criterions, huge effort is taken to understand what ultimately limits power and efficiency. Even in devices using sophisticated epitaxial designs, power saturation is still observed and the root-cause remains subject of active research. Power saturation mechanisms are highly controversially discussed in present literature, as the relative impact changes with device configuration, optical power level, operating current and temperature. To name a few examples, it is claimed in [8] that the optical loss in the waveguide dominates power saturation, considering a diode laser using a bulk active region. It is shown theoretically in [9] that **T**wo-**P**hoton-**A**bsorption (TPA) and the resulting free-carrier absorption (secondary TPA) has strong impact on power saturation in devices using asymmetric waveguides that are driven at high optical pulsed powers. In [10] **G**ain **C**ompression (GC) is proposed as the overall dominating factor for BA lasers driven at high optical pulsed powers. In [11–14], carrier leakage and accumulation in the waveguide significantly reduce power and efficiency in devices using conventional symmetric waveguides.

The overlap of these mechanisms at high power levels and temperatures leads to a high level of complexity. A detailed bias and temperature dependent analysis of carrier and photon loss mechanisms is required to understand power saturation, which is therefore investigated in this work both experimentally and numerically. The above mentioned fundamental power and efficiency limiting mechanisms inside the semiconductor can be adressed by vertical epitaxial design, provided epitaxy and processing is performed to a high standard. The vertical epitaxial design allows to flexibly tailor the optical mode profile, which in turn regulates the modal overlap with the active region, termed as optical confinement. The modal gain, Γg_0, increases linearly with the optical confinement factor, Γ, provided a fixed configuration of the active region and therefore a fixed differential gain factor, g_0. Carrier loss rate increases with carrier density and the modal gain regulates the carrier density in the active region, the band and doping profile the carrier density in the waveguide [14–16]. The shape of the optical mode has influence on the photon density for a given optical power level, which in turn has impact on non-linear optical loss mechanisms, as three-particle processes get more probable (TPA) and spectral depletion of carriers is stronger (GC) [9, 10]. Furthermore, a high carrier density increases free carrier absorption loss [17]. Hence, varying the optical confinement by vertical design is an ideal instrument for the diagnosis of carrier and photon loss mechanisms.

This work uses variations in epitaxial device design to enable the diagnosis, identification and mitigation of the dominating power limiting mechanisms. The novel design seeks to change optical confinement by implementing only minor structural changes in the vertical layer stack. For improved power and efficiency at high optical power levels the design needs to feature a low series resistance, low optical loss, high optical confinement, suppressed electron leakage currents into the p-waveguide, a high energy barrier between active region and waveguide to suppress thermal spill-over and low rollover in the light-current characteristics. The claim is to develop a method to improve the short comings of present high power diode lasers by adressing these fundamental power limitations via epitaxial design.

1.1 Structure and method of this work

This work is structured as follows. After motivating this work by emphasizing the industrial demand and the market context, the bigger picture about laser technology and their applications is presented, with a focus on thin-disk solid state and **B**road **A**rea (BA) diode lasers. An overview of the fabrication and processing steps of BA diode lasers is provided, from epitaxy to the finished device. The mathematical framework is presented, which is necessary to perform the simulations and calculations of this work. As this approach targets to optimize a certain set of parameters that characterize laser performance, the most essential parameters of BA diode laser are introduced, connected to a method that allows experimental access to those. An overview is given about the simulation tools applied, the various devices tested and the measurement setups used. A review of the prior state of the art is presented, considering both knowledge about existent power and efficiency limiting mechanisms and published performance data of BA diode lasers in single emitter and bar configuration. Based on that the target specifications are drawn. At this point, the novel epitaxial design concept that is used for diagnosis and mitigation of power and efficiency limiting mechanisms, is introduced and differentiated from prior epitaxial designs. In the main section, a diagnosis and analysis of the realized series of devices that use the novel epitaxial design concept is presented. A root-cause analysis of a wide range of carrier and photon loss mechanisms is presented, narrowing down the dominant factors that ultimately limit power and efficiency in the devices presented. Applying these new insights led to devices with improved performance, which are presented in the context of prior state of the art devices. A short-term perspective for further improved performance is given, following the same approach but with optimized parameters. Finally a summary, conclusion and outlook is presented in order to motivate future possibilities for improvements and understanding of BA diode lasers, based on the insights from and the progress made in the underlying studies.

