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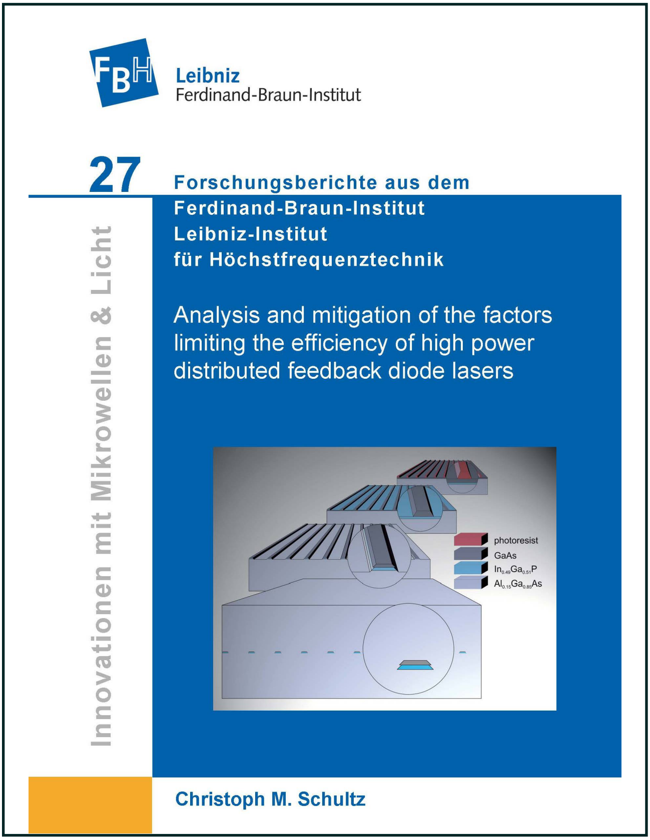
Analysis and mitigation of the factors limiting the efficiency of high power distributed feedback diode lasers



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Introduction

The subject of this work is the analysis and mitigation of the factors, limiting the performance and especially, the power conversion efficiency in high power distributed feedback (DFB) semiconductor lasers, compared to conventional high power lasers. The work is based on theoretical considerations and the development of a laser structure which is optimized for high power conversion efficiency operation of distributed feedback semiconductor lasers.

Until the beginning of this work, wavelength stabilized DFB lasers are experimentally found to be substantially degraded compared to conventional high power lasers in terms of the achievable optical output power, voltage and power conversion efficiency [Yor92], [Sch09a], [Sch09b]. Some appreciable improvement in the development of high power, high efficiency DFB lasers has been reported by Kanskar *et al.* in 2006 [Kan06]. On the one hand, the reasons for the degradation of the DFB lasers are unclear and very little studied to date. On the other hand, technical progress in the development of high power, high efficiency wavelength stabilized diode lasers is expected to be of a significant industrial importance [Roh09], [Hua11], [Gra12], [Hei12]. This makes it an appropriate subject for a detailed physical and technical study.

The aim of this work is to gain theoretical knowledge about the physical limitations to the power conversion efficiency of DFB lasers, improvement in the development of adequate laser designs and experimental experiences with the operation of highly efficient DFB lasers. Because of the following practical reasons, DFB lasers are not exclusively optimized for a maximum power conversion efficiency in this work: Firstly, high optical output powers in the $\sim 10\,\mathrm{W}$ range are required for many possible applications and can be already achieved with conventional semiconductor diode lasers without spectral stabilization. Secondly, the wavelength stabilization and the spectral width should be significantly improved, compared to conventional semiconductor diode lasers. Thirdly, the spatial emission properties, such as the divergence angle of the laser beam, must be at least comparable to what is achieved with conventional semiconductor diode lasers. Therefore, all these additional properties must be considered during the development and have to be investigated with the devices. Taking into account additional requirements limits the design options and must also be considered to possibly limit the achievable power conversion efficiency.

