Chapter 1

Introduction

The market demand for high-power diode lasers with a highly focusable beam in applications such as free space optical communications, medical therapy, display technologies and material processing is in constant rise. Their popularity stems from the inherent high electrical to optical conversion efficiency, their small size, their high reliability, and their cost-effectiveness [1].

The determining factor in how tightly the emission of a laser can be focused is the beam quality [2]. One common measure of the latter, set by the ISO standard [3], is the beam propagation ratio, denoted by M^2 that takes values greater or equal to one. A beam of optimal quality has an M^2 value of one, corresponding to a Gaussian distribution of the intensity. Owing to the geometry of their optical resonator, diode lasers emit such a beam in the fundamental mode. Therefore, the design of diode lasers, meant to have a very good beam quality, includes a mechanism that ensures fundamental mode operation. In the vertical axis (perpendicular to the p-n junction), optical confinement is provided by a waveguide structure built in the epitaxial layers. In the present work, a large optical cavity (LOC) structure is used, which yields a near-Gaussian mode [2, 4].

One design strategy used to force single-mode operation in the lateral axis of diode lasers is the ridge-waveguide (RW) laser. The RW is defined by two etched trenches, whose depth and separation are tailored in such a way that the thus created waveguide cuts off the propagation of higher order modes. Depending on the depth of the trenches (that create a refractive index step) and the emission wavelength, the ridge is typically some micrometers wide. The maximum output power achieved by such a device is limited by catastrophic optical mirror damage (COMD) and/or thermal rollover, and does not exceed $2\,W$ [5].

When it comes to raising the maximum output power of RW lasers, the most effective solution lies in the broadening of the active region of the diode in the lateral direction [6]. Such lasers, called broad area (BA) lasers, have been demonstrated to emit up to $20\,W$ of output power in continuous wave (CW) operation with a stripe width of $96\,\mu m$ [7]. However, in such a case, it is not possible to maintain single mode operation and, as a consequence of the apparition of higher order modes and the influence of non-linear effects [8], the beam quality is seriously degraded, with M^2 values lying typically above 10 [9].

A method of improving the beam quality of BA lasers while maintaining the high output power is the use of an external resonator. Here, one of the facets of the laser diode is anti-reflection (AR) coated and the laser resonator is bounded by the remaining facet with a given reflectivity R (5 $\%$ in the present study), and an external mirror with high reflectivity (HR). The facet with reflectivity R acts as output coupler. It is a very simple and versatile scheme since the geometry of the external resonator can be modified and optical elements can be added into it without requiring further wafer processing.

The aim of this work is to study the feasibility of such external cavity lasers (ECL) with test BA laser diodes that are 1.3 mm long and have a width of the active region of 100 μm. The choice of the external resonator concept should take the following into account:

- An 'on-axis' design is required, since the far-field profile of the laser emission is centered on the optical axis.
- The number of intra-cavity elements should be small so as to minimize internal losses, to enable an eventual miniaturization of the concept, and to reduce the cost of assembly.

To date, the highest output power reported for a BA laser with an external resonator that yields a near-diffraction-limited output beam is 2.46 W [10]. However, the optical setup is designed off-axis, making it suitable only for BA lasers that emit in a double-lobed far-field. Furthermore, in addition to the laser diode and a collimation lens, two volume Bragg gratings (VBG) are required inside the external cavity laser (ECL), that make it relatively expensive to assemble.

Sharfin et al. [11] have proposed a simple ECL that consists only of a lens and a conventional external mirror in addition to the laser diode. The concept, where the filtering of higher order modes is achieved by the active region of the diode itself, is compatible with an 'on-axis' design. Due to its small amount of intra-cavity elements, this ECL offers potential advantages such as minimized internal losses, ease of alignment and a possibility for miniaturization. However, the maximum output power obtained with this scheme in a laterally single mode beam is 100 mW.