The method of this work is as follows. An iterative device design optimization process is performed for a controled step-by-step improvement of the device. After studies of the prior state of the art and benchmark devices, the first step is to create a working thesis. This may include ideas and anticipations, based on previous experiences or published loss mechanisms, that might apply in the device configuration investigated here. A precise thesis is formulated about which change in the device potentially leads to the desired outcome. After defining the thesis, comprehensive device simulations are performed to define the specific device configuration that leads to the optimal target parameter. This device configuration is then delivered to the epitaxy department for crystal growth, followed by a short-loop process that enables fast and cost-efficient testing of the processed wafers, using a four-probe method to characterize slope efficiency, laser threshold, wavelength and the characteristic temperature, T_0. Details about the process and measurement setups are given in section 2.2.2 and 2.6. If this first quality check is successful, it can be proceeded with facet coating, packaging and standard tests to receive a first full power-voltage-current (PUI) characteristics and spectral data, measured at moderate currents as chips are not passivated at this stage. If the devices meet the expectations and deliver the expected improvements as simulated, another unprocessed copy of that wafer goes into a full process, followed by passivation, facet coating and packaging. This time the devices can be measured up to high currents and deliver data that is comparable with benchmark designs. The experimental data is to be analyzed, the initial thesis to be evaluated (confirmed or discarded) and next steps to be defined. This whole procedure describes one iteration, which always provides a subsequent follow-up thesis to initiate the next iteration. Thesis making, short-loop processes, full processes, simulations, analysis and measurements overlap during the whole procedure. Within this dissertation, three iterations were performed.

2 Fundamentals

This chapter provides the background knowledge needed to put this work into context. It starts with an overview of the laser technology market, in particular for solid state lasers and diode lasers. A brief comparison of various diode lasers and different laser systems for material processing applications is given. Broad area diode lasers used as optical pumps in thin-disk-laser systems are the key elements of this work and therefore are discussed in more detail. A summary of the most important fabrication steps, from epitaxy to mounting, is given. Furthermore, a detailed mathematical framework is presented, containing a description of all numerical models used for the simulations. Finally, the measurement setups, simulation details, device configurations and the scientific method are described.

2.1 Laser technology and market context

An overview of the commercially available laser systems for material processing applications and the market context of this research is presented here. The diode lasers in this work are specifically designed for optical pumps for Yb:YAG based thin-disk lasers. A brief overview on the technical aspects of this special kind of solid-state laser is given, focusing on the requirements for the pump diodes. Different semiconductor laser types are introduced here and compared with broad area diode lasers. This section details why GaAs based high power broad area diode lasers are the most suitable semiconductor devices for

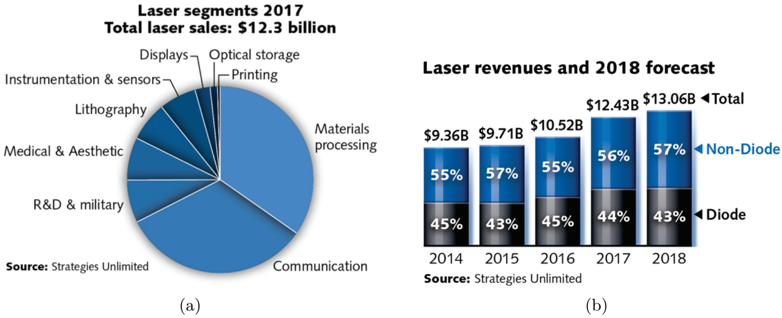


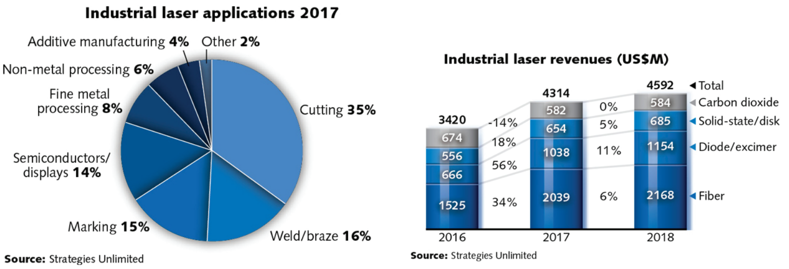
Figure 2.1: Laser Focus World - Annual Laser Market Review & Forecast, 2018 [18].

thin-disk laser pumping.

The material processing and communication sectors are with a big distance the strongest markets for lasers (see Fig. 2.1). In the year 2017 [18], the materials processing sector has taken the leadership in the category of total laser sales with approximately one third of the total revenue, as shown in Fig. 2.1a. In contrast, in 2016 [19] the communication sector was slightly stronger. They are followed by R&D & military, medical & asthetics, lithography, sensors and entertainment&storage media in descending order but in approximately similar parts. To date, diode lasers account for about 43% of the total revenue in the laser industry, as shown in Fig. 2.1b. The graphic also shows the steadily growing annual revenue, in the year 2017 sales reach a total of 13.06 billion USD.

