*Semiconductor-glass Waveguide
Hybrid Lasers
with Ultra-high Spectral Purity*

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SEMICONDUCTOR-GLASS WAVEGUIDE HYBRID LASERS
WITH ULTRA-HIGH SPECTRAL PURITY

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Cover: Front-A photo of a prototype integrated hybrid laser based on the design presented in Chapter 7. Background-A photo of Northern lights in Iceland, which shows the beauty of lightwaves.

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DISSERTATION

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on the authority of the rector magnificus,
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on account of the decision of the graduation committee,
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To my family.

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1

Introduction

Theodore Maiman demonstrated the first laser operation [1] in 1960, which marked the advent of a new paradigm in the generation and control of light. The novel quality in light generation with lasers was already realized by Arthur Schawlow and Charles Townes [2], Nikolay Basov and Alexander Prokhorov [3], when they concluded that lasers would enable to generate light with so far unprecedented, extremely high spectral purity. Intrigued by this and similar prospects, researchers began proving that almost all of the properties of light, if generated by lasers, can be controlled to an ever-increasing extent. These properties include not only spectral purity but also the polarization of the light, the light frequency, as well as the temporal and spatial structure of light, such as in the form of pulses and beams. With these fundamental options and based on rapidly advancing laser technology, lasers became an absolutely essential tool for pursuing fundamental research questions and to discover, enable, and explore a huge wealth of applications.

A most striking feature of lasers is indeed the capability of generating light with highest spectral purity, which manifests itself as a narrowband spectral linewidth that can be made available across wide wavelength ranges [4]. The advancement of such lasers sources has been, and is with growing pace, playing a central role in fundamental research. Examples are high-resolution spectroscopy that has unraveled the fine structure of atoms [5–7], of molecules [8, 9] and of condensed matter [10]. Nonlinear spectroscopy and nonlinear optics enabled with lasers have been central for exploring and exploiting the quantum properties of light and entanglement phenomena, such as for investigations of quantum computing [11]. Laser precision metrology enables to measure the value of fundamental constants and test symmetries in nature with unprecedented precision [12, 13]. Most recently, the first direct confirmation of the existence of gravitational waves [14] was enabled with laser-based ultra-precise measurements of relative length changes in the order of 10^{-21} .

Parallel to fundamental research, laser sources providing light with high spectral purity have enabled numerous applications that have greatly shaped our modern life. A most widely known application that is intimately related to high-resolution spectroscopy is the development of optical clocks which provide the world time standard and enable worldwide navigation via global satellite systems [15, 16].

Even more dominant in our connected world is optical communications where lasers enable to transmit huge data streams over large distances, thereby forming one of the backbones of the internet. Specifically, coherent optical communication systems are gaining rapid importance because they allow to increase the speed (data rate) of transmission, by making use of the phase-predictability of lasers with narrow spectral linewidth.

Regarding the future development of optical communication it is required to recall the currently involved technologies. The required high-speed internet connectivity that most of us have been taking for granted is only made possible thanks to the availability of the tremendous bandwidth brought by the

employment of optical fiber links as information transportation channel and, importantly, the exploitation of laser light as optical carrier onto which the huge amount of digital information that we generate is written. For providing increasingly higher data rates as demanded by the expected exponential growth of information flow, more complex modulation formats have to be introduced, a solution known from the radio frequency domain. These modulation formats are to be employed in the optical domain [17], in order to increase the spectral efficiency, i.e., leveraging the limited data bandwidth that is offered by standard fiber transmission. As an example, the utilization of 16-fold quadrature amplitude modulation (16-QAM) would enable transmission systems with a single-channel rate of 40 Gbit/s at the required low bit error rate of 10^{-4} , if lasers with a small linewidth, at the 20-kHz level, would become available in an application ready format [18]. Moreover, the requirement for narrower laser linewidth will become more strict, for enabling even higher-order modulation formats and longer transmission distances [19], possibly at the sub-kHz level, as is required to meet the rapidly growing demand in data rate. Of equal importance is finding ways for fabricating such ultra-narrowband lasers reliably in high-volume with low cost as possible only via integration on optical chips.

There is another important backbone in present and future communication benefiting from narrow linewidth chip-sized lasers as well. This is data transmission and reception to and from mobile stations, specifically satellites, airplanes, cars and mobile phones, via phased array antennas. With properly and quickly adjusting the mutual delay of signals to and from the individual antenna elements, the antenna becomes highly directional and can follow the motions of transmitters and receivers. This allows to send data specifically to individual receivers which increases the signal-to-noise ratio. Introducing this technology is expected to increase the overall data rate. A well-recognized problem in this approach is, however, that conventional microwave delay technology, which is based on digital electronics, is reaching its limits in terms of speed and power consumption. A solution to this problem is to transfer the signal manipulation, i.e., separation (filtering) of channels as well as adjusting signal delay into the optical domain, an approach called microwave photonics [20]. As with fiber communication networks, after writing the information onto one or many ultra-narrowband carriers provided by a single laser or an array of lasers, the advantage is that optical (instead of electronic) delay lines can be employed for fast directional steering of antennas. This offers a much larger bandwidth while also significantly reducing the power consumption.

The highest promise for such revolution in mobile communication technology lies in the integration of all the required functionalities with each other in a chip-sized format. The functionalities to be integrated can be coarsely divided into active-optical ones - comprising multiple narrowband lasers (laser arrays), electro-optic modulators and photodiodes - and passive-optical ones - comprising low-loss optical filters and optical delay lines. A general concept that appears capable of integrating microwave photonics on optical chips, by including special optical waveguides with record-low loss and coupling them

with optically active semiconductor components is described in Refs. with [21–23]. The concept includes a hybrid integration approach that enables lasers with ultra-low linewidth, as the key for providing on-chip laser light that can serve as on-chip optical carrier in integrated microwave photonics.

These hybrid integrated semiconductor lasers, i.e., their theoretical description, design, realization and characterization of spectral properties are the theme of this thesis.

When considering the communication applications described above, semiconductor lasers which can be easily pumped with an electric current, are unarguably the most suitable candidate with the highest prospects. The reason lies in the large degree of technological maturity that these lasers have reached and that they combine the potential of narrow optical linewidths across widely selectable wavelength ranges with the required multiple-tens of milliwatt power. Of similar importance for application in microwave photonics is the possibility of mass production, i.e., relatively low manufacturing cost and a small size suitable for integration with waveguide circuits.

Monolithically integrated semiconductor lasers, such as distributed Bragg reflector (DBR) lasers and distributed feedback (DFB) lasers, have so far been the most attractive diode laser candidates for offering a narrow spectral linewidth. However, typical DFB and DBR lasers show either a limited tuning range (a few nm) [24] or relatively large linewidths at the MHz level [25]. The latter limit is set by the fundamental Schawlow-Townes linewidth for diode lasers [26] and is the result of a relatively short photon lifetime in the order of a few ps [27]) in the laser cavity, due to a short cavity length (a few hundred μm) and relatively high roundtrip losses (tens of percent).

