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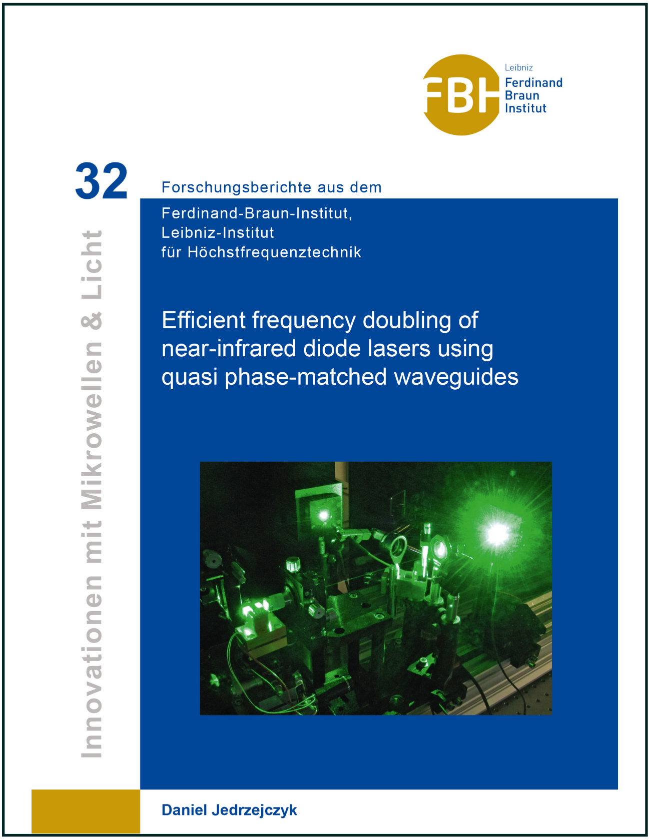
Efficient frequency doubling of near-infrared diode lasers using quasi phase-matched waveguides



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Chapter 1

Introduction

In over five decades since its invention [1], not only has the laser found widespread applications in science and industry, but it has also become an irreplaceable tool in our everyday life. Due to a permanent improvement in its performance, flexibility and diversity, the number of applications has been growing rapidly over the years. However, in spite of a high demand, the availability of efficient and compact laser systems in the green spectral range has been limited until recently.

Such lasers, that are additionally characterized by an output power of several hundred milliwatt in continuous-wave operation and a nearly diffraction limited beam quality, are required in a variety of application fields. The green spectral region, characterized by a very low absorption in water, is particularly interesting for bio-medical and bio-technical applications, such as, for example, flow cytometry [2]. In addition, such laser systems are also required in the fields of spectroscopy, in which case single-frequency emission is often indispensable [3]. Furthermore, efficient and compact lasers in the green spectral region with moderate power have already found wide application in the rapidly growing field of laser display technology [4]. Finally, in the high-power range, a laser with the aforementioned characteristics can be utilized as a pump source for a Ti:Sapphire laser [5].

In recent years, a few approaches to realize miniaturized and efficient green emitting lasers have been introduced, among which frequency doubling of near-infrared diode lasers in quasi phase-matched nonlinear bulk crystals provides a number of advantages. In comparison to direct diode lasers based on InGaN [6, 7, 8], the aforementioned concept enables a higher output power [9, 10]. In addition, it provides single-frequency emission and is also suitable for generation of laser radiation in the yellow spectral range [11, 12]. As opposed to frequency doubled solid-state lasers [13, 14, 15] and blue diode laser pumped Pr:YLF lasers [16, 17, 18], frequency doubling of near-infrared diode lasers is not limited to strict atomic transitions and, therefore, enables generation of arbitrary wavelengths. Furthermore, wavelength tuning over a range of several hundred picometer can be achieved by adjusting the temperature and the injection current. An important additional argument in favor of direct second-harmonic generation with diode lasers is also the already demonstrated miniaturization of this concept in a straightforward single-pass configuration [19, 20].