2.1.1 Laser systems for material processing

Material processing is the strongest sector in the laser industry. As seen in Fig. 2.2a, fields of application are in descending order cutting, welding & brazing, marking, displaying, fine metal processing, non-metal processing, additive manufacturing and others. Cutting applications alone account for over one third of the total industrial laser applications. The applications with the the highest demand for maximized output power and efficiency (cutting, welding and brazing) own 51% of the material processing market. These high-power applications are dominated by a few types of lasers, specifically by solid state lasers, fiber lasers, gas lasers and direct-diode laser systems. As seen in Fig. 2.2b, CO_2-lasers are still widely used, but overall sales decrease strongly due in part to the less competitive conversion efficiency of typically 15-20% . The strongest growth in revenue is accounted by diode lasers. As diode lasers become more efficient and brilliant over time, direct-diode



(a) (b)

Figure 2.2: Laser Focus World - Annual Laser Market Review & Forecast, 2018 [18].

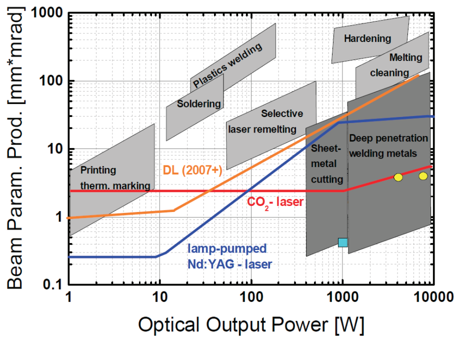


Figure 2.3: Requirements of certain industrial laser applications on beam parameter product, BPP, and optical output power [20].

applications become more attractive. High diode laser performance also facilitates growth in sales of **D**iode **P**umped **S**olid **S**tate **L**asers (DPSSL) like thin-disk lasers, whose cost and performance subsequently also improves.

The possible applications of a laser system depend on its optical power level and beam quality, which can be described by the beam parameter product

$$BPP = \varphi \cdot w_0 \tag{2.1}$$

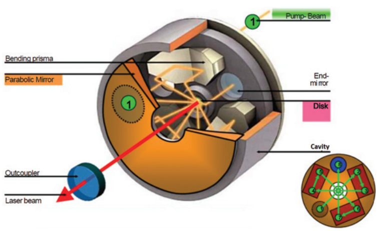
where φ is the half aperture angle and w_0 the radius of the beam waist. An overview of the requirements for various industrial laser applications on beam parameter product and optical output power is given in Fig. 2.3. As a rule of thumb, the applications metal cutting and welding require optical CW output powers in excess of 1 kW with a $BPP <$

10 mm · mrad. The competition is high in this area, so efficiency and therefore energy consumption of a laser system is a cruicial specification, that can lead to the decision wheter a manufacturing chain shall be equipped by one system or another. If the maximum achievable output power and brightness of diode lasers can be increased, this technology has high potential to substitute more costly solid-state, gas or fiber laser systems.

2.1.2 Thin-disk lasers

A thin-disk laser is a type of a DPSSL that uses a thin disk of about 100-200 μm thickness (for Yb:YAG) as active laser medium (see Fig. 2.4a). An excellent overview of thin-disk laser technology, its capabilities and scalability is given in Ref. [21]. The schematic multi-pass pumping process of a thin disk inside a cavity is shown in Fig. 2.4b. The pump beam is coupled into the cavity (either via an optical fiber or free-space) where it propagates between a parabolic mirror, several prisms and the solid-state disk for over 20 times in order to compensate the low propagation distance inside the thin-disk. The resulting laser beam from the disk can then leave the cavity through the outcoupler window located on the opposite side. The disk itself has a high reflective dielectric coating (for pump and laser beam) at the backside and is directly connected to a heatsink. Multi-pass pumping enables an optimal usage of the pump beam and therefore a high optical-optical conversion efficiency, also termed as pump efficiency. In addition this configuration allows the temperature gradient inside the active medium to be strongly perpendicular to the disk surface which minimizes material strain, thermal lensing and penalties in beam quality. Fig. 2.5 shows for Yb:YAG slab amplifiers that the optical-optical pump efficiency scales with the pump intensity, which makes high pump intensities desirable and beneficial for the overall wall-plug efficiency of a DPSSL system. This reduces the cost per Watt ratio

(a) Fotography of interior of disk-laser cavity [22].