It is well-known that the spectral purity and tunability of semiconductor lasers can largely be improved via optical feedback, by extending the cavity length with bulk optics, such as diffraction gratings [28]. Similarly long Bragg fibers can reduce the linewidth to the sub-kHz [29] and even sub-Hz instantaneous linewidths have been achieved using bulk-optical feedback from low-loss microdisks [30]. While the demonstrated spectral linewidths are certainly impressive, these lasers are of little practical use in the named communication applications because their concept intrinsically relies on bulk optical components which gives rise to two serious shortcomings: i) these lasers cannot be integrated with optical waveguides on a chip which severely limits the maximum functionality as compared to the required high complexity in microwave photonic circuits; ii) bulk optical devices are intrinsically susceptible to external perturbations, such as thermal drift and acoustic noise. Essentially, to date, a readily available alternative semiconductor laser, providing ultra-narrow spectral linewidth at widely selectable wavelengths in a chip-sized format compatible with integrated optical waveguide circuits, does not exist.

In this thesis, in order to explore the feasibility of realizing the desired lasers, we have explored a novel approach: we equip semiconductor optical amplifiers with highly frequency selective photonic waveguide feedback circuits to form, what we call, semiconductor-glass waveguide hybrid lasers. A photo

of such a laser is shown in Fig. 1.1.

Figure 1.1: Photograph of a hybrid InP semiconductor - $\text{Si}_3\text{N}_4/\text{SiO}_2$ glass waveguide laser as investigated in this thesis.

Among the various waveguide platforms that have been previously been investigated for providing waveguide feedback circuits, such as Si [31], SiON [32], polymer [33], silica [34] and Si_3N_4 [35], we have chosen to employ Si_3N_4 waveguides¹ to form our feedback circuits. The main reason for this choice is that these waveguides, as compared to other waveguide platforms, have many fundamental as well as technological advantages:

- compared to silica that has only a low index contrast ($\Delta n \approx 10^{-2}$ [36]) which gives rise to high loss at short waveguide bends, the index contrast with Si_3N_4 is very high, $\Delta n \approx 0.5$. This renders an approximately three to four orders smaller footprint at the same optical length and loss;
- Si_3N_4 waveguides provide a very large transparency range, from 400 nm to 2400 nm [37], which means that a large variety of semiconductor materials other than InP might be used, to form hybrid lasers working at other wavelengths including the visible range. This property is important when targeting other telecom wavelength ranges [38] or for serving rather different applications, such as sensing and metrology with visible wavelengths;
- The linear propagation loss can be very low, in the order of 0.1 dB/cm [39] when using a double-stripe (double-core) cross-section, while record-low losses of less than 0.001 dB/cm may be achieved with a single-stripe cross-section [40];

¹The chosen Si_3N_4 waveguide technology offers a variety of cross-sections, with various different trade off between minimum bending radii and propagation losses.

- At the typical power levels delivered by single-spatial mode diode amplifiers, in the tens and hundreds of milliwatt range, the nonlinear response is extremely low, which safely prevents undesired nonlinear losses, such as two-photon absorption or Raman scattering [41];
- The Si_3N_4 waveguide platform has gained an appreciable maturity which means that also rather complex waveguide circuits involving hundreds of optical elements (splitters, resonators, tapers, interferometers) can be reproducibly fabricated [23];
- Finally the optical properties of many of these optical elements can be externally controlled via electronic signals either thermally or piezoelectrically [42] such as to implement programmable and reconfigurable circuits [43] with complex functionalities on the same photonic chip.

In this thesis, we investigate and present the essential aspects of semiconductor-glass hybrid waveguide lasers based on InP amplifiers and spectral feedback from Si_3N_4 waveguide circuits. The content is presented in a cumulative manner. Chapters 3-5 are based on published work and Chapters 6 and 7 are being prepared for publication, such that each of these chapters begins with a self-contained introduction. After presenting some theoretical background in Chapter 2, we present a first version of a hybrid laser that possesses reduced roundtrip losses as achieved with an improved optical coupling between the diode and silicon nitride waveguide mode fields. To explore the potential of using narrowband amplification, frequency and phase synchronization, such as for application in the emerging field of microwave photonics [44]. In Chapter 4 we report the first injection locking experiments with such hybrid lasers; in Chapter 5 we report the first integration of a hybrid InP- Si_3N_4 laser; in Chapter 6 we present a theoretical analysis of such hybrid lasers that for the first time reveals index-induced spatial broadening effects with a spatially resolved modeling of the gain section. Finally, in Chapter 7 we describe how the expertise gained with modeling, laser-design and experimental investigation is used to realize a semiconductor-glass hybrid laser with a record-low Schawlow-Townes linewidth of 290 Hertz.

In brief, this thesis describes a most powerful approach towards spectral control of diode lasers for unprecedented high spectral purity, and with large relevance for high-impact applications.

Bibliography

- [1] T. H. Maiman, “Stimulated optical radiation in ruby,” *Nature* **187**, 493–494 (1960).
- [2] A. L. Schawlow and C. H. Townes, “Infrared and optical masers,” *Phys. Rev.* **112**, 1940–1949 (1958).
- [3] N. Basov and A. Prokhorov, “About possible methods for obtaining active molecules for a molecular oscillator,” *Sov. Phys.-JETP*. **1**, 184–185 (1955).
- [4] J. L. Hall, “Nobel lecture: Defining and measuring optical frequencies,” *Rev. Mod. Phys.* **78**, 1279–1295 (2006).
- [5] T. Hänsch, I. Shahin, and A. Schawlow, “Optical resolution of the lamb shift in atomic hydrogen by laser saturation spectroscopy,” *Nature* **235**, 63–65 (1972).
- [6] I. Klaft, S. Borneis, T. Engel, B. Fricke, R. Grieser, G. Huber, T. Kühl, D. Marx, R. Neumann, S. Schröder, P. Seelig, and L. Völker, “Precision laser spectroscopy of the ground state hyperfine splitting of hydrogenlike $^{209}\text{Bi}^{82+}$,” *Phys. Rev. Lett.* **73**, 2425–2427 (1994).
- [7] G. Huber, F. Touchard, S. Büttgenbach, C. Thibault, R. Klapisch, H. T. Duong, S. Liberman, J. Pinard, J. L. Vialle, P. Juncar, and P. Jacquinet, “Spins, magnetic moments, and isotope shifts of $^{21-31}\text{Na}$ by high resolution laser spectroscopy of the atomic D_1 line,” *Phys. Rev. C* **18**, 2342–2354 (1978).
- [8] W. Demtröder, *Atoms, Molecules and Photons: An Introduction to Atomic-, Molecular- and Quantum-physics*, Advanced texts in physics (Springer, 2006).
- [9] J. Bagdonaite, W. Ubachs, M. T. Murphy, and J. B. Whitmore, “Analysis of molecular hydrogen absorption toward QSO B0642–5038 for a varying proton-to-electron mass ratio,” *Astron. J.* **782**, 10 (2014).
- [10] M. Fleischhauer and M. D. Lukin, “Quantum memory for photons: Dark-state polaritons,” *Phys. Rev. A* **65**, 022314 (2002).