The above-named concept is investigated at output powers in the Watt range. In particular, the principles underlying the spatial mode filtering process inside the laser and their validity at high power operation are studied. The theoretical model is refined in order to accommodate thermal lensing, the main contribution to non-linear effects that gain in influence inside the gain medium (the BA laser diode) as the injection current is increased. Subsequently, an additional lens is included inside the setup in order to optimize the mode filtering. The concept is implemented with a test BA laser diode that emits in the wavelength region of 1.06 μm.

This thesis is organized as follows: chapter two deals with the BA laser diode as a free running laser. Generalities about semiconductor lasers are briefly presented, followed by a description of the laser structure used as gain medium inside the ECL. Its characterization (as free running laser) and a brief discussion on different means of improving the beam quality of BA lasers complete the chapter.

Chapter three goes into the details of the theoretical model, based on the ABCD-matrix treatment of Gaussian beams, underlying the functioning of the external resonator. The conditions for spatial mode filtering are looked into, and the limitations of the model at high power operation are discussed. A novel resonator geometry is presented, that takes into account the thermal lensing arising inside the gain medium, and its influence on the mode formation is studied.

Chapter four comprises a description of the experimental setup used for the measurement of the power, the spectrum and the beam quality of the different laser diodes used in the study. The definitions used for the characterization of the spatial distribution of the modes are set, and the ensuing measurement procedure is detailed.

Chapter five deals with the measurement of the thermal lens inside the laser diodes acting as a gain medium inside the ECL. A novel method that allows the determination of the thermal lens coefficient in a laser diode is presented. The experimental results are validated by two methods. The first one is based on the thermal lens dependent M^2 value of a free running laser, while the second one uses a finite element method (FEM) simulation of the temperature distribution inside the laser diode.

In chapter six, the implementation of the ECL is discussed and, with the help of the theory developed in chapter three, and the values of the thermal lens obtained in chapter five, the geometries that yield optimal spatial mode filtering are investigated. In order to monitor the beam diameter inside the resonator, and at the same time to increase the effectiveness of the spatial mode filtering, a series of measurements is carried out with an intra-cavity slit. The different experimental results are compared with each other, and with the free running BA laser.

Chapter seven comprises a summary of the main themes encountered in the present work and a conclusion about the feasibility of the BA laser in such an external resonator at high power operation.

Chapter 2

The high power broad area semiconductor laser

The broad area (BA) semiconductor laser is the central device in the study of the external cavity laser (ECL). In fact, the main goal of the ECL is going to be the improvement of the lateral beam quality of the BA laser, while maintaining the same output power levels. The present work can also be seen as a comparison between a BA laser with both its mirrors lying on the facets (free running laser), and one operated in an external resonator. So, the BA laser diode acts both as reference value for the ECL and as its gain medium.

While it is not in the scope of this work to study the BA laser in depth, it is however important to explain how it functions and how its design has evolved to the present version that is capable of supplying several Watts of optical power. The tools used to assess the performance of a BA laser are introduced next. Based on its electro-optical and thermal properties, a particular BA laser structure is chosen for the purposes of the study. Its epitaxial structure, the layout of the chips, the different facet coatings and the packaging are shortly introduced.

The free running version of the chosen laser structure is characterized with respect to output power, spectrum, and lateral beam quality. The chapter is concluded with a concise literature review of the different methods used for the improvement of the lateral beam quality of high power diode lasers.

2.1 General aspects of semiconductor lasers

Laser radiation is achieved when three conditions are fulfilled, namely [12]:

- The presence of an active medium that, under population inversion, coherently amplifies a beam of radiation (stimulated emission).
- A process, commonly named as 'pumping', that enables the population inversion in the active medium.
- An optical feedback mechanism that allows the radiation to repeatedly bounce back and forth inside the active region.