Apart from the advantages of direct diode laser frequency doubling in a single-pass configuration, the low conversion efficiency of the nonlinear interaction in a bulk crystal represents the main disadvantage of this concept. This impediment, which is induced by a relatively low fundamental radiation intensity resulting from crystal length dependent laser beam focusing [21], is additionally reinforced in case of diode lasers by laser beam quality degradation with increasing output power. The improvement of the conversion efficiency during frequency doubling of near-infrared diode lasers is therefore a key factor to ensure high wall-plug efficiency of miniaturized green emitting laser modules, based on this approach [19, 20]. The target of this thesis is to investigate the potential of quasi phase-matched waveguide structures for this purpose. In this context, an extensive study of second-harmonic generation in ridge and planar waveguides is conducted in order to identify all benefits and limitations for both geometries with respect to maximum conversion efficiency and accessible second-harmonic power range.

This thesis is organized as follows: in Chapter 2 fundamentals of diode lasers are discussed, followed by the presentation of requirements for single emitters suitable for frequency doubling, and the description of near-infrared diode lasers applied in this work. Chapter 3 covers the fundamentals of integrated optics and nonlinear optics. In case of the latter field the focus is laid on the concepts of second-harmonic generation and quasi phase-matching. Subsequently, the waveguide structures applied in this work for second-harmonic generation into the green spectral region are discussed.

In Chapter 4, efficient frequency doubling of a diode laser in a ridge waveguide structure is demonstrated. In particular, the influence of structural imperfection, optical absorption and subsequent heat generation on the conversion efficiency of the nonlinear interaction is investigated in-depth by means of experiments and numerical simulations.

In Chapter 5, efficient high-power frequency doubling of a diode laser in a planar waveguide is demonstrated. Prior to high-power experiments, the second-harmonic generation process is investigated extensively with respect to near-infrared pump beam parameters, resulting in a definition of their optimum values with corresponding tolerances. Summary, conclusions and perspectives are presented in Chapter 6.

Chapter 2

Design and selection of NIR diode lasers for frequency doubling

2.1 Fundamentals of diode lasers

Laser operation from a semiconductor material was demonstrated for the first time in 1962 [22, 23, 24, 25, 26]. In the following years a room-temperature continuous-wave (CW) operation [27, 28] and significant reliability improvement [29, 30, 31] were achieved. The robustness and small footprint of diode lasers, as well as the feasibility of mass-production at low cost resulted in two early commercial applications in the field of data storage and optical communication [32, p. 3]. Over the years, diode laser technology evolved further enclosing diverse new applications in different spectral and power ranges.

At the present day, diode lasers are the most efficient lasers reaching maximum electro-optical conversion efficiency in extent of 70 % [33, 34, 35]. They find application in a wide scope of fields, ranging from pumping of solid state and fiber lasers [36, 37], through material processing [38], spectroscopy [39, 40] and metrology [41] to free space communication [42, 43].

In this section, the fundamentals of diode lasers are discussed. The population inversion and optical gain are described in Sect. 2.1.1, followed by the concept of optical cavity and laser threshold in Sect. 2.1.2. In Sect. 2.1.3 and 2.1.4 the resonator concepts for longitudinal single-mode operation and the methods for lateral confinement are presented, respectively. Finally, in Sect. 2.1.5 the spatial characteristics of a diode laser beam are discussed.

2.1.1 Inversion and optical gain

Selective doping with donors and acceptors as well as concentration variation of semiconductor layers during growth enables the fabrication of a double heterostructure, a fundamental component of a diode laser. This is basically a pin-junction complemented by a joint confinement region for both charge carriers and photons. The charge carriers are confined due to lower band gap energy, the photons due to higher refractive index, as presented in Fig. 2.1 (a) and (b), respectively. Under forward bias this structure provides a local inversion in the population of energy states, a condition which needs to be fulfilled in order for laser operation to take place. The dominant optical transition between the conduction and valence band in the confinement region determines the wavelength of the emitted electro-magnetic radiation. This generated optical field propagating through the junction is amplified further by means of stimulated emission due to the presence of population inversion. The amplification is described by the relation