- [11] J. Benhelm, G. Kirchmair, C. F. Roos, and R. Blatt, “Towards fault-tolerant quantum computing with trapped ions,” *Nat. Phys.* **4**, 463–466 (2008).
- [12] J. Biesheuvel, J.-P. Karr, L. Hilico, K. Eikema, W. Ubachs, and J. Koelemeij, “Probing qed and fundamental constants through laser spectroscopy of vibrational transitions in HD+,” *Nat. Photon.* **7** (2016).
- [13] G. Gabrielse, N. S. Bowden, P. Oxley, A. Speck, C. H. Storry, J. N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T. W. Hänsch, and E. A. Hessels, “Background-free observation of cold antihydrogen with field-ionization analysis of its states,” *Phys. Rev. Lett.* **89**, 213401 (2002).
- [14] B. P. Abbott, et al., “Observation of gravitational waves from a binary black hole merger,” *Phys. Rev. Lett.* **116**, 061102 (2016).
- [15] M. Takamoto, F.-L. Hong, R. Higashi, and H. Katori, “An optical lattice clock,” *Nature* **435**, 321–324 (2005).
- [16] ESA, “GALILEO begins serving the globe” (2016), http://www.esa.int/Our_Activities/Navigation/Galileo_begins_serving_the_globe.
- [17] P. J. Winzer and R. J. Essiambre, “Advanced optical modulation formats,” *Proc. IEEE* **94**, 952–985 (2006).
- [18] M. Seimetz, *High-order modulation for optical fiber transmission*, vol. 143 (Springer Series in Optical Sciences, 2009).
- [19] I. Fatadin and S. J. Savory, “Impact of phase to amplitude noise conversion in coherent optical systems with digital dispersion compensation,” *Opt. Express* **18**, 16273–16278 (2010).
- [20] J. Capmany and D. Novak, “Microwave photonics combines two worlds,” *Nat. Photon.* **1**, 319–330 (2007).
- [21] A. Meijerink, C. G. H. Roeloffzen, R. Meijerink, L. Zhuang, D. A. I. Marpaung, M. J. Bentum, M. Burla, J. Verpoorte, P. Jorna, A. Hulzinga, and W. van Etten, “Novel ring resonator-based integrated photonic beamformer for broadband phased array receive antennas -part I: Design and performance analysis,” *J. Lightw. Technol.* **28**, 3–18 (2010).
- [22] L. Zhuang, C. G. H. Roeloffzen, A. Meijerink, M. Burla, D. A. I. Marpaung, A. Leinse, M. Hoekman, R. G. Heideman, and W. van Etten, “Novel ring resonator-based integrated photonic beamformer for broadband phased array receive antennas -part II: Experimental prototype,” *J. Lightw. Technol.* **28**, 19–31 (2010).

- [23] C. G. H. Roeloffzen, L. Zhuang, C. Taddei, A. Leinse, R. G. Heideman, P. W. L. van Dijk, R. M. Oldenbeuving, D. A. I. Marpaung, M. Burla, and K. J. Boller, "Silicon nitride microwave photonic circuits," *Opt. Express* **21**, 22937–22961 (2013).
- [24] M. Faugeron, M. Tran, O. Parillaud, and M. Chtioui, "High-power tunable dilute mode dfb laser with low rin and narrow linewidth," *IEEE Photon. Technol. Lett.* **25**, 7–10 (2013).
- [25] Y. A. Akulova, G. A. Fish, P.-C. Koh, C. L. Schow, P. Kozodoy, A. P. Dahl, S. Nakagawa, M. C. Larson, M. P. Mack, T. A. Strand, C. W. Coldren, E. Hegblom, S. K. Penniman, T. Wipiejewski, and L. A. Coldren, "Widely tunable electroabsorption-modulated sampled-grating DBR laser transmitter," *IEEE J. Sel. Top. Quantum Electron.* **8**, 1349–1357 (2002).
- [26] C. Henry, "Theory of the linewidth of semiconductor lasers," *IEEE J. Quantum Electron.* **18**, 259–264 (1982).
- [27] W. Zheng and G. W. Taylor, "Determination of the Photon Lifetime for DFB Lasers," *IEEE J. Quantum Electron.* **43**, 295–302 (2007).
- [28] S. D. Saliba and R. E. Scholten, "Linewidths below 100 kHz with external cavity diode lasers," *Appl. Opt.* **48**, 6961–6966 (2009).
- [29] F. Wei, F. Yang, X. Zhang, D. Xu, M. Ding, L. Zhang, D. Chen, H. Cai, Z. Fang, and G. Xijia, "Subkilohertz linewidth reduction of a DFB diode laser using self-injection locking with a fiber Bragg grating Fabry-Perot cavity," *Opt. Express* **24**, 17406–17415 (2016).
- [30] W. Liang, V. Ilchenko, D. Eliyahu, A. Savchenkov, A. Matsko, D. Seidel, and L. Maleki, "Ultralow noise miniature external cavity semiconductor laser," *Nat. Commun.* **6** (2015).
- [31] A. J. Zilkie, P. Seddighian, B. J. Bijlani, W. Qian, D. C. Lee, S. Fatholouloumi, J. Fong, R. Shafiha, D. Feng, B. J. Luff, X. Zheng, J. E. Cunningham, A. V. Krishnamoorthy, and M. Asghari, "Power-efficient III-V/Silicon external cavity DBR lasers," *Opt. Express* **20**, 23456–23462 (2012).
- [32] T. Matsumoto, A. Suzuki, M. Takahashi, S. Watanabe, S. Ishii, K. Suzuki, T. Kaneko, H. Yamazaki, and N. Sakuma, "Narrow spectral linewidth full band tunable laser based on waveguide ring resonators with low power consumption," in "Optical Fiber Communication Conference," (Optical Society of America, 2010), p. OThQ5.
- [33] D. de Felipe, Z. Zhang, W. Brinker, M. Kleinert, A. M. Novo, C. Zawadzki, M. Moehrle, and N. Keil, "Polymer-based external cavity lasers: Tuning efficiency, reliability, and polarization diversity," *IEEE Photon. Technol. Lett.* **26**, 1391–1394 (2014).

- [34] K. Numata, J. Camp, M. A. Krainak, and L. Stolpner, “Performance of planar-waveguide external cavity laser for precision measurements,” *Opt. Express* **18**, 22781–22788 (2010).
- [35] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and K.-J. Boller, “25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity,” *Laser. Phys. Lett.* **10**, 015804 (2013).
- [36] H. Ou, “Different index contrast silica-on-silicon waveguides by PECVD,” *Electron. Lett.* **39**, 212–213 (2003).
- [37] K. Wörhoff, R. Heideman, A. Leinse, and M. Hoekman, “Triplex: A versatile dielectric photonic platform,” *Adv. Opt. Techn.* **4**, 189–207 (2015).
- [38] Y. Zhang, S. Yang, X. Zhu, Q. Li, H. Guan, P. Magill, K. Bergman, T. Baehr-Jones, and M. Hochberg, “Quantum dot SOA/silicon external cavity multi-wavelength laser,” *Opt. Express* **23**, 4666–4671 (2015).
- [39] L. Zhuang, D. Marpaung, M. Burla, W. Beeker, A. Leinse, and C. Roeloffzen, “Low-loss, high-index-contrast $\text{Si}_3\text{N}_4/\text{SiO}_2$ optical waveguides for optical delay lines in microwave photonics signal processing,” *Opt. Express* **19**, 23162–23170 (2011).
- [40] J. F. Bauters, M. J. R. Heck, D. D. John, J. S. Barton, C. M. Bruinink, A. Leinse, R. G. Heideman, D. J. Blumenthal, and J. E. Bowers, “Planar waveguides with less than 0.1 dB/m propagation loss fabricated with wafer bonding,” *Opt. Express* **19**, 24090–24101 (2011).
- [41] J. P. Epping, T. Hellwig, M. Hoekman, R. Mateman, A. Leinse, R. G. Heideman, A. van Rees, P. J. van der Slot, C. J. Lee, C. Fallnich, and K.-J. Boller, “On-chip visible-to-infrared supercontinuum generation with more than 495 THz spectral bandwidth,” *Opt. Express* **23**, 19596–19604 (2015).
- [42] N. Hosseini, R. Dekker, M. Hoekman, M. Dekkers, J. Bos, A. Leinse, and R. Heideman, “Stress-optic modulator in triplex platform using a piezoelectric lead zirconate titanate (PZT) thin film,” *Opt. Express* **23**, 14018–14026 (2015).
- [43] L. Zhuang, C. G. H. Roeloffzen, M. Hoekman, K.-J. Boller, and A. J. Lowery, “Programmable photonic signal processor chip for radiofrequency applications,” *Optica* **2**, 854–859 (2015).
- [44] J. Capmany and D. Novak, “Microwave photonics combines two worlds,” *Nat. Photon.* **1**, 319–330 (2007).