A motivation, why it is desirable to improve the power conversion efficiency of DFB lasers, can be derived from the technological requirements to semiconductor lasers for a selection of important industrial applications. DFB lasers and other semiconductor diode lasers with wavelength stabilization and narrow spectral width can be utilized for applications, where a narrow spectral width or a weak dependence of the emission wavelength on changes of the ambient temperature or injection current is required. One kind of such applications is the pumping of narrow absorption bands in the gain media of solid state lasers, fiber lasers and fiber amplifiers. Another example is the need to increase the optical output power of laser systems for the direct application of multiple semiconductor diode lasers, focused into a large mode area optical fiber. In both cases, the output power can be further increased by use of spectral beam combining [Sev08], [And09], [Roh09], [Hua11], [Gra12], [Hei12]. One typical example is the pumping of the ~ 976 nm absorption bands of ytterbium (Yb) doped crystals and germanosilicate glasses (as Yb^{3+}-ion). Paschotta *et al.* [Pas97] discuss the advantages and disadvantages of pumping fiber-amplifiers, based on Yb-doped germanosilicate glass, at the comparatively narrow ~ 976 nm absorption band with a high absorption cross-section, instead of the broad absorption peak between 870 and 950 nm, used conventionally. Semiconductor diode lasers with wavelength stabilization can be used to replace conventional diode lasers, light-emitting diodes (LEDs) or even less efficient lamps as pump sources in kW-class solid state or fiber laser systems [Vai08], [Hu09], [Köh09], [Pat09], [Vai10], [Wol11], [Köh12], [Gal12] or used in direct diode applications [Koe11], [Wol11], [Coh09]. In the context with such applications, increasing the power conversion efficiency of the whole laser system by a more efficient pumping scheme and by an increased efficiency of the pump source can drastically decrease the power consumption.

Wavelength stabilized diode lasers with a narrow spectral width can be obtained by the use of different concepts, such as external wavelength stabilization, by use of a distributed Bragg reflector (DBR) or DFB. For external wavelength stabilization, one facet of the laser is anti-reflection (AR) coated and an externally adjusted mirror is used to obtain optical feedback just over a very narrow spectral range. A grating, for example a volume Bragg grating (VBG) [Sch07], [Cru12c], or a Fabry-Pérot (FP) etalon can be used for this application. Nevertheless, external wavelength stabilization requires a very precise and stable fine-adjustment of the optical elements, a comparatively huge amount of space and is therefore cost-intensive. The application of DBR or DFB lasers with monolithic integrated (on-chip) wavelength-selective feedback-elements has many advantages in terms of stability, place requirement and costs. Both concepts which allow monolithic integration – DBR and DFB – have in common, that they function on the basis of Bragg reflection. Indeed, the Bragg reflector in a DBR laser is a passive optical element, which is not pumped electrically. In contrast, a DFB grating in a one-section diode laser is an active optical element because the whole region is electrically pumped. From this reason, DBR and DFB lasers have a different behavior under changes of the injection current I. In opposite to a DFB grating, a DBR is not directly heated by the thermal dissipation loss. As a consequence, the temperature-induced refractive index-change in the DBR region and the wavelength change of the laser wavelength λ, is smaller than for a DFB laser. Thus, DBR and DFB lasers have a comparable dependence of the laser wavelength on the ambient temperature $\mathrm{d}\lambda/\mathrm{d}T \cong 0.07\,\mathrm{nm\,K^{-1}}$ but DFB lasers have a stronger dependence of the laser wavelength on the injection current $\mathrm{d}\lambda/\mathrm{d}I$.