$$\mathcal{J}(x) = \mathcal{J}(0)\, e^{\gamma x} \tag{2.1}$$

in accordance with [44, Eq. 9.28, p. 225], where $\mathcal{J}$ is the intensity of light, x is the propagation direction and γ is the material gain. Since gain is directly proportional to the difference between the electron populations in the conduction and valence band [44, Eq. 9.29, p. 225], negative gain and therefore attenuation of radiation is present in case of thermal equilibrium, i.e. no forward bias. However, as mentioned above, under forward bias the population inversion

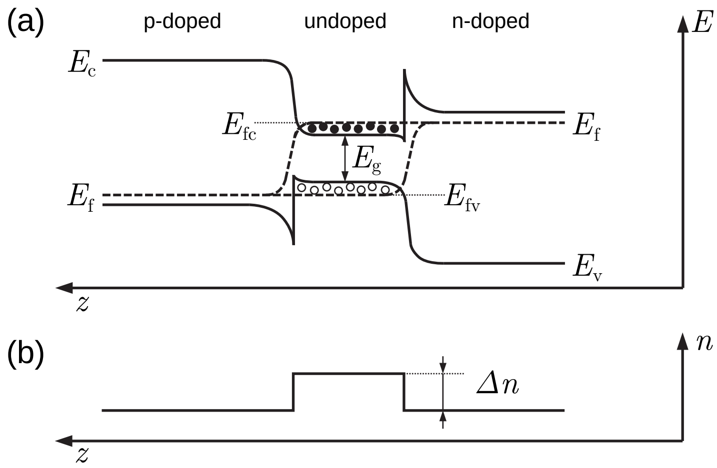

Figure 2.1: Schematic depiction of a double heterostructure under forward bias with regard to energy levels (a) [45, Fig. 3, p. 7] and refractive index (b)

results in a positive value of γ and a corresponding amplification. In general, photon energy and carrier density have a significant influence on the optical gain profile [44, p. 225], calculation of which is however beyond the scope of this work. Positive gain is expected in the photon energy region given by

$$E_g < h\nu < E_{fc} - E_{fv} \tag{2.2}$$

in accordance with [44, Eq. 9.33, p. 226], where E_g is the band gap energy, $h\nu$ is the photon energy and E_{fc} and E_{fv} are the conduction and valence quasi Fermi levels, respectively, as depicted in Fig. 2.1 (a).

Modern diode lasers consist of a separate confinement double heterostructure [44, p. 242] with separate confinement regions for charge carriers and photons, as presented schematically in Fig. 2.2 (a). The latter are confined in a thicker optical waveguide, preferably in the waveguide lowest-order mode, the former

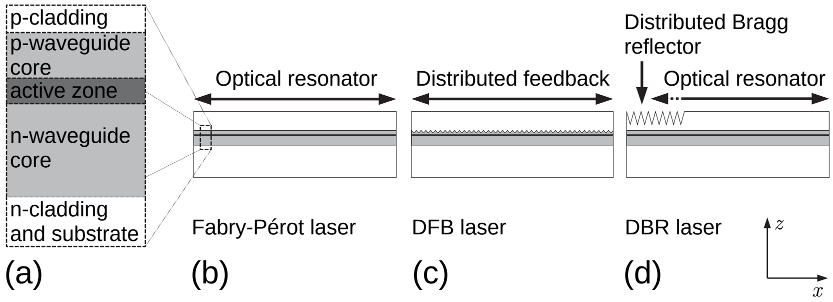

Figure 2.2: Schematic depiction of a separate confinement double heterostructure (a), depiction of a Fabry-Pérot laser (b), a DFB laser (c) and a DBR laser (d)

are confined in a much thinner active zone. The confinement factor [45, Eq. 21, p. 11]