2

Theoretical background

2.1 Introduction

Widely tunable diode lasers with narrow spectral linewidth (well below 1 MHz) are of interest for a large number of applications in, e.g., coherent optical communications [1], light detection and ranging (LIDAR) [2], spectroscopy [3] or optical sensing [4]. The prerequisites of a tunable laser are that it should operate at an externally selectable single longitudinal mode, at any wavelength within the laser's gain profile. This is different with a simple Fabry-Perot laser which usually shows multimode laser output or emits at a dominate mode, i.e., with a wavelength that is closest to the wavelength with maximum gain within the spectral gain profile. The single mode condition is commonly fulfilled by implementing intra-cavity filtering elements, which can be realized in a monolithic form or via an external cavity. Typical examples of monolithic tunable diode lasers are distributed Bragg reflector (DBR) lasers and distributed feedback (DFB) lasers. Typical DFB and DBR lasers show either limited tuning range (a few nm) [5] or large linewidths at the MHz level [6], the latter being set by the fundamental Schawlow-Townes linewidth [7] via the combination of a short cavity length and relatively high roundtrip losses. Recently, novel monolithic diode lasers with intra-cavity filtering based on cascaded Mach-Zehnder interferometers are also reported [8, 9], which provides a record tuning range of almost 80 nm although the spectral linewidth is still about several hundreds of kHz. In contrast, external cavity diode lasers (ECDLs), via providing frequency selective optical feedback and an extended cavity to a solitary diode laser, can offer both a wide tuning range and narrow spectral linewidths much smaller than 1 MHz.

ECDLs have been in use since long and have shown widest tunability, with very narrow linewidth, utilizing free space optical elements, such as lenses and bulk gratings. However, because it is difficult to reduce the roundtrip losses that occur in the diode laser internal waveguide, a narrow spectral linewidth in the order of a few kHz or tens of kHz require to provide a large optical length of the external cavity path and thus also a large physical size of tens of cm [10–12]. The large physical size associated with the free-space optics renders such laser sources inherently prone to mechanical vibrations and rule out the chance of integration in a small format. If employed for research or under specific technological circumstances, the physical size of a laser source might not play an important role, and acoustic perturbations can be counteracted with high-performance frequency stabilization schemes based on actuators and electronic servo loops. However, in applications as mentioned above, a miniature-size format is highly desired as well as laser resonators with high immunity to external perturbations, which strongly calls for the use of integrated optics.

In this chapter we introduce the concept of a novel class of external cavity diode lasers, which we call semiconductor-glass waveguide hybrid lasers. In such lasers, a semiconductor optical amplifier receives widely tunable frequency-selective optical feedback from a low-loss glass waveguide circuit. Via optically coupling these two central elements, such hybrid lasers offer the superior spec-

tral properties as can be offered by traditional bulk ECDLs. These are such as single frequency oscillation with a wide spectral coverage and strikingly, narrow spectral linewidths of a few tens of kHz and even sub-kHz, as will be presented in later chapters.

2.2 External cavity diode lasers

2.2.1 Spectral linewidth of solitary diode lasers

Provided that single longitudinal mode operation is achieved with appropriate spectral filtering in the laser cavity, a fundamental problem with obtaining a narrow spectral linewidth is phase noise induced by quantum noise in the form of spontaneous emission. A first estimation of the laser linewidth was given by Schawlow and Townes with their well-known formula [13] where the laser is modeled as a harmonic oscillator driven by white frequency noise with the electric field oscillating inside a linear (two-mirror) resonator. Although this formula successfully predicted the inversely proportional dependence of linewidth *vs* increasing output power, it failed to explain the much broader linewidth of semiconductor diode lasers, as observed in early experiments done by Fleming and Mooradian [14]. It was later on that Henry introduced an improved theory, in which the stronger linewidth broadening of diode lasers was ascribed to a mechanism called index-gain coupling [7] which is particularly prominent in semiconductors. In more detail, spontaneous emission events not only cause instantaneous random phase changes, but also lead to intensity changes, ΔI , which are restored via damped relaxation oscillations. Because of the intensity changes, ΔI , a change in the carrier density, ΔN , and a change in the gain coefficient, Δg , is induced as well. The gain coefficient is related to the imaginary part of the refractive index, n'' , as $g = 2k_0 n''$ [15], where k_0 is the vacuum propagation constant of the light, i.e., there is also a change in the imaginary refractive index, $\Delta n''$. From the Kramers-Kronig relations this also leads to a correlated fluctuations of the real refractive index, $\Delta n'$. These cause fluctuations of the optical length of the laser medium which results in corresponding phase changes per time interval. These intensity induced phase changes increase the spectral broadening of the laser emission line, beyond what is caused by the direct phase changes via spontaneously emitted photons.

With the broadening effect induced by index-gain coupling taken into account, one obtains a modified (increased) Schawlow-Townes linewidth:

$$\Delta\nu_{ST} = \frac{v_g^2 h\nu n_{sp} (\alpha_i + \alpha_m) \alpha_m (1 + \alpha^2)}{8\pi P_{out}}, \quad (2.1)$$

In this expression, v_g is the group velocity of light in the diode waveguide, n_{sp} is the spontaneous emission factor, α_i is the internal loss, α_m is the distributed mirror loss, and P_{out} is the output power per facet (assuming equal facet reflectivities). The discussed increase of the linewidth through gain-index

coupling is described by the parameter $\alpha = \frac{dn'/dN}{dn''/dN}$, which is the so called linewidth enhancement factor, also named Henry factor [7]. It can be seen that the Henry factor is given as the ratio between the change of the real refractive index dn' and that of the imaginary index dn'' and a change in carrier density, dN .