For this work, goals have been defined, which are based on technical requirements for possible applications of such diode lasers. These goals are to achieve a continuous wave optical output power of $\geq 10\,\mathrm{W}$ with a power conversion efficiency of $\geq 60\,\%$, a spectral width of $\leq 0.3\,\mathrm{nm}$ and a vertical beam divergence of $\leq 45\,°$, both with 95 % power content. Furthermore, the following limitations have been made: This work concerns the development and analysis of DFB lasers. DBR lasers and diode lasers with external wavelength-stabilization have not been considered. The limitation was made on the basis of already published experimental results on efficient DFB lasers in the $\leq 5\,\mathrm{W}$ range [Kan06], as well as on the basis of promising experimental results with conventional FP diode lasers [Kan05], [Kni05] and DFB gratings. The targeted power range also requires the use of broad-area (BA) lasers, which typically have a contact stripe width of 50 to 200 μm. A stripe width of $\approx 100\,\mu$m is optimum for coupling the emitted power into standard 100 μm core optical fibers. In contrast to narrow stripe ridge-waveguide (RW) lasers with a typical contact stripe width of 2 to 8 μm, BA lasers operate in multiple higher-order optical modes in the transverse in-plane (epitaxy-plane) direction (lateral direction) of the laser cavity. Thus, for high optical output powers, disadvantages in the beam quality have to be accepted. Several industrial applications such as pumping and many material processing applications do not require a high beam quality, which is characterized by a beam parameter product [Ren92], [Sie98], [Eic04], [Hod05] value $M^2 \approx 1$. DBR or DFB tapered diode lasers would be another approach for high power levels and of better beam quality than a BA laser, but with disadvantages for the power conversion efficiency and have not been considered. Limitations were also made concerning the DFB grating itself. Second-Bragg-order DFB gratings will be used, because this allows one to enlarge the grating period by a factor of two. Furthermore, only refractive index DFB gratings, will be used, which are formed by a modulation of the refractive index with a certain period along the longitudinal direction of the diode laser. In principle, DFB can be also achieved by introducing a modulation of gain or loss with a certain period along the longitudinal direction [Kog71], [Kog72], [Luo90], [SZA00]. Gain or loss gratings are preferred for DFB lasers, if a high side-mode suppression ratio (SMSR) must be achieved [Kam01], for example in telecommunication applications. A high SMSR is not critical for efficient high power DFB-BA lasers and is therefore not considered here.

Using DFB-BA lasers for the development of wavelength stabilized high power lasers with a power conversion efficiency close to the theoretical limits has some advantages and disadvantages and requires to overcome technical difficulties. The following advantages are crucial factors for the decision to use DFB-BA lasers for the approach, mentioned above: Firstly, DFB-BA lasers with a buried overgrown DFB grating (no surface grating) can be soldered and mounted like a conventional high power BA laser, because the grating corrugation is thoroughly embedded inside the laser chip (in contrast to a DBR surface grating, for example). Secondly, the fact that the DFB grating is extended over the whole laser enables a design freedom in terms of a wide range of possible coupling strengths, which can be translated into an effective front facet reflectivity (identical mirror and DFB loss), if the rear facet is high reflection (HR) coated and the front facet AR coated. Thirdly, the demand on wafer area is smaller than for a DBR laser and roughly identical to a FP laser. The stronger dependence of the Bragg wavelength on the injection current is a disadvantage, compared to a DBR laser. Technical difficulties for the fabrication of a DFB-BA laser with a very high power conversion efficiency must be expected in the lithographic structuring and epitaxial overgrowth of the buried DFB grating, for example because of possible contamination with oxygen [Bug11], crystal defects [Bug11], incomplete planarization of the growth surface and self-assembly of structured material hetero-interfaces [And89], [Hof01], [Bug11]. In an ideal case, the monolithic integration of the DFB grating should cause no degradation in the electrical properties and internal loss of the laser, compared to a reference laser design without the DFB grating and grown in a single, un-interrupted epitaxy.

This work is subdivided into three main chapters. In chapter 1 “Theoretical foundation for high power distributed feedback lasers”, the differential quantum efficiency, internal quantum efficiency, internal optical loss and series resistance are figured out to be critical parameters, possibly limiting the power conversion efficiency of DFB lasers. Experimental results, obtained with DFB-BA lasers, fabricated until the beginning of this work, have shown, that the slope efficiency of DFB-BA lasers is too low and the resistance too high, compared to FP reference devices [Sch09a]. If one assumes that it is possible to integrate a DFB grating into a laser structure without adding significant series resistance, internal loss and without significant reductions in the internal quantum efficiency (which is in fact essential), the coupling coefficient, the cavity length and facet coatings determine the optical output power from the front facet. For a DFB laser of a specific cavity length with a HR coated rear facet and AR coated front facet mirror, the coupling coefficient determines the value of the threshold current and slope efficiency, analogous to the front facet reflectivity of a FP laser. Thus, the coupling coefficient must be chosen to achieve the optimum DFB resonator loss, like the front facet reflectivity of a FP laser can be adjusted for an optimum mirror loss, adequate to achieve the maximum optical output power at a specific injection current. Coupled mode theory [Kog72], [Str75], [Str77], [Kaz85], [Wen06] is used to derive the coupling coefficient and threshold conditions for a DFB laser with a second-order index grating [Kaz85]. Based on these calculations, threshold gain and differential quantum efficiency can be determined. The influence of the phase relation between the last grating stripe and the facet is studied and a simple a-priori approach is motivated which is assumed to solve this problem for BA lasers.