$$\Gamma = \frac{\displaystyle\int_{\mathrm{AZ}} \mathfrak{J}^{(m)}(z)\, dz}{\displaystyle\int_{-\infty}^{+\infty} \mathfrak{J}^{(m)}(z)\, dz} \tag{2.3}$$

defines the overlap between the intensity distribution $\mathfrak{J}^{(m)}(z)$ of the optical waveguide mode $m = 0, 1, 2, ...$ and the active zone (AZ). The gain of the corresponding optical mode γ_{modal} amounts to

$$\gamma_{\mathrm{modal}} = \Gamma\gamma, \tag{2.4}$$

as described in detail in [45, p. 10]. During design of diode laser structures care needs to be taken for the modal gain of waveguide higher-order modes to be lower than of the fundamental mode.

Primarily, quantum-well structures [46] utilizing quantum effects [44, p. 49] are applied as active region, since they assure lower threshold current density and a lower linewidth enhancement factor [44, p. 243]. Furthermore, the polarization or emission wavelength in a quantum-well can be adjusted due to strain effects. In addition, multiple quantum-wells [47] provide a higher overall gain and a superior performance at high currents [44, p. 243].

2.1.2 Optical cavity and laser threshold

For laser operation to begin, optical feedback into the active medium is required. A resonant cavity providing optical oscillation is well suited for this purpose. In case of edge-emitting diode lasers, a Fabry-Pérot resonator, consisting of two parallel mirrors as depicted in Fig. 2.2 (b), is created through proper facet cleaving.

The consideration of gain and loss during single resonator roundtrip allows to define the threshold gain value [45, Eq. 24, p 13]

$$\Gamma\gamma_{\mathrm{th}} = \alpha_{\mathrm{i}} + \alpha_{\mathrm{M}} \tag{2.5}$$

$$= \alpha_{\mathrm{i}} + \frac{1}{2L_{\mathrm{R}}} \ln \frac{1}{R_{\mathrm{f}}R_{\mathrm{r}}}, \tag{2.6}$$

at which the internal loss α_i and the mirror loss α_M are compensated and the laser operation begins. Here, L_R is the resonator length and R_f and R_r is the reflectivity of the front and rear facet, respectively. The radiation coupled out from the resonator through the facet forms the laser beam which is then available for the desired application.

The threshold gain γ_{th} is reached at a threshold current density $\mathcal{I}_{th}$, which, for a given injection area, corresponds to a threshold current I_{th}. Below this value the output power P, driven by spontaneous emission, increases insignificantly with increasing current I, as shown schematically in Fig. 2.3. The transition to

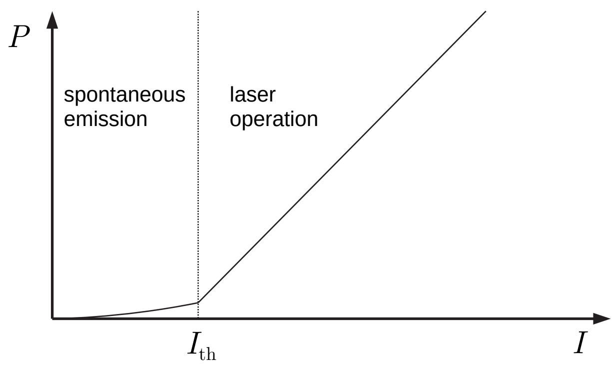

Figure 2.3: Schematic depiction of power-current dependency for a diode laser

stimulated emission at the threshold current I_{th} induces a linear dependency between the output power and the injection current. The output power is then given in accordance to [45, Eq. 93, p. 44] by

$$P = \eta_d \left(\frac{h\nu}{q} \right) (I - I_{th}) \tag{2.7}$$

with differential conversion efficiency η_d, photon energy $h\nu$ and electron charge q.

An optical resonator provides oscillation for its resonance frequencies defined as

$$\nu = \frac{c_0}{2\,L_R\,n(\nu)}\,m \tag{2.8}$$

in accordance to [44, Eq. 9.44, p. 234] with velocity of light in vacuum c_0, resonator length L_R, refractive index n and an integer m. All resonance frequencies, for which the threshold gain defined in Eq. (2.5) is reached, can contribute to the laser operation. In general, this results in a broadband laser emission.

