1. INTRODUCTION

Tunable diode lasers are key tools in various fields such as precision time keeping, geodesy, geophysics, navigation, exploration [1] and in quantum optics metrology experiments aiming at atomic and fundamental physics questions [2, 3]. For example, optical clocks are expected to soon replace microwave atomic clocks for the realization of the unit of time, the second [4]. Cold atom matter wave interferometers can be used for inertial navigation and specifically work in an environment, where a GPS-type of navigation is not possible, for example under water or on deep space satellite missions. Atom interferometers are also considered for precision tests of the equivalence principle in space [5–9]. As cold atom based quantum sensors are moving out of quantum optics laboratories into the field or even to space, cold atom based quantum sensor technology in general, and diode laser technology in particular, has to mature.

Currently, activities are moving towards carrying out quantum optics precision experiments under micro-gravity conditions [10] at a drop tower or in space. The German Space Agency DLR is currently supporting a sounding rocket mission that will lead to a Bose-Einstein-Condensate (BEC) onboard a sounding rocket in 2017. Commercially and lab-based laser technology, at the time the research and development described in this thesis work was initiated, did not meet the requirements regarding compactness and reliability.

This thesis work therefore seeks to develop the laser technologies that to allows for the implementation of the diode laser systems that are required for the sounding rocket mission that will, for the first time, demonstrate BEC and atom interferometry in space.

Portable as well as space based precision quantum optics sensors depend on the availability of appropriate laser systems. Depending on the specific application the requirements typically are [11]

(i) that a specific atomic transition frequency is met. The laser technology concept should provide access to the full optical spectrum, from IR down to UV.

(ii) that continuous tunability is provided, typically at the order of a few to a few tens of GHz.

(iii) that the free running spectral stability corresponds to a short term emission linewidth that ranges between 1 MHz and 1 kHz on ms time scales.

(iv) that the emission frequency can be stabilized well enough, e.g. down to the sub-Hz level for optical clocks, or that phase locks with mrad residual phase error can be implemented.

(v) that an output power at the 1 mW to 1 W level can be provided.

(vi) that, specifically for space applications, the laser system is energy-efficient, compact, and robust.

The research was carried out as a part of the project "LASUS" for the sounding rocket mission MAIUS. During the project, (i) monolithic diode laser systems, (ii) macroscopic test devices were electro-optically characterized and optimized, (iii) micro-optical (hybrid) integrated for the continuous-wave operation were developed and realized. This thesis work can thus be summarized as follows

- detailed electro-optical characterizations and optimization of the monolithic lasers for the wavelength of 767 nm and 780 nm.

- electro-optical characterizations of ridge waveguide (RW) laser chips for extended cavity diode lasers (ECDLs) operating at 767 nm and 780 nm.

- development and first realization of a micro-integrated extended cavity diode laser for rubidium (Rb) and potassium (K) BEC and atom interferometry experiments in space.

Monolithic systems are functionally and physically less complex than hybrid systems and therefore tend to be more robust and stable. Hybrid systems allow a more detailed system optimization and provide better spectral stability than monolithic systems. In comparison to well established commercial or lab-style "macroscopic" systems they are much more compact and robust. For example, the micro-integrated ECDL occupies a volume of 30 cm^3 which is smaller by a factor of 100 when compared to a commercial system (Lion 520 by Sacher). One important goal of this thesis work is to provide a comparison of monolithic systems, of macroscopic "classical" extended cavity systems and of their micro-integrated analogue with regard to laser metrology applications in space. Specifically, this work provides the following technical goals:

- monolithic distributed feedback (DFB) lasers for 767 nm (potassium) and 780 nm (rubidium) should provide output power of at least 50 mW, and linewidth of less than 200 kHz.

- micro-integrated extended cavity diode lasers (ECDL) for 767 nm (potassium) and 780 nm (rubidium) should provide output power of at least 50 mW, and linewidth of less than 200 kHz.

- comparative study on the potential of the hybrid and monolithic integrated diode laser systems for an application in micro-gravity and in space.

- transfer of design of rubidium micro-integrated ECDL for potassium micro-integrated ECDL.