2.2.2 General aspects of external optical feedback

A tunable external cavity diode laser is usually composed of a semiconductor diode laser with or without anti-reflection coatings, a coupling element and an external spectral filter which selects a single longitudinal mode. In general, the properties of light generated by such a diode laser which receives feedback from an external cavity can change greatly, depending on the configuration, including the feedback level, optical power level, external cavity length, and the diode laser parameters. The effects of external optical feedback (OFB) on diode lasers have been studied quite extensively [16–38] and a wide range of dynamics such as chaotic output, self-pulsing, bistability were observed.

When aiming at narrow spectral linewidth, there are two major approaches of implementing the desired optical feedback in an external cavity:

- Beginning with a solitary diode laser that does not require external feedback to oscillate due to sufficiently high facet reflectivities, a smaller part of the laser's output is sent to a high-Q optical resonator [29, 32, 34]. Light leaving the resonator possesses a reduced spectral bandwidth and is sent back to the laser in order to achieve injection locking. With an appropriate optical geometry, lasers optically lock themselves to a resonance of a separate Fabry-Perot reference cavity [29] or a confocal Fabry-Perot (CFP) cavity [32, 34] which greatly facilitates the coupling of the diode laser to the external resonator. This approach is also called self-injection locking.
- The second approach requires that at least one of the facets of the diode laser is anti-reflection coated, ideally such that no laser oscillation is achieved without external feedback. The external feedback is then implemented with maximum coupling, i.e., with minimum loss. In this case of maximally strong coupling the feedback elements form an essential part of the laser resonator required to reach the laser threshold. This approach is what is called an external cavity diode laser (ECDL).

In the first scheme some of the laser output characteristics are highly sensitive to the feedback parameters, specifically the phase of the feedback. Furthermore, the tuning range is usually very limited if the solitary diode is not equipped with an internal frequency selection filter, for instance a Bragg structure. In the second scheme the laser operates as a long cavity laser with a short active region. If there is sufficient frequency selectivity in the cavity, the laser operates on a single longitudinal mode with narrow linewidth for all phases of

the feedback. In this regime of operation, the laser is relatively insensitive to additional external optical perturbations. In order to explore in how far one can make use of this stability advantage, this thesis investigates the second approach, i.e., it investigates external cavity diode lasers with a strongly coupled feedback.

2.2.3 Principle of longitudinal mode selection

The gain spectrum of typical diode lasers usually spans tens of nanometers. Considering for simplicity a Fabry-Perot laser, i.e., with a linear (standing wave) cavity formed by two broadband reflective mirrors, laser oscillation might occur at multiple longitudinal modes, the wavelengths of which are defined by a roundtrip constructive interference condition. However, due to gain competition, often one of the modes dominates in terms of power. The power ratio of the main longitudinal mode and the other modes, called side modes, is called side mode suppression ratio (SMSR). Achieving a high SMSR is important in many applications because this increases the signal-to-noise ratio of laser-based measurements. In the following section, we show how to design the external optical feedback that incorporates a frequency-selective element, i.e., a spectral filter for the longitudinal modes, in order to achieve a single-mode laser with a high SMSR.

In order to identify the necessary requirements that a longitudinal mode filter needs to meet for realizing laser oscillation at a single longitudinal mode output, let us recall the general operation principle and mode selection scheme of an external cavity hybrid laser. Fig. 2.1 shows both the generalized schematic and the mode selection principle of the hybrid laser under investigation. It is well-known that the laser output wavelength is determined by the mutual spectral alignment of the diode gain spectrum with the transmission resonances of the employed mode filter and with the wavelengths of the longitudinal modes of the laser resonator [15].

Longitudinal modes of the entire laser cavity (with a length $L_1 + L_2$) are defined by a phase condition for constructive interference in a full roundtrip that can be expressed as:

$$\Phi(\lambda) = kn_{eff1}2L_1 + kn_{eff2}2L_2 + 2\varphi(\lambda) = m2\pi \quad (2.2)$$

where $\Phi(\lambda)$ is the roundtrip phase for a given vacuum wavelength λ , n_{eff1} is the effective refractive index in the waveguide of the InP gain chip and n_{eff2} is the index in the Si_3N_4 waveguide chip; k is the wavenumber in vacuum; $\varphi(\lambda)$ is the single-pass (half-roundtrip) phase shift, induced by the mode filter that is inserted into the laser cavity and m is a integer number. The wavelengths that fulfill Eq. 2.2 represent a large number of longitudinal modes that the laser could potentially operate at, indicated by the finer comb of wavelengths in Fig. 2.1 (b). A close look at Eq. 2.2 reveals that the FSR of the laser, $\Delta\lambda_{FSR,Laser}$, can be calculated via the following expression:

Figure 2.1: (a) Generalized schematic of the hybrid laser under consideration. The InP gain section that possesses a length of L_1 is equipped with a high reflection (HR) front facet and an anti-reflection (AR) back facet via which the gain section is butt-coupled to an external feedback circuit. R_1 and R_2 are power reflectivities of the HR facet and AR facet respectively. β is the power coupling efficiency between the diode waveguide and the Si_3N_4 waveguide. L_2 is the physical length of the Si_3N_4 circuit excluding the mode filter. Extra optical length may be added to the laser cavity via inducing an frequency-dependent phase shift. The mode filter has a power transmittance of T and the external part is terminated with a output mirror with a power reflectivity of R_3 ; (b) Mode selection principle of an external cavity hybrid laser: the blue dotted curve represents the gain spectrum provided by the InP diode and the green curve shows the spectral filtering characteristic of the mode filter. Positions of the cavity longitudinal modes are marked with vertical black lines.

$$\Delta\lambda_{FSR,Laser} = \frac{\lambda^2}{2n_{g1}L_1 + 2n_{g2}L_2 + 2n_{g2}L_{eff}} \quad (2.3)$$

where n_{g1} and n_{g2} are group indices of the two chips respectively, and L_{eff} is the effective length of the mode filter, $L_{eff} = -\lambda/(n_{eff}k)d\varphi(\lambda)/d\lambda$ [39].

Equation 2.2 and Fig. 2.1 (b) reveal several important requirements that the longitudinal mode filter needs to fulfill for single longitudinal mode oscillation:

1. The free spectral range of the filter ($\Delta\lambda_{FSR,Filter}$) should be larger than the bandwidth of the gain spectrum;
2. Any spectral side peaks of the mode filter should be suppressed sufficiently;
3. The spectral bandwidth of the mode filter, $\Delta\lambda_{Filter}$, should be smaller than the FSR of the laser cavity ($\Delta\lambda_{FSR,Laser}$) such that only one longitudinal mode is selected.

2.2.4 Spectral linewidth of ECDLs under strong optical feedback

With the goal of a quantitative modeling, an ECDL, as shown in Fig. 2.1 (a), can be simplified into an equivalent two-mirror Fabry-Perot laser via incorporating all the external feedback part into an effective complex amplitude reflectivity, $r_{eff}(\omega)$, as depicted in Fig. 2.2.

The effective complex amplitude reflectivity $r_{eff}(\omega)$ is given by:

$$\begin{aligned} r_{eff}(\omega) &= r(\omega)\exp(-j\varphi_{eff}(\omega)) \\ &= \beta t^2(\omega)\sqrt{R_3}\exp(-L_2\alpha_{ext})\exp(-2jk n_{eff}L_2), \end{aligned} \quad (2.4)$$

where α_{ext} is the power propagation loss of the external cavity and $t(\omega) = t_r(\omega)\exp(-j\varphi(\omega))$ is the frequency-dependent complex amplitude transmittance of the intra-cavity longitudinal mode filter. In this equation it is assumed that R_2 is very small ($R_2 \approx 0$), which is a good approximation when the diode is equipped with an AR coating and the diode waveguide is tilted *vs* the facet normal.