The resonance frequencies from Eq. (2.8) correspond to longitudinal modes in the wavelength distribution. The permitted wavelength values are defined as

$$\lambda = \frac{2L_R n(\lambda)}{m} \tag{2.9}$$

according to [45, Eq. 19, p. 10] with the corresponding mode spacing [45, Eq. 54, p. 33]

$$\Delta\lambda = \frac{\lambda^2}{2L_R n_{gr}}, \tag{2.10}$$

where n_{gr} is the group index of refraction [48, p. 298].

2.1.3 Longitudinal single-mode operation

Laser operation in a longitudinal single-mode can be obtained through a targeted control of the mirror loss α_M from Eq. (2.5) by an application of a wavelength selective mirror. A grating is well suited for this purpose, since the periodic modulation of a refractive index induced in this manner leads to a wavelength dependent Bragg reflection.

Two sorts of diode lasers with distributed-feedback can be distinguished. A distributed feedback (DFB) laser, in case of which the grating is integrated in the active region over its entire length, is presented schematically in Fig. 2.2 (c). A distributed Bragg reflector (DBR) laser makes use of a biased active region and a passive grating region operating as a cavity mirror, as depicted in Fig. 2.2 (d). In both cases the effective refractive index is modulated, either by longitudinal refractive index variation in the waveguide core [49, 36] or by surface etching of the cladding layer [50, 51]. For a grating period Λ_{DBR}, effective refractive index N and integer grating mirror order m, a targeted DBR emission wavelength

$$\lambda_{\mathrm{DBR}} = \frac{2\,N}{m}\,\Lambda_{\mathrm{DBR}} \tag{2.11}$$

is expected [44, Eq. 9.69, p. 260]. According to the coupled-wave theory [52, 53] for wavelengths around this value the forward and backward traveling waves are coupled. The strength and the spectral range of this interaction is defined by grating properties, such as its order and shape, corrugation duty cycle and depth and residual distance to the active region [54]. The proper choice of these parameters results therefore in a longitudinal single-mode operation.

2.1.4 Lateral confinement

Gain-guided lasers make use exclusively of current confinement in the lateral direction, based on current injection through a defined conductive area on the surface of a diode laser, as shown schematically in Fig. 2.4 (a). In such devices

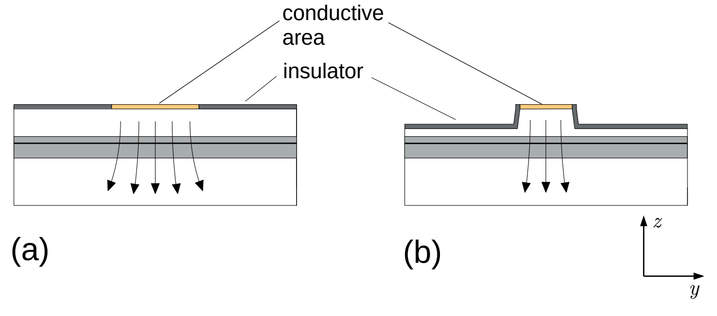

Figure 2.4: Schematic depiction of lateral confinement concepts: gain-guiding (a) and index-guiding (b)

the inversion and therefore the positive material gain γ can only be generated below the conductive stripe area. Outside of it the laser operation is not possible due to optical loss. Furthermore, during laser operation a thermally induced refractive index increase due to resistive heating in the current injection area can lead to a lateral wave-guiding.

Geometrical index-guiding resulting from a difference in the effective refractive index is presented schematically in Fig. 2.4 (b). This method is used, additionally to current confinement, in ridge-waveguide (RW) lasers in order to induce injection current independent optical wave-guiding in the lateral direction. Proper choice of the index step and the ridge width leads to laser operation in the lateral lowest-order waveguide mode, which is of major significance for good lateral beam quality.