2. BASIC PRINCIPLE OF SEMICONDUCTOR DIODE LASERS

This chapter describes the principle of the operation of semiconductor diode lasers and, then, specifies their basic electro-optical characteristics, which are the starting point of the study of electro-optical performances of the studying monolithic lasers and extended cavity lasers in this research. First, Section 2.1 will discuss the background of semiconductor diode lasers is based on the electro-optical properties of the $p-n$ junction in a semiconductive material. A laser oscillation, which can be realized by an electron transition, is a fundamental property of laser. Thus, three types of electron transitions: spontaneous emission, stimulated absorption and stimulated emission will be mentioned here. Next gain medium, optical waveguide, optical resonator and lateral confinement, which are most important components for a realization of the semiconductor laser, will be discussed in Section 2.1. Finally, a threshold condition of the semiconductor diode laser and some basic and advanced electro-optical characteristics of the semiconductor diode laser will be introduced in Sections 2.2 and 2.3.

2.1 Introduction to semiconductor diode lasers

The principle of the semiconductor diode lasers is based on the electro-optical properties of the $p-n$ junction, that is formed between p-type and n-type regions if a block of n-type and p-type semiconductive materials are brought into contact. Since most of the current carriers are electrons, a semiconductor is a n-type semiconductive material. Likewise, since most of the current carriers are holes, a semiconductor is a p-type semiconductive material [13–15]. In semiconductors, the energetically highest band is called the valence band that is fully occupied by electrons at $\mathrm{T}=0\,\mathrm{K}$ and the energetically lowest band is called the conduction band that is completely empty at $\mathrm{T}=0\,\mathrm{K}$. The difference in energy between the valence band and the conduction band is called an energy gap, E_g. This corresponds to the amount of energy that a valence electron must have in order to make a transition from the valence band to the conduction band. If an electron acquires sufficient additional energy from an external pump source to make a transition to the conduction band, it becomes a free electron and leaves a hole in the valence band. Both, the electron and hole now contribute to the conduction of electrical current [13–15].
The induced carrier recombinations between the conduction and valence bands generate the emission photons. A recombination of an electron and a hole in the conduction and valence bands, respectively, leads the generation of a photon with energy $h\nu$ [14, 16].

$$E_{ph} = h\nu \tag{2.1}$$

where h is the Planck's constant and $\nu = \omega/(2\pi)$ is the frequency.

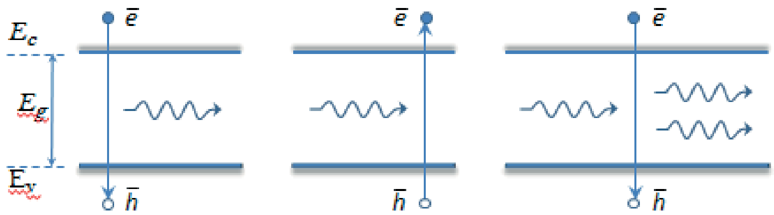

Fig. 2.1: The three fundamental radiation processes between energy levels in the conduction and valence band. Spontaneous emission (links), stimulated absorption (center), stimulated emission (right).

There are three different types of processes that describe how photon can interact with electron of the semiconductor. They are shown in Fig. 2.1. The first process is called spontaneous emission (Fig. 2.1(links)), where a recombination of an electron-hole pair leads to the emission of a photon. Photons are created via different spontaneous emission processes are incoherent, i.e., they typically differ with respect to phase, frequency, propagation direction and polarization. Stimulated absorption is the second of processes (Fig. 2.1(center)): an electron-hole pair is generated by absorption of a photon. The third is called stimulated emission (Fig. 2.1(right)). A recombination of an electron-hole pair is stimulated by a photon and a second photon is generated simultaneously which has the same direction, phase, frequency and polarization as the first photon, i.e., this is a coherent emission process. The emission of photons realizes the optical amplification that can be provided by the gain medium at optical frequencies [13, 14]. A gain medium consists of a central intrinsic (i) active undoped layer embedded between high-band-gap p- and n-doped regions. When forward bias of this $p-i-n$ junction is applied, carriers are injected into the active layer and optical gain by stimulated emission is generated. However, an amplifying medium, by itself, it does not constitute a laser. Laser oscillation requires optical feedback, to trigger the stimulated emission processes, and is provided by a confinement of the radiation emitted by the gain medium. For optical confinement mirrors are used, that, very generally speaking, can be implemented by mirrors for example in case of gas or solid state lasers, or by the facets of monolithic semiconductor lasers. Monolithic semiconductor lasers also require lateral confinement that is implemented e.g., by waveguides [14,16]. An optical waveguide consists of a high refractive index optical medium, called the core layer, which is transversely surrounded by low refractive index medium, called the cladding layer. Therefore, the laser active layer is the core of the optical waveguide at the same time. Fig. 2.2 shows the optical waveguide for a double heterostructure laser. The active layer is embedded between cladding layers with band gap $E_{g,cl}$ and refractive index n_{cl}. The active layer has band gap E_g, refractive index n_f and thickness d. The higher refractive index of the active layer is compared to the refractive index of cladding which confines the generated photons in the active region. The difference in refractive index between the active layer and the cladding layer is called an index step, Δn. Assuming small enough the index step $\Delta n = n_f - n_{cl}$ and the active layer thickness d of the optical waveguide, the fundamental mode (Gaussian field) can travel in the waveguide where an effective refractive index n_{eff} [14].

