1. Introduction

Hybrid integrated diode laser systems are key components for various demanding applications. In hybrid systems, diode lasers are combined with other optical components to realize tailored light sources, from single prototypes to commercial products.

By directly coupling of the emission of diode lasers into optical fibers [1], [2], the light can be made available via standardized interfaces, enabling integration into arbitrary applications. The pumping of fiber laser systems is only one example [3]. In hybrid master oscillator power amplifier (MOPA) systems a low power diode laser with specific emission characteristics is combined with a semiconductor optical amplifier (SOA). Thereby high-power laser sources with narrow spectral emission bandwidth [4]–[6] for atomic cooling and trapping applications [7] are realized. By exploiting nonlinear optics, the emission wavelength range of diode lasers can be extended. For example, while no suitable diode lasers are yet available in the yellow-green spectral range, corresponding emission wavelengths can be realized with systems consisting of near-infrared emitting diode lasers and periodically poled nonlinear crystals (PPNC) for second harmonic generation [8]–[10]. In particular, laser emission at 561 nm is required for high resolution microscopy [11], [12] in biomedical applications.

On the one hand, hybrid systems combine the respective advantages of different optical components and to achieve the required emission characteristics. On the other hand, each optical element can be a source of unwanted optical feedback. It has been shown early on in [13] that optical feedback has negative effects on the emission characteristics of diode lasers. In hybrid systems, both SOAs [14] and PPNCs [15] introduced optical feedback that negatively affected the emission characteristics of the laser.

Optical isolators are therefore used in hybrid systems to shield the respective laser source from optical feedback e.g. due to SOAs [6], [16], [17] or PPNCs [18]. However, there are several limitations in the use of optical isolators. While diode lasers allow a particularly high level of miniaturization of hybrid systems, miniaturized optical isolators are not available for all wavelengths. In addition, the available micro-optical isolators are limited to hundreds of milliwatts of maximum power, and transmission can be low depending on the wavelength range. Nevertheless, the isolation is finite so feedback effects can still be observed [19].

Optical feedback is an inherent aspect that has to be considered in the design of hybrid integrated diode laser systems. Therefore, it is necessary to analyze in detail the feedback emission characteristics of the optical components as well as the operating behavior under external feedback. PPNCs, SOAs, and diode lasers are studied in the most common assemblies of hybrid systems. In this way, the individual optical components can be optimally matched to each other in future developments. In addition, new approaches for optimizations arise in order to reduce optical feedback influences in hybrid integrated diode laser systems.

Thesis outline

This thesis is organized as follows: First, chapter 2 gives a general overview of hybrid integrated diode laser systems. In addition to the basics of the most commonly used components, examples of the occurrence of optical feedback effects are also shown. The subsequent detailed analysis of feedback aspects in hybrid integrated diode laser systems is divided into two parts.

The first part focuses on the sources of optical feedback. In chapter 3, the reflection properties of periodically poled nonlinear crystals (PPNC) for nonlinear frequency conversion are discussed. The optical feedback properties of PPNCs with different geometries and applications are investigated in various experiments and compared with a tailored theoretical description. Chapter 4 covers the optical feedback emitted by semiconductor optical amplifiers (SOAs). The feedback emission of two SOAs, a ridge waveguide amplifier (RWA) and a tapered amplifier (TPA), is characterized with respect to the operating conditions by experiments and numerical simulations. The results of the feedback studies of the first part are concluded in chapter 5 and discussed with respect to hybrid integrated diode laser systems.

The second part deals with the effects of optical feedback on typical diode laser sources. In chapter 6 the influences of external optical feedback on the operational behavior of TPAs are analyzed. The output emission characteristics as well as the feedback emission characteristics of the TPA are examined under different feedback conditions by means of experiments and numerical simulations. In chapter 7 the emission behavior of distributed Bragg-reflector ridge waveguide lasers (DBR-RWLs) with different resonator configurations exposed to optical feedback is studied. The experimental results are also compared with theoretical calculations. Chapter 8 concludes this second part and classifies the results in relation to hybrid diode laser systems.

Finally, chapter 9 gives the final conclusion of this work and points out future directions.