The advantage of the equivalent laser cavity is that a standard analysis under the so-called mean-field approximation can be carried out under the condition that $|r_{eff}|$ in Eq. (2.4) is on the order of unity. This is the case when β , R_3 and T are close to unity while α_{ext} is close to zero. Also in order to increase the power efficiency of the external cavity laser, it can be concluded that in the expression for $r_{eff}(\omega)$, β should be maximized while α_{ext} should be kept low.

Figure 2.2: Equivalent cavity model of the external cavity diode laser with strong external optical feedback. $r_1 = \sqrt{R_1}$ and $r_3 = \sqrt{R_3}$ are amplitude reflectivity of the diode back facet and external mirror, respectively; $t(\omega)$ is the frequency-dependent complex amplitude transmittance of the intra-cavity longitudinal mode filter and $\eta = \sqrt{\beta}$ is the amplitude coupling efficiency.

Under these assumptions, the laser spectral linewidth, $\Delta\nu$, derived under the context of chirp reduction [28], can be expressed as a corrected Schawlow-Townes linewidth from Eq. 2.1:

$$\Delta\nu = \frac{\Delta\nu_{ST}}{F^2}, \quad (2.5)$$

with

$$F = 1 + A + B, \quad (2.6)$$

$$A = \frac{1}{\tau_{LD}} \left(\frac{d}{d\omega} \varphi_{eff}(\omega) \right), \quad (2.7)$$

and

$$B = \frac{\alpha}{\tau_{LD}} \left(\frac{d}{d\omega} \ln r(\omega) \right), \quad (2.8)$$

where F is the total linewidth reduction factor which is closely related to the complex amplitude reflectivity ($r_{eff}(\omega)$) of the external cavity via the terms A and B . Term A can be easily re-written as $A = (2n_{g2}L_{eff} + 2n_{g2}L_2)/(2n_{g1}L_1)$ where L_{eff} can be seen as the effective length of the mode filter given by $L_{eff} = \omega/(n_{eff}2k)d(\varphi(\omega))/d(\omega)$ [39] with $\varphi(\omega)$ the phase shift in the mode filter *vs*

light frequency. It can be seen that a steep slope of phase response of the mode filter, as is found in narrowband filters, increases L_{eff} , A, and F, thereby reducing the laser linewidth, $\Delta\nu$ in Eq. 2.5. The term B describes additional linewidth reduction that occurs only at the rising slope of the spectral peak of the external feedback, where $(\frac{d}{d\omega} \ln r(\omega))$ is positive.

Summarizing these design aspects of the external cavity, presuming that single longitudinal mode oscillation is achieved, it is beneficial to include a mode filter that has long effective length, to have long passive propagation section, and to operate the laser at a wavelength slightly longer than the peak wavelength of the spectral reflectivity of the external cavity. The former two help to increase A, while the latter helps to increase B, both of which is desired to narrow the laser spectral linewidth.

As discussed above, Eqs 2.1 and 2.6 to 2.8 are derived under the mean-field approximation (MFA) and apply strictly only to situations where the light field and carrier density is uniformly distributed along the diode cavity. However, as will be discussed later in Chapter 6, the MFA may break down in hybrid lasers. To investigate the consequences for the laser linewidth more carefully, in Chapter 6 we recall and re-use the expressions for the waveguide feedback (Eqs. 2.6 to 2.8), but we replace modeling with the MFA with a spatially resolved model.

2.3 External cavity semiconductor-glass waveguide hybrid lasers

In this thesis, we follow a novel paradigm for external cavity diode lasers, which we call semiconductor-glass waveguide hybrid lasers. In such lasers, we make use of two different material platforms for integrated optical waveguides and optically couple the two with low loss. One is a waveguide in a semiconductor laser diode for light generation and amplification and the other is a glass waveguide circuit for spectral control of the generated light. In such hybrid lasers, the external optical feedback light path is optically integrated on a glass chip in the form of a waveguide circuit with a unique combination of lowest propagation loss and a high index contrast. The latter is enabled by an important emerging photonic platform which is based on Si_3N_4 waveguide cores buried in a SiO_2 cladding [40]. The advantage of employing feedback based on waveguides with low loss and high contrast is that long external feedback paths and also finely resolving spectral filters can be incorporated in a chip. Thereby one eliminates largely all stability issues that an equivalent bulk-optical and even fiber-optical feedback would have. Such $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguides also offer an extremely wide transparency wavelength range, extending from the visible (at around 400 nm) into the mid-infrared range (at about $2.5 \mu\text{m}$). Within this spectral range, the absorption loss and propagation loss can be very low, (e.g., down to 0.001dB/cm) at a wavelength of $1.55 \mu\text{m}$ and one could, with

the same approach as described above, construct hybrid lasers operating at any wavelength in this visible-to-mid-infrared interval via selecting a semiconductor material that amplifies the selected wavelength. Such ultra-wide spectral coverage, offered by the semiconductor-glass waveguide hybrid lasers, is of both great technological and fundamental importance and will be of benefit for a wide range of fields.

In the following section we elaborate on various design aspects for the essential elements that constitute such hybrid lasers, for instance the gain section and the feedback circuit that contains the frequency-selective element. We use InP based laser diodes that operate at around $1.55\ \mu\text{m}$ telecom wavelength, as an important example. Fabrication technology is mature for laser diode amplifiers at this particular wavelength and thus, such amplifiers are easily commercially available. Furthermore, hybrid lasers operating at $1.55\ \mu\text{m}$ are of central relevance for important state-of-the-art microwave photonic applications, such as optical beam forming networks (OBFNs) [41–43]. We note again that the general design principles, as will be laid out, apply to hybrid lasers at wavelengths other than $1.55\ \mu\text{m}$ as well.

2.3.1 InP Gain section

Diode laser amplifiers are an essential photonic elements capable of efficient and strong light generation and amplification. When coupled to an external cavity formed by a waveguide circuit, a hybrid laser is formed. Such external cavity hybrid lasers can coarsely be operated in two regimes, self-injection locking or as an ECDL, depending on the strength and optical bandwidth of the external feedback that the diode laser receives. As explained earlier, the regime operating as ECDL requiring strong optical feedback, can offer high spectral purity and a wide tuning range with a favourable stability in terms of operational parameters (temperature, driving current, etc).

In order to achieve strong optical feedback, it is important that the strength of the external reflectivity, $|r_{eff}|^2$, (including any possible loss that occurs in the external cavity) is much larger than any residual feedback from the diode facet, R_2 , where the light is coupled into the external waveguide circuit.

The typical Fresnel reflectivity of as-cleaved semiconductor-air interfaces is about 0.3, due to the relatively high effective refractive index contrast (between 3 and 3.6 *vs.*, e.g., the near unity index of air) at the facet of a semiconductor. For reducing the reflectivity R_2 , the following measures can be taken.