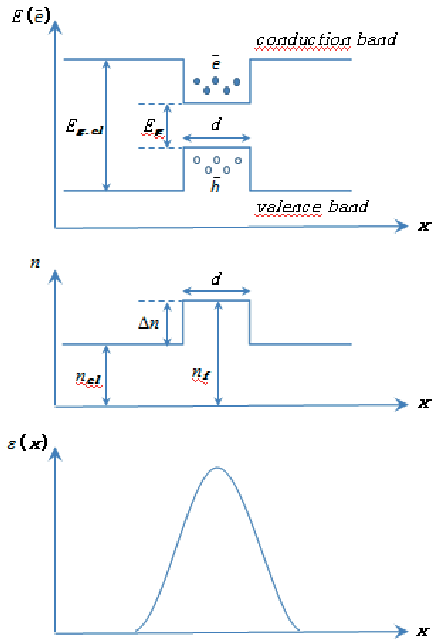

Fig. 2.2: Confinement of the carriers using a double heterostructure in the vertical direction x (upper graph), refractive index profile (middle graph), and the electric field (lower graph) in vertical direction. The energy-band diagram $E(x)$ with conduction and valence bands (top), the refractive index profile $n(x)$ of the dielectric waveguide (center), and the electric field distribution ε of the fundamental mode traveling in the direction of the optical waveguide (bottom) [14].

$$n_{cl} \leq n_{eff} \leq n_f \tag{2.2}$$

The refractive indices of the active and cladding layers are different from the effective one [14]. An optical resonator provides optical feedback. A Fabry-Perot (FP) resonator is one type of the optical resonator which, generally speaking, consists of two mirrors with distance L around a laser active material. In a standing wave resonator optical fields can build up that obey the resonance condition, which requires that the optically effective length, $(n_{eff}L)$ of the resonator be an integer multiple of a half-wavelength [14, 16].

$$L = q\frac{\lambda_0}{2n_{eff}} \tag{2.3}$$

where q ($q = 1, 2, 3, ...$) is the number of the nodes of the standing wave, i.e., the order number of the longitudinal mode, and λ_0 is the vacuum wavelength. By appropriate lateral confinement a stable, transverse single-mode operation can be established in the dielectric waveguide. There are three types of lateral confinement: current confinement, optical confinement, and buried heterostructure that are described more detail in [13–15]. For the current confinement the optical gain is possible. It occurs only if pumped by the electrical current. Diode lasers using current confinement are called gain-guided lasers. A gain-guided laser is relatively easy to fabricate, but it has high threshold due to lossy nature of the lateral waveguiding.

An optical confinement based on index-guiding uses an effective lateral refractive-index step. The index step is implemented by a ridge above the active region along the mode volume of the semiconductor chip. In this case, a lateral single-mode operation depends on the magnitude of the refractive-index step and the width of the ridge. A ridge-waveguide (RW) laser is a typical example among the index-guided laser. The index guiding provides current and optical confinements for the RW laser. Index-guided lasers show stable, lateral single-mode emission with a low threshold current. The lateral diffusion of electrons and holes is prevented by the barriers. Thus, a buried heterostructure combines all confinements of carrier and photon. The threshold is extremely low enabling low power consumption in these lasers [13–15].