The overwhelming majority of semiconductor lasers are grown with the so-called III-V materials, that is materials from the columns III and V of the periodic table. A mixture of binary, ternary and quaternary materials are used, examples of those being $GaAs$, $In_xGa_{1-x}As$, $Al_xGa_{1-x}As$ or $In_xGa_{1-x}As_yP_{1-y}$. The indices $(x,y,..)$ represent the fractions of the given element in the material. The extended used of III-V materials lies in the fact that they have a direct band gap [2], which implies that the efficiency of the radiative recombination between the conduction band and the valence band is high relative to materials with an indirect band gap.

In semiconductor lasers, the active medium lies in the space charge zone at the pn-junction when a p-doped semiconductor layer and a n-doped semiconductor layer are brought together. Population inversion comes in the form of electrons and holes that are made to gather at the junction. For the sake of high confinement of the carriers in the space charge zone, which in turn improves the internal efficiency and thermal stability, semiconductor lasers are nowadays built as double heterostructure, where an intrinsic layer of semiconductor material with a given band gap energy E_g is sandwiched between a p-doped layer and a n-doped layer of another semiconductor material with a higher band gap energy [13–15]. A simplified energy band diagram of a double heterostructure is sketched in figure 2.1 [16]. When a forward voltage V is applied, such that $qV \gtrsim E_g$ (q being the charge of the electron), the Fermi levels of the electrons (E_{F_c}) and of the holes (E_{F_v}) in the region of the intrinsic layer lie in the conduction band (E_c) and in the valence band (E_v) respectively, such that the respective carriers can flow there, where they remain confined due to the barrier created by the higher band gap energy of the doped layers. The pumping process is the flow of electric current across the p-i-n diode, that in turn induces the bias voltage. The three transition processes between the conduction band E_c and the valence band E_v involving carriers and photons are absorption, spontaneous emission and stimulated emission. In the latter process, a stimulating photon with energy $h\nu$, with h being the Planck constant and ν the frequency of the photon, induces the emission of another photon with identical wave function. This happens via the radiative recombination of an electron-hole pair at respective energies that fulfill the condition of Bernard et Duraffourg [17]:

$$E_g \leq h\nu \leq E_{F_c} - E_{F_v} \tag{2.1}$$

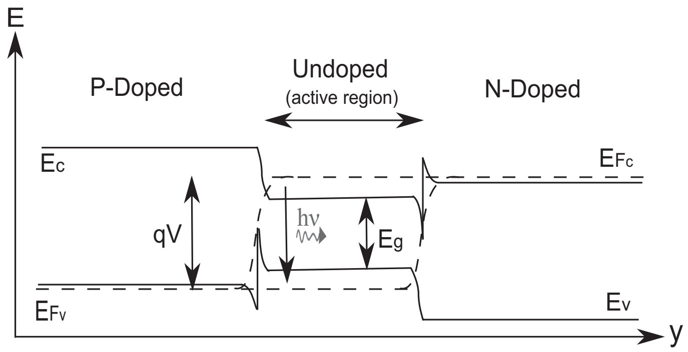

Figure 2.1: Simplified energy band diagram of a double heterostructure in the growth direction of the layers (y).

If the thickness of the active region, that is the intrinsic semiconductor layer, is reduced to the order of the De Broglie wavelength of the electrons in the material, quantum confinement of the carriers occurs in the direction along the thickness of the layer and their energy levels become discrete, yielding a quantum well structure [2,18]. Due to their small active volume as compared to bulk materials, quantum well lasers characteristically have a reduced threshold current density with respect to bulk heterostructure lasers. Moreover, the lattice mismatch between the quantum well material and the neighboring layers can be chosen so as to induce strain in the former. Strained quantum wells enable the enlargement of the spectrum of semiconductor laser diodes to wavelengths not available with standard materials [19] and reduce the threshold current density further than with unstrained quantum wells [20,21].