2. Hybrid Integrated Diode Laser Systems

In hybrid integrated diode laser systems, diode lasers are combined with other optical components to develop unique laser light sources tailored to the application requirements. The systems are characterized by a high potential for miniaturization and customization. Thereby, the spectral and spatial emission properties, such as the emission wavelength and the beam quality, can be designed almost arbitrarily. Furthermore, different operation modes are possible to achieve either continuous wave or pulsed emission. Thus, the compact and robust laser modules are promising alternatives to large and complex laser systems based on solid-state or dye lasers.

Figure 2.1 shows a photo of a hybrid integrated diode laser system in a module the size of a matchbox. The system is based on a diode laser that emits a single spatial and spectral mode at an emission wavelength of 1122 nm. Using a master oscillator power amplifier (MOPA) scheme, the laser emission is amplified by two orders of magnitude to several watt optical power in a semiconductor optical amplifier (SOA). In a periodically poled nonlinear crystal (PPNC), the near-infrared laser emission is efficiently converted to the visible yellow-green spectral region by nonlinear frequency conversion. At an emission wavelength of 561 nm, watt-level powers are realized. Finally, the visible laser light is coupled into an optical fiber. The light is shaped between the optical components

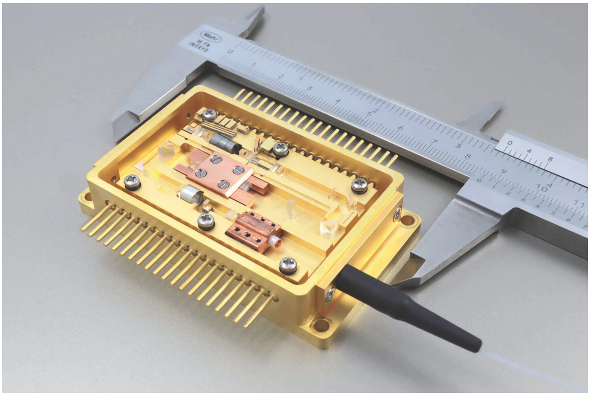


Figure 2.1.: Photo of a hybrid integrated diode laser system for watt-level output power in the yellow-green spectral region. The module features a hybrid master oscillator power amplifier diode laser source, second harmonic generation by a periodically poled nonlinear crystal, and an optical fiber output.

by means of microlenses. The system shown is just one example that illustrates the combination of various active and passive optical components in a compact module.

In the next sections, the fundamentals of high-power diode laser sources and PPNCs, two commonly used components in hybrid integrated diode laser systems, are briefly presented. In addition, two examples of the occurrence of optical feedback effects in hybrid integrated diode laser systems are presented.

2.1. High-Power Diode Laser Sources

Diode lasers are typically based on epitaxially grown vertical layers of n- and p-doped semiconductors that form a p-n junction. By applying a forward bias voltage, a population inversion between the conduction band and the valence band is created in the active zone, i.e. the junction. Thereby, optical gain for the stimulated emission of radiation is provided. The focus in this work is on edge-emitting diode lasers based on gallium arsenide compound semiconductors. In these diode lasers, the vertical epitaxial layer structure also forms a planar waveguide for the radiation surrounding the active zone. The cleaved and optically coated facets can then be used as resonator mirrors. By selecting the material composition, emission wavelengths in the range of 620 nm to 1200 nm can be achieved [20]–[22].

Diode lasers have many advantages that clearly distinguish them from other types of lasers. Direct electrical pumping at low voltages allows simplified control of the laser operation, including direct modulation capability. In addition, their electro-optical efficiency is exceptionally high and their small size makes them ideal for micro-integration. However, the operating principle of diode lasers also brings challenges that must be considered in the development of diode laser systems.

To realize the emission of only one single spatial mode, the diode laser has to be structured accordingly. In addition to the vertical waveguide, the light must also be guided in the horizontal direction, for example by forming a ridge waveguide. However, in these ridge waveguide lasers (RWL), the optical output power is usually limited to around 1 W by damage thresholds due to high optical peak intensities [23], [24].

Due to the large number of possible band transitions between the conduction and valence bands, the optical gain extends over a spectral range of several nanometers. Therefore, spectrally selective structures such as a distributed Bragg-reflector (DBR) are monolithically integrated into the diode laser and act as a resonator mirror instead of the facet. When integrated into an RWL, the laser is referred to as DBR-RWL and single spectral mode emission with a spectral width around 1 MHz is achieved [5], [25].