In chapter 2 "DFB-BA laser review", experimental results and theoretical findings on DFB-BA lasers are reviewed which have been published before the beginning of this work. The aim of this chapter is to draw relevant conclusions for the development of high efficiency, high power DFB-BA lasers from the state of the art technology.

Chapter 3 "Experimental and theoretical results from iteration I" describes in detail, how an epitaxy design for a laser waveguide is developed, which offers promising prospects to fabricate high power, high efficiency reference lasers (without a DFB grating) and is, as well, suitable for the integration of a DFB grating. Reference FP-BA lasers are fabricated from this material and the power-voltage-current (PUI) characteristics, spectral properties, spatial emission characteristics are investigated. Indeed, these FP-BA reference lasers were found to reach power conversion efficiencies of $> 60\,\%$ at 10 W output power. Afterwards, the development of a DFB grating, optimized for high power, high efficiency DFB-BA lasers is explained and the manufacturing and optimum coupling strength is discussed. Fabricated DFB-BA lasers have a record high peak power conversion efficiency up to 59 % and $> 50\,\%$ at 10 W. Experiments prove that the internal loss and internal quantum efficiency of the DFB-BA lasers are comparable to the FP reference lasers. Compared to FP reference lasers, the DFB-BA lasers are still slightly degraded due to a lower slope efficiency and an increased series resistance. Further improvement of the performance of DFB-BA lasers is analyzed to be possible in all likelihood by reducing the coupling strength for a higher slope efficiency and by a DFB grating design which enables a better charge transport through it and thus, reduces the series resistance. Experimental results for the threshold current and slope efficiency are in good agreement with the values which have been obtained with coupled mode theory and BA laser approximation. Results from the first experimental iteration have been published in [Sch10a], [Sch10b], [Cru10] and [Wen11].

A second experimental iteration has been executed, because the results from iteration I have shown, that the power conversion efficiency and spectral properties of DFB-BA lasers can be further optimized. The results are presented in chapter 4 "Experimental and theoretical results from iteration II". Firstly, a concept for the improvement of the electro-optical properties of DFB-BA lasers is discussed. Secondly, a DFB grating, further optimized for a lower series resistance and an even smaller coupling coefficient for a higher slope efficiency is developed. Afterwards, fabricated DFB-BA lasers are investigated and an increase of the peak power conversion efficiency to $> 60\,\%$ and up to $59\,\%$ at $10\,\mathrm{W}$ is observed. A very low reflectivity of the front facet is found to be crucial for a sufficient wavelength stabilization of these low-coupled high efficiency DFB-BA lasers. A high material quality in the re-grown grating region enables reliable operation of DFB-BA lasers over $> 5000\,\mathrm{h}$ at $10\,\mathrm{W}$ output power. Results from the second experimental iteration were reported in [Sch11], [Cru11a] and [Cru11c].

In chapter 5, the gained results are evaluated on the basis of other publications about DFB lasers and one publication about high power DBR-BA lasers. Finally, the results of this work are summarized and conclusions are drawn, how the performance of DFB broad area lasers can be further improved.

Chapter 1

Theoretical foundation for high power distributed feedback lasers

The aim of this chapter is to provide the theoretical background which is required to comprehend how factors, limiting the efficiency of DFB lasers were identified, and how high power, high efficiency DFB lasers can be developed. The chapter begins with definition of the power conversion efficiency and continues with the calculation of the optical output power and electrical power consumption of an in-plane edge emitting diode laser. This calculation is done for a Fabry-Pérot laser with reflecting mirrors at both ends of the cavity. Most of the definitions are also valid for DFB lasers. If this is not the case, it is mentioned and adequate definitions are derived later in this chapter. Based on these calculations, it is shown, how a high peak power conversion efficiency can be achieved in combination with a high optical output power. Afterwards, it is discussed, how in practice parameters can be optimized for a high optical output power and low electric power consumption. The impact of dissipated power on selected laser properties is discussed subsequently.