2.1.5 Spatial properties of a diode laser beam

During propagation in free space the laser beam diameter alters with increasing distance due to diffraction. In the consequent laser beam caustic a beam waist diameter d_0 and a divergence full angle θ_{div} can be specified, as presented in Fig. 2.5. These two parameters define the beam propagation ratio M^2 through the relation

$$\frac{d_0 \cdot \theta_{\text{div}}}{4} = \mathrm{M}^2 \frac{\lambda}{\pi} \tag{2.12}$$

in accordance with [55, Eq. 5.29 and 5.30, p. 226], where λ is the wavelength of radiation. The value of M^2 describes the beam quality of a laser beam. Please note that the beam quality decreases with increasing M^2 value. A Gaussian

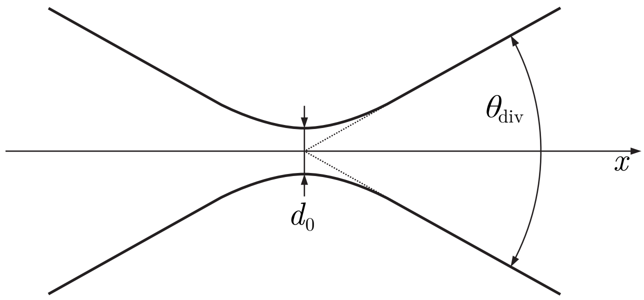

Figure 2.5: Schematic depiction of a laser beam caustic

beam [56, p. 52] represents a diffraction-limited 3-dimensional eigensolution of the wave equation for a laser beam propagating in free space under slowly varying envelope approximation and is characterized by an $\mathrm{M}^2 = 1$. Real laser beams possess beam propagation ratio M^2 equal to 1 or larger. In this work, the laser beam quality is determined by means of a caustic measurement, which is described in detail in Appendix A.1.

In general, a diode laser beam is simple astigmatic, which means that two principal directions can be distinguished, as shown schematically in Fig. 2.6. A caustic measurement in these two directions, the fast- and the slow-axis to be specific, enables a complemented spatial laser beam characterization. The fast-axis denotes the vertical direction, which is characterized by a large beam divergence due to tight confinement in the waveguide structure defined during epitaxial growth. Hence, optics with high NA values needs to be applied in front of a diode laser in order to collimate its radiation in the fast-axis. In addition, this principal direction is characterized by a nearly diffraction-limited beam quality.

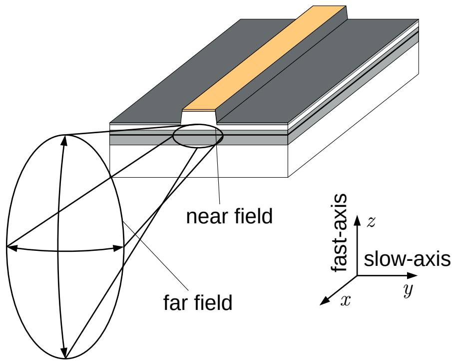

Figure 2.6: Schematic depiction of a diode laser and its emission characteristics. The principal directions are fast- and slow-axis

The lateral direction is referred to as the slow-axis. It exhibits smaller beam divergence compared to the fast-axis, which, in addition, depends significantly on the lateral resonator design. Narrow emitters, such as for example RW lasers, are characterized by a larger far field distribution than their wide counterparts [45, Sect. 3.3, p. 29]. In addition, due to lateral wave-guiding in the spatial fundamental mode, RW lasers exhibit a nearly diffraction-limited beam quality in the slow-axis. Their maximum output power is limited due to small light emitting area and the consequent catastrophic optical damage [57] or catastrophic optical mirror damage [58, 59] caused by a too high power density. An increase in the maximum output power can be achieved with wider resonator geometries, characteristic for broad area emitters, which, however, is accompanied by a significant degradation of the lateral beam quality.