To overcome the limited optical power of lasers emitting a single spatial and spectral mode, the master oscillator power amplifier (MOPA) concept can be used. The laser acts as the master oscillator while its emission is coupled into a semiconductor optical amplifier (SOA). This increases the optical power without significantly degrading the spectral and spatial beam characteristics. In addition, the spatial separation of the diode laser and the SOA provides the advantage of power scaling without changing the operating point of the diode laser. SOAs are generally similar to diode lasers except for the absence of a resonator. Depending on the required output power level, different types of SOAs are used. Ridge waveguide amplifiers (RWA) are similar to RWLs and provide watt-level output power. In tapered amplifiers (TPA) the light is not entirely guided in the horizontal direction allowing the light to diverge. Since the optical intensity is thereby reduced, much higher optical powers up to 10 W are possible [26], [27].

2.2. Frequency Conversion using Periodically Poled Nonlinear Crystals

Nonlinear frequency conversion is based on the fact that the electrical polarization in a medium is generally a nonlinear function of the local electric field. When excited by an oscillating electric field, such as a monochromatic electromagnetic wave, additional frequencies appear in the resulting oscillation of the polarization. Since an oscillating electric polarization is a source for the emission of electromagnetic radiation, waves with different frequencies can thus be generated from the incident wave.

The nonlinear dependence of the material polarization $\mathcal{P}$ on the electric field strength $\mathcal{E}$ is usually expressed as a power series in the electric field strength [28]

$$\mathcal{P}(t) = \varepsilon_0\chi^{(1)}\mathcal{E}(t) + \varepsilon_0\chi^{(2)}\mathcal{E}^2(t) + \varepsilon_0\chi^{(3)}\mathcal{E}^3(t) + \mathcal{O}\left(\mathcal{E}^4(t)\right). \tag{2.1}$$

While ε_0 is the vacuum permittivity, the coefficients $\chi^{(i)}$ are the ith order electrical susceptibilities of the medium. In general, both the polarization and the electric fields are vectors, and the susceptibilities are tensors of rank $i+1$. Furthermore, the polarization may not respond to temporal variations of the electric field instantaneously, which makes the relation more complex. However, for most practical cases with electromagnetic waves, the simple scalar equation (2.1) is sufficient, noting that the susceptibilities depend on the orientation of the medium relative to the incident wave.

The exploitation of high second-order susceptibility $\chi^{(2)}$ in certain crystalline materials is widely used and enables a variety of different frequency conversion processes such as second harmonic generation (SHG), sum frequency generation (SFG), or spontaneous parametric down conversion (SPDC). However, efficient frequency conversion is generally limited by the dephasing of the electrical polarization and the radiated frequency-converted waves.

The effect is illustrated by the example of SHG, which generates light with a doubled frequency. Assuming a monochromatic wave propagating in z-direction and oscillating with frequency ω and wave vector k, the second-order term of the polarization oscillates with 2ω and $2k$. The corresponding radiated wave oscillates with 2ω but wave vector k_{SH}. Thus, after a distance Δz a phase difference [29] of

$$\Delta\phi = (k_{\mathrm{SH}} - 2k)\Delta z \tag{2.2}$$

is accumulated. Since the wave vectors $k = 2\pi n/\lambda$ and $k_{\mathrm{SH}} = 2\pi n_{\mathrm{SH}}/\lambda_{\mathrm{SH}}$ contain the refractive indices n and n_{SH} at the respective wavelengths λ and $\lambda_{\mathrm{SH}} = \lambda/2$, the phase difference is generally non-vanishing due to dispersion. When the phase difference reaches $\Delta\phi = \pi$, the generated waves superimpose destructively.

Minimizing the phase difference or at least the occurrence of destructive superpositions is called phase matching and is mandatory for efficient frequency conversion. The most common phase matching schemes are birefringent phase matching (BPM) and quasi phase matching (QPM). For ferroelectric crystals such as lithium niobate (LN), lithium tantalate (LT) or potassium titanyl phosphate (KTP), QPM is widely used. In QPM, the crystal structure is periodically inverted in the plane perpendicular to the propagation direction of the incident light beam (z), resulting in a sign change of the second-order susceptibility. Consequently, the second-order polarization term is phase shifted by π and generated second harmonic (SH) waves can still constructively superimpose. The period Λ_{QPM} of the periodic poling [29] is then given by

$$\Lambda_{\mathrm{QPM}} = \frac{\lambda}{2\left(n_{\mathrm{SH}} - n\right)}. \tag{2.3}$$

With the periodic poling the phase matching condition can be defined as

$$\Delta k = 2k - k_{\mathrm{SH}} - \frac{2\pi}{\Lambda_{\mathrm{QPM}}}, \tag{2.4}$$

where ideal phase matching consequently yields a phase mismatch $\Delta k = 0$. According to the dispersion and the temperature dependence of the refractive index, phase matching can only be guaranteed within a small wavelength and temperature range, typically far below 1 nm and 1 K, respectively [30].