In the second part of the chapter, the principle of distributed feedback is introduced and the calculation of coupling coefficients for second-order DFB gratings is derived. Afterwards, the threshold condition for DFB lasers is derived in order to calculate the threshold current and slope efficiency. An approximation for broad are lasers is motivated and numerical calculations for broad area lasers are explained. Finally, the threshold gain and differential quantum efficiency is compared between a DFB-BA laser and a FP reference laser and consequences onto the power and efficiency characteristics are discussed.

1.1 Power conversion efficiency

1.1.1 Power conversion efficiency in DFB and FP lasers

The power conversion efficiency describes the fraction of power that has been obtained by a conversion process from an original nature of power into another nature of power. In real physical processes, the conversion efficiency is < 1 and a fraction from the original amount of power is not converted into the wanted nature of power but into further natures of power, which is often – heat. Power conversion and the related achievable conversion efficiency are of an enormous importance for many natural an technical processes. To achieve higher power conversion efficiencies in technical processes is expected to be an essential contribution to decreasing the net energy consumption. In this work, the power conversion efficiency η_{pc} of a semiconductor laser is defined as the amount of optical power P_{opt} that can be generated from an original amount of electric power input into the device P_{el}. The electric power is defined as the product of the diode voltage $U(I)$ and the current I, which is injected into the device.

$$\eta_{pc}(I) = \frac{P_{opt}(I)}{P_{el}(I)} = \frac{P_{opt}(I)}{U(I) \cdot I} \tag{1.1}$$

The overall amount of electric power that is required to operate a semiconductor laser in an experiment or in an industrial application is higher because of the need of additional power for the electric power supply, temperature stabilization as well as due to the electrical resistance of external electrical connections. Nevertheless, the power conversion efficiency of the diode laser is a convenient measure because it is a physical variable with good comparability and is the ultimate limit in a system.

For the optimization of the power conversion efficiency, the optical power $P_{opt}(I)$ has to be maximized and the voltage drop $U(I)$ to be minimized. In this work, high optical output power is also targeted. This requires an accordingly high injection current I. Therefore, both, $P_{opt}(I)$ and $U(I)$ have to be optimized especially in the range of injection currents, where high optical output power can be achieved. In the following subsections the optical output power of an edge emitting in-plane diode laser will be derived, as well as the voltage drop over the diode. With the results gained, the peak power conversion efficiency and the corresponding optical output power is calculated. The calculations allows to study the influence of individual parameters that affect the power conversion efficiency.

1.1.2 Optical output power

Understanding the power conversion efficiency η_{pc} requires to derive the optical output power P_{opt} and the electrical power consumption P_{el} of a diode laser. In this subsection, the optical output power is calculated, based on the derivation presented in [Col95]. The derivation is valid for an edge emitting in-plane diode laser with a waveguide structure and reflecting mirrors, defining the cavity. Thus, it is a derivation for FP lasers. Nevertheless, most of the considerations are always true for DFB lasers where a periodic modulation of the index of refraction along the cavity axis provides the major optical feedback. It will be explicitly denoted, if an equation is not valid for a DFB laser. The corresponding relations for DFB lasers are derived later in this chapter.

Intuitively, the derivation must be based on the definition of rate equations for the generation and recombination of electrons and photons. Firstly, one can define a rate equation for electrons that is valid inside the active region, which will be formed by one or more quantum wells. The time evolution of the electron density N depends on the rate of injected and recombining electrons G_{gen} and R_{rec}, respectively. The density of electrons, injected per second into the active region of volume V is given by $(\eta_i I)/(qV)$. Here, I is the electric current which is injected into the laser diode, η_i is the internal quantum efficiency and q the charge of a single electron. It should be noted, that the internal quantum efficiency is defined differently below and above the lasing threshold. Below threshold, it indicates the fraction of electric current that generates carriers inside the active region [Col95]. Therefore, it is sometimes called an injection efficiency. In contrast, the internal quantum efficiency above threshold is the fraction of current, which results in stimulated emission [Col95]. The recombination of electrons is determined by the rates for spontaneous recombination R_{sp}, nonradiative recombination R_{nr}, carrier leakage R_l and stimulated recombination R_{st}. Thus one obtains,