2.2 Basic characterizations of diode lasers

The output power, spectral emission and especially threshold determine the basic performance of a diode laser. In this section, the threshold condition for a FP diode laser as well as some basic electro-optical characteristics such as output power and optical spectrum will be described.

2.2.1 Threshold condition

The threshold condition can be determined in the FP resonator. In the FP resonator, the optical plane waves travel between the two plane mirrors. The incident spontaneous emission is further amplified by the stimulated emission inside the resonator. Fig. 2.3 shows multiple reflections that occur at the mirrors. The mirrors

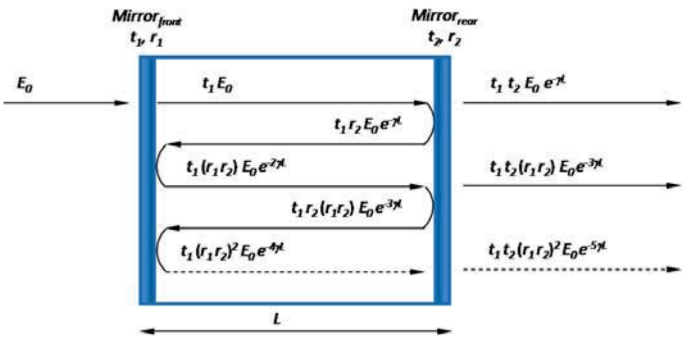

Fig. 2.3: Multiple reflections of a plane wave inside a FP resonator with a cavity length L. The mirrors have amplitude transmissions t_1, t_2 and amplitude reflectivities r_1, r_2

are described by transmission coefficients t_1, t_2 and reflection coefficients r_1, r_2 for the amplitudes of the waves. The waves propagate along the z axes in the optical waveguide with an absorption coefficient α and effective index n_{eff}. Therefore, the electrical field E of the circulating wave can be expressed as a superposition of the contributions from the multiple reflections [13, 14, 16].

$$E = E_0 \left(\frac{t_1 t_2 e^{-i\gamma L}}{1 - r_1 r_2 e^{-2\gamma L}} \right) \tag{2.4}$$

In the expression, E_0 is an initial value of wave and γ is the complex propagation number [14, 16]:

$$\gamma = \frac{\alpha}{2} + i\kappa_0 n_{eff} \tag{2.5}$$

where

$$\kappa_0 = \frac{\kappa}{n_{eff}} = \frac{2\pi}{\lambda_0} \tag{2.6}$$

In this equation, κ describes the propagation along the waveguide. Generally speaking, when lasing occurs the gain g provided the optical mode compensations of the intrinsic absorption and the mirror losses for a single round trip. Gain requires a pumping mechanism. In case of diode lasers the gain is proportional to the injection current. The minimum injection current, at which the round trip gain equals to the round trip losses, is called the threshold injection current, the corresponding round trip gain is referred to as the threshold gain g_{th}. Under lasing condition, the transmitted wave E after a round trip in the resonator reproduced itself, which is referred to as the oscillation condition. When a threshold condition is met, the transmitted wave has infinitely large amplitude [13, 14, 16]
.

$$1 - r_1 r_2 e^{(-2\gamma L)} = 0 \tag{2.7}$$

The threshold condition can be written by substituting of Eq. 2.5 to Eq. 2.7

$$r_1 r_2 e^{(-\alpha L)} e^{(-i\frac{4\pi}{\lambda_0} n_{eff} L)} = 1 \tag{2.8}$$

The first part in the equation describes the amplitude condition (Eq. 2.9) and the phase condition (Eq. 2.10) is derived by the second part in the equation [14].

$$r_1 r_2 e^{(-\alpha L)} = 1 \tag{2.9}$$

$$e^{(-i\frac{4\pi}{\lambda_0} n_{eff} L)} = 1 \tag{2.10}$$

Above threshold, when the injection current is increased beyond the threshold value, gain saturation sets in and reduces the small signal gain to the threshold gain. Therefore the two regimes, below and above threshold, correspond to the round trip gain to be described by the small signal gain and gain saturation, respectively. For a mode traveling along the optical waveguide, the total absorption coefficient α is usually split into two components, intrinsic absorption α_i and modal gain Γ_g [14].