For the optimization of the efficiency of the diode laser, the photons should be confined as much as possible in the active region. Due to the extremely thin active region in quantum well lasers, the separate confinement heterostructure (SCH) is widely used, where the confinement of the optical mode is provided by waveguiding layers directly adjacent to the active layer, and an additional cladding layer, with a lower refractive index, adjacent to the waveguide layer [22]. The refractive indices and the thicknesses of the waveguide and cladding layers are adjusted such that only the fundamental mode is guided. Furthermore, it is desirable that the guided mode be large enough in order to reduce the facet load of the device. Additionally, a large optical mode ensures a reduced far-field angle of the emission in that dimension. Therefore, the concept of large optical cavity (LOC) is often implemented [2,4,23]. The waveguide layer is broadened while its single-mode operation is maintained. The confinement factor of the mode however falls to very small values (typically under $1\,\%$), thus reducing the modal gain. However it is compensated by the very small losses in the waveguide structure such that long resonator lengths are possible, thus maintaining the overall efficiency of the laser. The number of quantum wells in the device can also be increased in order to yield higher efficiencies.

Until now, the semiconductor laser has been considered only in the dimension perpendicular to the plane of the pn-junction. This direction shall be referred to as the vertical direction. Current is injected inside the device via a metal contact stripe that extends along the lateral dimension, and, to the exception of some current spreading, it remains confined into the area defined by the stripe. The width of the active region in that direction will then approximately be defined by the width of the stripe. In fact, stimulated emission will occur only in regions pumped by the electric current. Optical confinement also takes place under the current injection stripe. Modes that propagate within its width experience gain and are amplified whereas those propagating beyond it suffer high losses and progressively decay. In steady-state operation, only those modes who experience net gain oscillate in the laser resonator. Such an optical confinement process is called gain guiding. The current stripe can be made small enough such that only the fundamental mode experiences net gain. An alternative to gain guiding under the current injection stripe is index guiding of the optical modes. Just like in the vertical direction, a waveguide structure can be built in the lateral dimension. Its width and the refractive index step can be set such that only the fundamental mode is guided.

Stimulated emission only is not sufficient to guarantee steady-state laser emission. Optical feedback, which increases the photon density inside the active material, is a prerequisite. It comes most often in the form of a Fabry-P$\acute{e}$rot resonator, where the cleaved facets of the semiconductor material act as resonator mirrors. The Fresnel reflectivity of these facets lies in the region of 30 $\%$, for typical effective refractive indices around 3.3 encountered by the laser beam inside the diode.
Based on the principles mentioned in the previous section, semiconductor laser diodes with near-single mode operation in both the vertical and the lateral dimensions have been demonstrated up to a power of approximately 2 W [5]. This result has been achieved by a ridge-waveguide (RW) laser, where the lateral confinement of the optical mode is achieved by index guiding. However, The narrow width of the output facet inherently limits the output power because of the small light-emitting area and the high optical intensity, which induces catastrophic optical mirror damage (COMD) [24]. Moreover, the small contact area (perpendicular to the plane of the p-n junction) results in high values for the thermal resistance and the series resistance of the device. Thermal rollover may then become the main limiting factor to the high power output, especially when the facets are passivated [25], which drives the optical intensity required for COMD higher. When higher output power is required, the broadening of the region of optical confinement in the lateral dimension is opted for. The current injection stripe is made much wider, such that the broader spot falling on the facet reduces the incident intensity significantly and, at the same time, the thermal resistance and series resistance are lower, implying higher output powers are possible before thermal rollover appears (also dependent on the packaging scheme of the device). Due to their extended width in the lateral direction, such lasers are called broad area (BA) lasers. A maximum output power of 20 W in continuous-wave (CW) operation has been demonstrated for a width of the active region of 96 μm in the lateral dimension and a diode length of 4 mm. The maximum COMD level in that case has been registered to be 31 $MWcm^{-2}$ [7].

With the broadening of the current injection stripe in the lateral direction, the extended active region enables higher order modes to oscillate in the laser resonator. The emission is no more single-mode in that direction, which results in the broadening of the far-field profile of the emission, and consequently a higher M^2 value [26]. Hence the present study, where the operation of a BA laser diode in an external cavity should improve the beam quality of the system whilst maintaining the high power output level as in an identical free running laser (except for the facet reflectivities).