A common technique to reduce R_2 is deploying an anti-reflection (AR) coating. Typical values of reflectivity after AR coating are of the order of 10^{-2} to 10^{-3} . To reduce R_2 even further, one can tilt the diode-internal waveguide with respect to the normal of the facet [44]. The reflectivity for light in the tilted waveguide at the facet is given by:

$$R_2 = R_{AR} \exp \left[- \left(\frac{2\pi n w_0 \theta}{\lambda} \right)^2 \right] \quad (2.9)$$

where R_{AR} is the Fresnel reflectivity of the interface reduced by an AR coating while the exponential term denotes the tilting induced reflectivity (R_t), θ is the waveguide tilt angle and the exponential factor describes the power coupling by diffraction back into the laser waveguide mode, n is the effective refractive index of the diode waveguide mode, w_0 is the 1/e field strength mode field radius and λ is the wavelength.

As an example, the diode laser used in Chapter 7 has a mode field diameter of $3.5 \mu\text{m}$ in both transverse directions, an effective refractive index of 3.2 and a tilt angle of 9° (within the diode). In this case, applying Eq. 2.9 yields for R_2 a value of about a very low value (10^{-5} - 10^{-4}), which is beneficial for the diode to be spectrally controlled by external optical feedback.

2.3.2 $\text{Si}_3\text{N}_4/\text{SiO}_2$ based external feedback circuits

We design the external feedback circuits utilizing $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguide technology with longitudinal mode filtering using microring resonators (MRRs), fabricated with a double-striped cross section of the waveguide core [40]. This particular choice is strongly motivated by the feasibility of achieving with fine spectral filtering, low losses and a long cavity length a high spectral purity of the laser output, namely a high SMSR and a narrow spectral linewidth. Specifically, microring resonators designed for a high quality factor (Q-factor), when the light performs a large number of roundtrips, are suitable to significantly increase the effective cavity length, as compared to filters where the light performs only a single pass (MZIs, AWGs).

Indeed, double-stripe $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguides offer very low losses in the order of 0.1 dB/cm and MRRs can be used to form highly frequency-selective longitudinal mode filters with long effective lengths [39]. In the following section, we discuss how a longitudinal filter based on MRRs (a MRR-filter) is constructed.

We start with recalling the properties of a single so-called add-drop MRR, as is schematically depicted in Fig. 2.3 (a). An example of its spectral transmittance at the drop port, is shown in Fig. 2.3 (b). The spectral distance between two adjacent peaks, defined as the resonance frequencies of the MRR, is called the free spectral range (FSR) which is denoted as $\Delta\lambda_{FSR}$. The spectral full width at half maximum (FWHM) is denoted as $\Delta\lambda_{FWHM}$ which is approximately the same for all the resonances.

The FSR of the MRR, if the optical length of the resonator is much bigger than a wavelength, can be calculated as [45]:

$$\Delta\lambda_{FSR} = \frac{\lambda_0^2}{n_g 2\pi S}, \quad (2.10)$$

Figure 2.3: (a) Schematic of an add-drop MRR and (b) its spectral transmittance of the drop port. The spectral transmittance is calculated, as an example, for a radius of $S=99\ \mu\text{m}$ and power coupling coefficients (from the input to the ring path and from the ring path to the drop waveguide) of $\kappa^2=0.1$, assuming that other losses can be neglected. The group index of the waveguide, n_g , is about 1.715.

where λ_0 is one of the resonance wavelengths in vacuum, n_g is the group index of the waveguide (determined by the material dispersion and waveguide dispersion) and S is the radius of the MRR. We note that this expression is an approximation from the frequency domain to the wavelength domain that is valid if the considered wavelength range is small compared to the center wavelength. Resonance frequencies can be shifted by changing the optical length of the MRR. In our case, this is realized via the thermo-optic effect, by varying the temperature with resistive heaters that are deposited on top of the MRRs. In order to facilitate laser wavelength tuning it is desired to have a small value of S which increases $\Delta\lambda_{FSR}$. Here $S_1 = 99\ \mu\text{m}$ which is about the minimum bending radius where bending loss can be neglected compared to the propagation loss (about 0.1 dB/cm [40]). The $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguides used in this work possess a group n_g index of about 1.715, resulting a FSR of $\Delta\lambda_{FSR} \approx 2.2\ \text{nm}$ at a wavelength around 1550 nm.

In the next step we illustrate how to construct a mode filter employing several MRRs, for obtaining a refined filtering with a narrow bandwidth and larger effective FSR than possible with a single MRR. Here we discuss as an example the feedback circuit comprising three MRRs, as depicted in Fig. 2.4 (a) because such a circuit was used in the experiments as well (Chapter 7. Fig. 2.4 (b)-(d) displays the spectral characteristics of this three-MRR filter.

As is shown in Fig. 2.4, in order to extend the tuning range beyond the FSR of one single MRR, a second MRR that has a slightly different radius, here we select $S_2 = 102 \mu\text{m}$ as an example, is added sequentially. The result is a much enlarged total FSR that is brought by the so-called Vernier effect. The increased FSR can be calculated with the following expression [46–48]:

$$\Delta\lambda_{FSR,Vernier} = \frac{\Delta\lambda_{FSR1}\Delta\lambda_{FSR2}}{|\Delta\lambda_{FSR1} - \Delta\lambda_{FSR2}|} \quad (2.11)$$

Here $\Delta\lambda_{FSR1}$ and $\Delta\lambda_{FSR2}$ are the FSRs of the two MRRs that have radii of S_1 and S_2 respectively. In the example chosen here ($S_1 = 99 \mu\text{m}$, $S_2 = 102 \mu\text{m}$), the total FSR of the two-MRR filter is increased to about 74.3 nm. This value is comparable with the gain bandwidth of the particular InP diode used in the experiments of Chapter 7. For suppressing the side peaks in the spectral transmittance, the power coupling coefficients, $K = \kappa^2$, of both MRRs are chosen to be $K = 0.1$, where $\kappa = \sqrt{K}$ is the according field coupling coefficient. These values were calculated via the method described in the PhD thesis of Oldenbeuving [49].

In order to further increase the cavity length, an extra length of 5 cm waveguide is added, wound up in the form of a spiral, to retain a compact format. In order to increase the effective cavity length and further decrease the filter bandwidth while ensuring that the FSR of the laser (defined in Eq. 2.3) remains larger than the filter bandwidth, the third MRR is chosen to have a large radius, S_3 , again with power coupling coefficients $K = 0.1$. Regarding the choice for the radius of the third MRR, the FSR is taken to be larger than the FWHM bandwidth of the two-MRR Vernier filter which is fulfilled with a radius of 1485 μm . As can be seen in Fig. 2.4, such a three-MRR filter provides a very fine frequency selectivity with a FWHM of about 3.66 pm. The described configuration of our feedback circuit ensures single mode operation, and extends the effective length of the hybrid laser to a value of 15 cm. The main contribution to this (about 10 cm) stems from resonators, as can be coarsely calculated from their total single-pass length, $L_{RES} = 2\pi(S_1 + S_2 + S_3) \approx 1.1 \text{ cm}$, multiplied with an enhancement factor of $E = (1 - K)/K = 9$ ($K = 0.1$) [50]. Thanks to this effective length enhancement effect, our three-MRR configuration provides a full roundtrip cavity length of about 30 cm. The optical effect of such a long cavity is an extremely narrow fundamental (intrinsic) laser linewidth below one kilohertz, as will be shown in Chapter 7.