$$\alpha = \alpha_i - \Gamma_g \tag{2.11}$$

For the threshold condition, the modal gain $\Gamma_g = \Gamma_{g_{th}}$ is given by a combination of the Eq. 2.9 and Eq. 2.11, and by the replacing the reflection coefficients r_1 and r_2 by the intensity reflectivities $R_1 = r_1^2$ and $R_2 = r_2^2$ [14–16].

$$\Gamma_{g_{th}} = \alpha_i + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) = \alpha_i + \alpha_m \tag{2.12}$$

At threshold, the modal gain $\Gamma_{g_{th}}$ is the sum of the two terms in Eq. 2.9, the intrinsic absorption α_i and the mirror losses α_m. The mirror losses depend on the cavity length L and the mirror reflectivities r_1 and r_2 [14–16].

2.2.2 Output power

The output power is one of the important electro-optical properties a diode laser, which is obtained by using the rate equation. The rate equation is described more detail in [14, 15]. The output power P_{out} is determined as the energy leaving the laser facets per unit time. Thus, above threshold, the output power by stimulated emission in the laser cavity is [14, 16]

$$P_{out} = \eta_{sl}(I - I_{th}) \tag{2.13}$$

where I and I_{th} are the injection and threshold currents, respectively. The slope efficiency of semiconductor diode laser is given by [14, 16]

$$\eta_{sl} = \frac{dP}{dI} = \eta_{in}\frac{h\nu}{e}\frac{\alpha_m}{\alpha_t} \tag{2.14}$$

where η_{in} is defined as the internal quantum efficiency, which is fraction of carriers that radiatively recombined in the layer. $\alpha_t = \alpha_i + \alpha_m$ is the total losses of the laser. An example of the output power P_{out} as a function of the injection current is illustrated in Fig.2.4.

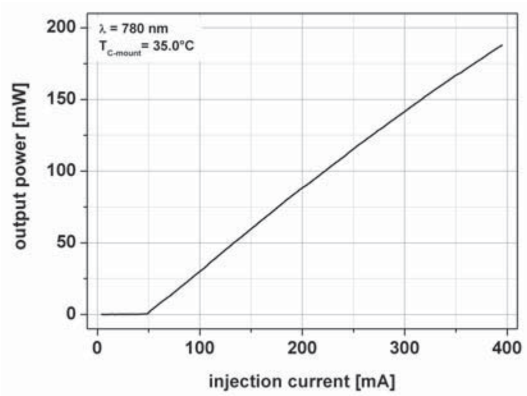

Fig. 2.4: Output power of a distributed-feedback diode laser for 780 nm with the cavity length of 3.0 mm. At the injection current of 395 mA, the DFB laser provides the output power of 188 mW. The slope efficiency corresponds to 0.6 W/A.

2.2.3 Diode laser spectrum

The optical spectrum of FP diode lasers describe how the optical energy or power is distributed over different wavelengths. For the laser to start lasing the peak of the modal gain must be raised to the threshold gain. If pumping is increased beyond the threshold, gain clamping sets in that affects all the whole gain spectrum provided that the gain medium is homogeneously broadened. Therefore only the mode closest to the gain peak is amplified, whereas for the other longitudinal modes, the losses exceed the modal gain. Hence, the peak wavelength λ_p can determine the operation mode for the diode laser, i.e., the laser mode is close to this value. The side-mode suppression ratio (SMSR) can be a measure to quantify a single-mode emission [13–15].

$$SMSR = 10 \log_{10} \frac{P_1}{P_2} \tag{2.15}$$

where P_1 and P_2 ($P_2 \leq P_1$) denote the output power of the two strongest modes in the optical spectrum. Fig. 2.5 shows an example of the spectral emission of a diode laser above threshold where a SMSR of 47 dB is achieved.

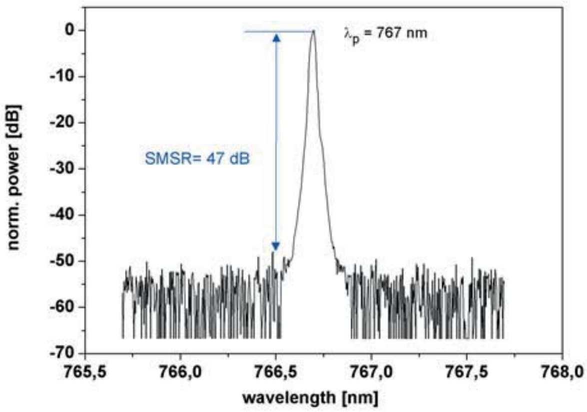

Fig. 2.5: Spectral emission of a distributed-feedback diode laser for 767 nm. A side-mode suppression ratio corresponds to 47 dB.