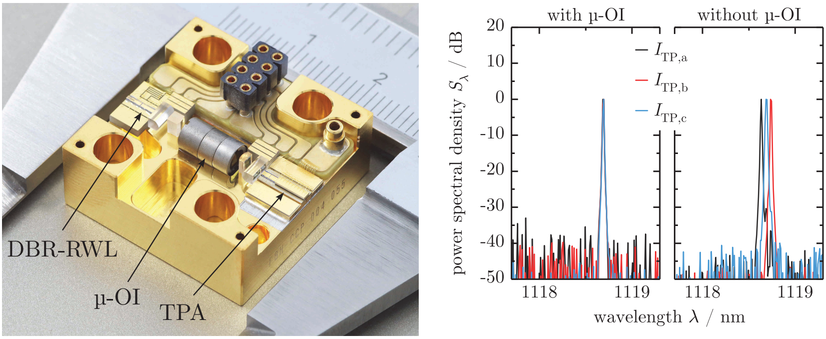
Periodically poled nonlinear crystals (PPNC) are commercially available and offer several advantages for hybrid integrated systems. The QPM principle allows to exploit the highest second-order susceptibility and achieve sufficient conversion efficiency even in a simple single pass configuration. In contrast to other phase matching schemes, no spatial walk-off occurs.

Depending on the intended application and material properties, PPNCs with different geometries are used. Due to the quadratic dependence on the fundamental electric field, the conversion efficiency raises with increasing field strength, i.e. higher optical intensity of the incident beam. Thus, PPNCs with waveguide structures for strong optical confinement provide the highest conversion efficiencies [31]. However, the maximum achievable optical power is limited by parasitic effects due to the high optical intensity [32]. In contrast, bulk PPNCs are less sensitive to limiting effects, but require well-defined beam shaping of the incident beam, which is ideally a Gaussian beam [33].

2.3. Occurrence of Optical Feedback

Hybrid integrated diode laser systems can contain a variety of different active and passive optical elements. In addition to the optical elements with considerably varying reflective characteristics, reflections outside the actual laser system can also be a source of external optical feedback. Therefore, the effects of optical feedback in hybrid integrated diode laser systems can manifest themselves in a variety of ways.

In figure 2.2a the photo of a typical hybrid integrated master oscillator power amplifier (MOPA) laser source is shown. The MOPA is intended as a laser source with a narrow-band emission spectrum with a fixed central emission wavelength near 1120 nm and variable output power up to several watts. A distributed Bragg-reflector ridge waveguide laser (DBR-RWL) provides laser emission with the desired spectral characteristics which is shaped and coupled into a semiconductor optical amplifier (SOA) by microlenses. Here, the SOA is realized as a tapered amplifier (TPA). A micro-optical isolator (µ-OI) is placed between the DBR-RWL and the TPA. While the DBR-RWL is usually operated at a constant working point, the working point of the TPA is varied to scale the optical output power.



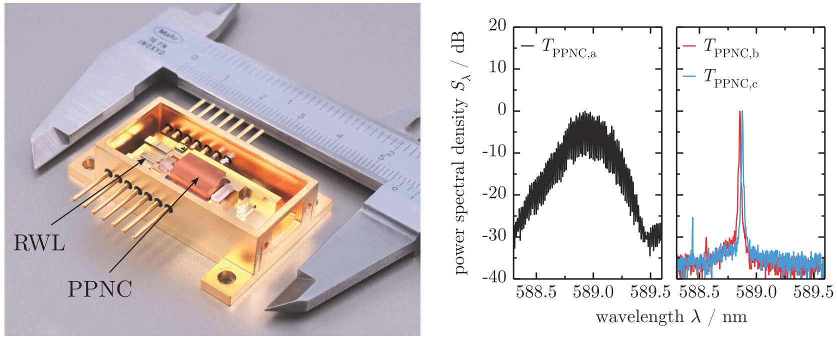
(a)