(b) Scheme of pumping process in a disk-laser cavity [23].

Figure 2.4

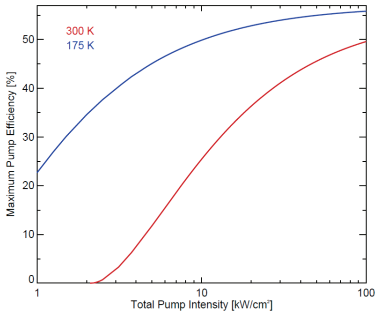


Figure 2.5: Optical-optical pump efficiency versus pump intensity in a Yb:YAG slab amplifier [24].

(€/W), provided the system performance is not compromized for example by material degrading or device failures. Pump efficiency values of up to 65% at ambient temperature can be achieved in such systems. The electro-optical conversion efficiency of the diode laser pump itself is typically over 60%, resulting in a wall-plug conversion efficiency of over 25%, but with significantly increased brightness [21]. For that reason these systems can be called brightness converters.

A highly established and suitable thin-disk gain medium is YAG, typically doped using the rare-earth, Yb. Its absorption spectrum is plotted in Fig. 2.6a where it shows its main absorption band in the range from λ =915 nm to λ =[940]nm with a local maximum at λ =940 nm under all temperature conditions. Lasing occurs at the peak gain of λ =1030 nm, as seen in 2.6b. To date, commercial Yb:YAG based multimode thin-disk laser systems deliver a reliable maximum optical CW power of 16 kW with a beam parameter product of below 8 mm×mrad [21, 22].

Concludingly CW driven Yb:YAG based thin-disk lasers require the maximum achievable pump power and efficiency at a wavelength between λ =935 nm and λ =940 nm, whereas pump beam quality can be compromised to a certain degree.

2.1.3 Diode laser types and their applications

Many different types of edge emitting diode lasers are commercially available, each serving a specialized purpose. In general, the most established versions of edge emitting diode lasers are ridge-waveguide (RW) diode lasers and broad area (BA) diode lasers. Devices might be longitudinally or laterally structured to regulate lateral beam quality. Gratings

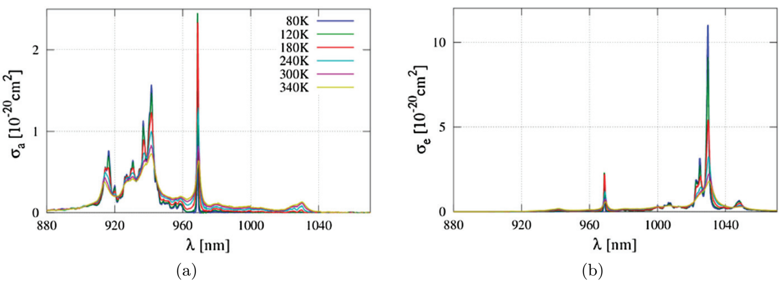


Figure 2.6: (a) Absorption and (b) emission cross section versus wavelength of Yb:YAG [25].

can be included for spectral stabilization, for example as in distributed feedback (DFB) diode lasers or distributed Bragg relector (DBR) diode lasers. The devices can also be designed to act as a power amplifier (PA), seeded by a master oscillator (MO), resulting in a MOPA system.

RW lasers operate in a single guided lateral mode and make use of lateral current confinement combined with strong lateral optical confinement via index guiding. Here, the region adjacent to the central ridge is etched away until close above the active region and the central ridge region has a typical remaining lateral width of 2...15 μm. Using this technique, a close to diffraction limited beam, quantified by the beam quality factor

$$M^2 = BPP\frac{\pi}{\lambda} \tag{2.2}$$

number, can be obtained in both lateral and vertical direction. A beam with $M^2 < 2$ in both directions [26–28] results in a circular shape that allows for example efficient fiber coupling. The narrow contact stripe (ridge area) strongly limits the maximum optical power per device, as the lateral aperture is small and optical power densities reach critical values at low absolute optical CW powers of below P_{opt} =3 W [28].

DFB and DBR lasers use longitudinally periodically structured waveguides. DBR laser typically use a gain region and a seperate DBR region. DFB laser integrate the grating along the whole cavity, typically applying epitaxial regrowth or surface etch techniques to fabricate a grating with a high enough index contrast. These periodic structures form a 1-dimensional grating that provides optical feedback for wavelength selective operation [29]. The resulting spectral width can drop to values below 0.1 nm [30] and single mode operation in longidtudinal operation can be obtained. These devices also offer the possibility of tuning the operating wavelength by adjusting current or temperature.