There are two effects to shift the emission wavelength. First, the wavelength of a diode laser shifts to larger values with increasing temperature, mainly because the refractive index increases with temperature. A shift of the effective index of refraction is translated into a shift of the emission wavelength. A higher emission wavelength can be allowed due to thermal expansion of the material where the length of the cavity extends because of the increase of temperature.

2.3 Spectral linewidth of diode lasers

Spectral linewidth of diode lasers is extremely important for some laser applications such as quantum optics sensor applications [17, 18], coherent optical communications [19, 20] and high resolution spectroscopies [21]. For the applications, the frequency noise at large Fourier frequencies, i.e. at the signal modulation frequency, is of interest rather than the short-term linewidth. In this section the definition of the laser linewidth will be explained.

2.3.1 Basics of laser linewidth

An excited atom can be regarded as an electric dipole that damped oscillates with an angular frequency ω, when it transmit from one energy level to other. Its radiation field has a spectral distribution. The center frequency (ν) of spectral distribution corresponds to the maximum intensity ($I(\nu)$) of the distribution. The center frequency is determined by the energy difference between the two energy levels of the simplified atom (two-level atom) (see Eq. 2.1) [22, 24].

$$\nu_0 = (E_1 - E_2)/h \tag{2.16}$$

The dependence of the spectral intensity on the optical frequency reveals a line profile as is depicted in Fig. 2.6. The two optical frequencies, at which the spectral intensity has dropped to half of the peak intensity, define a spectral bandwidth which is referred to as the full-width-at-half-maximum (FWHM) linewidth of the spectrum [22, 25]. These two frequencies have the same intensity of the line profile.

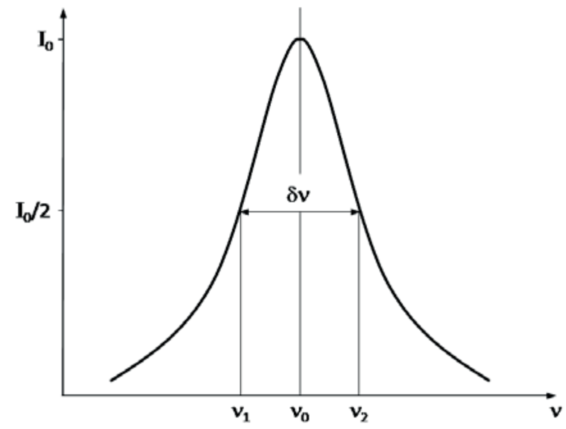

Fig. 2.6: A linewidth profile and a full width at half maximum of a spectral spectrum

The spectral region outside of the FWHM band is called the wings of linewidth [22]. The linewidth relates to fluctuations of spontaneous emission phenomenon to the phase of the optical field. The fluctuations discontinuously change the phase and intensity of the optical field that is shown in Fig. 2.7.

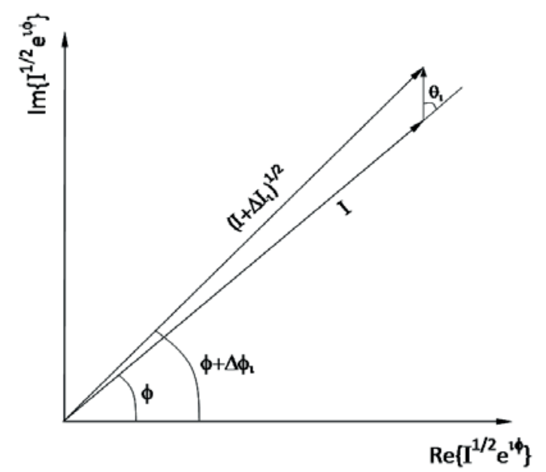

Fig. 2.7: Instantaneous phase change of an optical field by the spontaneous emission of a single photon into the lasing mode.

The phase is altered by $\Delta\phi$ resulting from the instantaneous change in field intensity.