$$\frac{\mathrm{d}N}{\mathrm{d}t} = G_{gen} - R_{rec} \tag{1.2}$$

$$G_{gen} = \frac{\eta_i I}{qV} \tag{1.3}$$

$$R_{rec} = R_{sp} + R_{nr} + R_l + R_{st}. \tag{1.4}$$

In the absence of generation and photons, the carrier recombination represents a natural decay with carrier lifetime τ, $\mathrm{d}N/\mathrm{d}t = N/\tau = R_{sp} + R_{nr} + R_l$. One can write

$$R_{rec} = \frac{N}{\tau} + R_{st}. \tag{1.5}$$

The confinement factor of the active region is defined as $\Gamma = V/V_{\mathrm{p}}$, where V_{p} is the cavity volume which is occupied with photons. The photon rate equation can be written as

$$\frac{\mathrm{d}N_{\mathrm{p}}}{\mathrm{d}t} = \Gamma R_{\mathrm{st}} + \Gamma \beta_{\mathrm{sp}} R_{\mathrm{sp}} - \frac{N_{\mathrm{p}}}{\tau_{\mathrm{p}}}, \tag{1.6}$$

where N_{p} is the photon density, β_{sp} the spontaneous emission factor and τ_{p} the photon lifetime in which the photon density decays in the absence of any photon generation. The stimulated recombination rate R_{st} represents a gain process for photons because it describes the photon stimulated recombination of electrons and holes which generates more photons. With the gain per unit length g and a cavity length element Δz one can write

$$N_{\mathrm{p}} + \Delta N_{\mathrm{p}} = N_{\mathrm{p}}\, \mathrm{e}^{g\,\Delta z}. \tag{1.7}$$

For sufficiently small Δz one can approximate $\mathrm{e}^{g\,\Delta z} \approx 1 + g\Delta z$. With the group velocity v_{g} one can write $\Delta z = v_{\mathrm{g}}\Delta t$ and $\Delta N_{\mathrm{p}} = N_{\mathrm{p}}\, g\, v_{\mathrm{g}}\, \Delta t$, where Δt is the time increment, a photon with group velocity v_{g} needs to cover the distance Δz. For the photon generation one obtains

$$\left(\frac{\mathrm{d}N_{\mathrm{p}}}{\mathrm{d}t}\right)_{\mathrm{gen}} = \Gamma R_{\mathrm{st}} = g\, v_{\mathrm{g}}\, N_{\mathrm{p}}. \tag{1.8}$$

Thus, the new expressions for the carrier and photon density rate equations are:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{\eta_{\mathrm{i}} I}{qV} - \frac{N}{\tau} - g\, v_{\mathrm{g}}\, N_{\mathrm{p}} \tag{1.9}$$

$$\frac{\mathrm{d}N_{\mathrm{p}}}{\mathrm{d}t} = \Gamma\, g\, v_{\mathrm{g}}\, N_{\mathrm{p}} + \Gamma\, \beta_{\mathrm{sp}}\, R_{\mathrm{sp}} - \frac{N_{\mathrm{p}}}{\tau_{\mathrm{p}}}. \tag{1.10}$$

The threshold gain in a diode laser can now be derived in the following way. The optical energy propagates in a dielectric waveguide mode. This allows one to make the ansatz to express the electric field $\overrightarrow{E}$ with a transverse field profile $U(x,y)$ and a magnitude E_0 that propagates along the cavity axes z with the complex amplitude propagation constant β and angular frequency ω in transverse electric (TE) polarization, indicated by the unity vector $\overrightarrow{e}_{\mathrm{y}}$:

$$\overrightarrow{E}(x,y,z,t) = \overrightarrow{e}_{\mathrm{y}}\, E_0\, U(x,y)\, \mathrm{e}^{i(\omega t - \beta z)}. \tag{1.11}$$

The real part of the complex propagation constant β contains the dependency on the effective index of refraction n_{eff} and wavelength λ, while the imaginary