2.2 Requirements for diode lasers intended for frequency doubling

Laser beam available for frequency doubling must possess specific characteristics, in order for the nonlinear process to be efficient. It has been recognized shortly after the first demonstration of second-harmonic generation (SHG) [60], that the efficiency of the frequency conversion process increases with increasing pump intensity [61, 62]. Higher power density in a nonlinear bulk crystal can be reached by a stronger focusing of the pump laser beam, which, however, leads to a shorter effective interaction length due to larger divergence. As has been investigated for a Gaussian pump beam in [21, 63, 64], the optimum focusing changes with the nonlinear crystal length. Later on, it has been also shown theoretically and experimentally, that longitudinal modes in the spectral distribution closely spaced within the acceptance bandwidth of the nonlinear crystal can additionally enhance the frequency doubling efficiency by a factor of two [65, 66]. Furthermore, other experiments have demonstrated, that too wide spectral emission leads to a decrease in conversion efficiency [67, 68]. Finally, the beam quality influence has also been investigated theoretically and experimentally in nonlinear bulk crystals, indicating that increasing beam quality parameter M^2 leads to a less efficient SHG [69, 70, 71, 72, 73].

For efficient frequency conversion process in quasi phase-matched waveguide structures diode lasers emitting nearly diffraction-limited radiation are required.

Good beam quality is of great relevance for high coupling efficiency into waveguide lowest-order mode in addition to its beneficial influence on the normalized SHG conversion efficiency during free beam propagation.

Spectrally narrow-band emission matching the acceptance bandwidth of the nonlinear crystal is crucial for an efficient SHG process. In case of diode lasers this condition can be fulfilled by longitudinal single-mode operation.

The diode laser output power does not influence the normalized SHG conversion efficiency. However, due to the nonlinear character of the interaction, increasing pump power results in an increasing opto-optical conversion efficiency. Additionally, the power level has to be chosen properly to the geometrical configuration of the SHG device applied for frequency doubling, as will be shown in successive chapters of this work.

2.3 Single emitters design and selection

In recent years diode lasers suitable for direct continuous-wave (CW) frequency doubling have been reported. In the power range of 1 W wavelength stabilized ridge waveguide diode lasers [49, 74, 75, 76, 77, 78] providing laser radiation in spectral and spatial single mode have been demonstrated. For high-power operation, DBR tapered diode lasers [79, 80, 81] and monolithic DFB tapered master-oscillator power-amplifiers (MOPA) [82, 83, 84, 85] have been introduced, which emit nearly diffraction-limited radiation in a longitudinal single-mode at power levels up to 12 W. These lasers are well suited for direct frequency doubling in a single-pass configuration both in bulk crystals and waveguide structures.

In this work, DBR ridge waveguide and DBR tapered diode lasers are applied for frequency doubling in a ridge and a planar waveguide nonlinear crystal, respectively. Below, in Sect. 2.3.1 and 2.3.2, their vertical structure design and resonator concepts are discussed in-depth, respectively.

2.3.1 Vertical design

DBR diode lasers applied in this work consist of an asymmetric super large optical cavity grown by metal-organic vapor phase epitaxy (MOVPE) on a (100) GaAs wafer. This vertical structure, introduced already in [81] and depicted

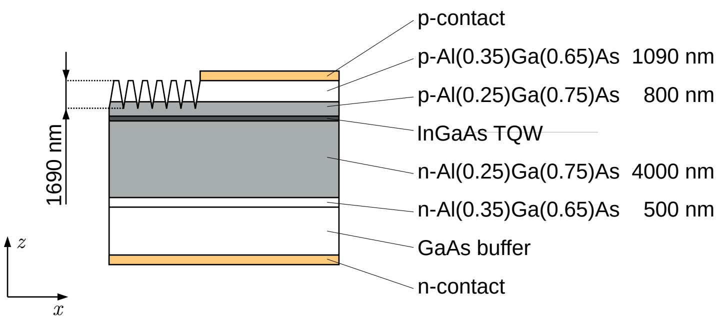

Figure 2.7: Asymmetric super large optical cavity with InGaAs TQW and surface grating