(b)

Figure 2.2.: (a) Photo of a hybrid integrated master oscillator power amplifier (MOPA) comprising a distributed Bragg-reflector ridge waveguide laser (DBR-RWL) as the master oscillator, a micro-optical isolator (µ-OI), and a tapered amplifier (TPA). The MOPA is designed to provide multiple watts of optical output power in a single spectral mode. (b) Emission spectra of a hybrid integrated MOPA with and without µ-OI at three working points $I_{\mathrm{TP,a}}$, $I_{\mathrm{TP,b}}$ and $I_{\mathrm{TP,c}}$ of the TPA. The DBR-RWL is operated at a constant working point.

In figure 2.2b the measured emission spectra of a MOPA are given. The left plot shows the measured emission spectra at three working points of the TPA. The obtained optical output power increases from 2.0 W at the working point $I_{\mathrm{TP,a}}$ to 2.3 W at the working point $I_{\mathrm{TP,c}}$. The corresponding emission spectra remain unchanged as desired. However, when the µ-OI is removed, a different behavior is observed. The emission spectra of the same MOPA without µ-OI, operated at the same working points, are shown in the graph on the right. At each working point still a single spectral mode is observed but the central emission wavelengths differ by about 50 pm. With respect to the internal spectral mode spacing of the DBR-RWL laser cavity the emission wavelength changes can be associated with spectral mode hops. Hence, it can be assumed that the TPA is a source of optical feedback which, if not blocked by an optical isolator, causes spectral mode hops in the DBR-RWL.

Figure 2.3a displays a photo of hybrid integrated laser system with a periodically poled nonlinear crystal (PPNC) for second harmonic generation (SHG). The laser system is developed to provide spectrally broadband laser emission with a central emission wavelength of 589 nm. A ridge waveguide laser (RWL) is used as the pump laser source whose emission is directly coupled into a ridge waveguide PPNC. Due to the absence of spectrally selective elements in the Fabry-Pérot cavity of the RWL, the emission spectrum can be broad, only defined by the spectral distribution of the optical gain. Consequently, an emission spectrum is obtained that contains numerous emission lines extending over several nanometers around a central wavelength of 1178 nm. In the PPNC, the laser emission is converted to the yellow spectral region by SHG. In order to achieve ideal phase matching at 589 nm, the crystal temperature is adjusted accordingly.



(a) (b)

Figure 2.3.: (a) Photo of a hybrid integrated diode laser system comprising a ridge waveguide laser (RWL) and a periodically poled nonlinear crystal (PPNC) for second harmonic generation. The module is designed for spectral broadband emission in the yellow spectral region. (b) Emission spectra of the hybrid laser system at three different temperatures of the PPNC $T_{\mathrm{PPNC,a}}$, $T_{\mathrm{PPNC,b}}$ and $T_{\mathrm{PPNC,c}}$. The RWL is operated at a constant working point.

In the left diagram in figure 2.3b the spectrum of the SH emission at the ideal working point with the crystal temperature $T_{\mathrm{PPNC,a}}$ is given. Here, a spectrally broadband emission with a spectral width around 0.3 nm is realized. As the PPNC temperature changes, it is found that the emission spectrum changes drastically, although the RWL is still operated at the same working point. In the right diagram in figure 2.3b the emission spectra at two different crystal temperatures $T_{\mathrm{PPNC,b}}$ and $T_{\mathrm{PPNC,c}}$ are shown. The spectra are characterized by only one single emission line with a spectral width below

10 pm. By increasing the crystal temperature the central emission wavelength is slightly red-shifted from initially 588.85 nm to 588.87 nm. Therefore, it can be assumed that the PPNC generates spectrally selective optical feedback. The RWL is thus spectrally stabilized so that essentially only one longitudinal mode with a central wavelength of 1177.7 nm is emitted.

In the following chapters, PPNCs, SOAs, and DBR-RWLs, the typical components of hybrid integrated diode laser systems, are analyzed with respect to optical feedback. Thereby, the strength of the optical feedback of SOAs is determined and the feedback conditions under which spectral mode hops occur in DBR-RWLs. Furthermore, it is resolved why the optical feedback of PPNCs is spectrally selective.