Figure 2.4: (a) Schematic of the three-MRR filter; (b)-(d) Calculated filtering characteristics of the three-MRR configuration, at a propagation loss of 0.1 dB/cm and power coupling coefficients $K = 0.1$; the radii of the MRRs are $S_1 = 99 \mu\text{m}$, $S_2 = 102 \mu\text{m}$, $S_3 = 1485 \mu\text{m}$, and the effective group index of the waveguides is $n_g = 1.715$. The filter is terminated with an adjustable loop mirror (discussed in details in Chapter 7); (b) Roundtrip transmittance spectrum of cascaded MRR1 and MRR2 (coarse Vernier filter), which shows a wide total FSR due to the Vernier effect; (c) a zoom-in version of the same spectrum as (b) centering around the Vernier peak wavelength; (d). Roundtrip transmittance spectrum of the three-MRR filter. The transmittance difference between the main peak and the dominating side peak is as high as 12.4 dB. The three-MRR filter shows a very fine frequency selectivity with a FWHM of about 3.66 pm and the roundtrip insertion loss (IL) of the filter is about 1.92 dB.

2.4 Injection locking

In the previous sections, general design aspects of the hybrid lasers under investigation were discussed. Specifically, it was described how to provide widely tunable external optical feedback to achieve single frequency oscillation with a narrow spectral linewidth. Another type of spectral control of lasers can be realized using the so-called injection locking [51–54]. This method allows for all-optical control of the frequency and phase of a laser (slave laser) oscillator by injection light from another laser (master laser). If the frequency difference of the master laser from the slave laser is smaller than a certain value called locking range, injection locking will occur. This means that the output frequency of the slave laser becomes equal to that of the master laser, and that the slave laser oscillation assumes a fixed phase relation with regard to the master laser. When the injected power is relatively weak, injection locking can also be understood as a regenerative amplification of the injected light. The original slave laser oscillation is extinguished due to insufficient gain caused by gain depletion through the master laser light. A major advantage, as compared to simple traveling-wave amplification is a significantly enhanced frequency selectivity [54] and a strong reduction of noise due to gain saturation by oscillation.

When injection locking is performed with multiple lasers, all of these lasers will oscillate at the same frequency and phase, which is of great importance for providing a phased array of local oscillators for certain applications.

As an example of rapidly emerging relevance, where such phased arrays of local oscillators might be used is the on-chip optical control of microwave communication systems, specifically phased antenna arrays. In such antennas, each element receives microwave signals from a large solid angle which means that there is no directionality. However, the antenna array becomes highly directional if the received signals from the different elements are constructively superimposed with appropriate mutual delays between the signals. Microwave signals possess a relatively large wavelength, which means that a direct delay in the microwave domain requires bulky equipment. Another option would be digital delay but this is limited in bandwidth and leads to significant power consumption.

An elegant solution that is also capable of handling extremely large signal bandwidths is delaying microwave signals in the optical domain. In this approach, a spectrally narrowband optical carrier is generated with a laser of small linewidth. This carrier is then distributed to a larger number of modulators, and here injection locking can be needed to maintain a sufficient power. Each individual carrier is modulated by one of the received microwave signals, thereby transferring the received information into the optical domain. In a next step, the optical signals stemming from the different antenna elements are given an appropriate delay in a corresponding optical delay line. Finally, the individual optical signals are superimposed on a photodetector with a non-modulated fraction of the narrowband laser as local oscillator. This reveals a

microwave signal received from a certain direction. Similarly a directed transmission in the form of a beam can be obtained with optical delay lines, therefore also called an optical beam forming network (OBFN) [41, 55]. The advantages of using optical methods for control and processing information, specifically if integrated on a chip are tremendous. The wavelength of lightwaves is 4 orders of magnitude smaller than that of microwaves, therefore using optical methods significantly reduces the required size for implementing delay lines. This has been demonstrated for instance by Eijerink et al. [56] with sixteen delay lines integrated in a photonic waveguide chip of only a few mm size.

A crucial requirement, to warrant stable superposition of many optical signals as described, is that the set of optical carriers used is having stable relative phases even after delay. This requirement rules out the possibility of using separate lasers as local oscillators if their relative phase is not controlled and if their spectral bandwidth is too large.

A potential approach to fulfill this need for mutually phase stable optical carriers in a chip-sized format is injection locking of hybrid lasers. In order to explore the feasibility of providing phase controlled local oscillators, we have investigated a corresponding prototype scenario, which is injection locking of a hybrid laser by another hybrid laser, as will be presented in Chapter 4.

2.4.1 Basic theory of injection locking

In order to recall some essential details on how to observe laser injection locking, we refer to a generic setup, as is shown in Fig. 2.5. The output from the master laser (ML) is injected into the slave laser (SL) via an optical isolator. This ensures that no backward locking can occur. The output of the two lasers is then superimposed at a photodetector. If the detuning of the ML frequency, ν_{ML} , from the free-running SL frequency, ν_{SL} , is larger than the locking range, i.e., $\Delta\nu_{lk} < |\nu_{ML} - \nu_{SL}|$, the two lasers will oscillate at different frequencies and have no predictable phase relation with regard to each other. In this case, the photodiode signal will contain a non-zero beat frequency, which is equal to the detuning of the lasers. This beat frequency can be observed, e.g., on a RF spectrum analyzer. Tuning the ML can then be observed as a tuning of the detected RF frequency. However, if the detuning becomes smaller than the locking range, $\Delta\nu_{lk} > |\nu_{ML} - \nu_{SL}|$, the SL starts oscillating at the injected ML frequency rather than at ν_{SL} and, simultaneously, the relative phase of the SL is locked to that of the ML [54]. In this case there is no RF beat frequency detectable, which indicates injection locking. Therefore, the locking range can be determined as the frequency range over which a beat signal is absent.

Injection locking phenomena were first theoretically investigated in early work by Adler [51]. Adler's results apply analogously to optical oscillators, and a comprehensive description for laser oscillators can be found, e.g., in [57]. For laser injection locking, the modeling yields the full locking range (which is twice the so-called locking half-range) as:

Figure 2.5: Schematic of the injection locking setup used by Stove and Steier [52]. Light from the master laser is split into two parts. One part passes an optical isolator (ISO) and enters the slave laser. The other part of light from the master laser is combined with the output light of the slave laser and is fed into a photodiode (PD). The beat signal from the photodiode is displayed on a RF spectrum analyzer.

$$\Delta\nu_{lk} = \frac{\nu_{SL}}{Q} \sqrt{\frac{P_i}{P_{SL}}} \quad (2.12)$$

In this expression, Q is the quality factor of the slave laser's resonator, which is defined as the ratio of the center wavelength to the cold cavity bandwidth; P_{SL} is the free running output power of the slave laser, and P_i is amount of optical power that is injected to the slave laser. The latter includes transmission and potential mode matching losses and is, thus, only a fraction of the ML's total output power.

Equation 2.12 reveals that the locking range not only depends on the operational and optical parameters of the SL, but also on the injected power from the ML.

To give an example of the involved numbers in a specific case, in the microwave photonic applications named above, it can be important to conduct injection locking for the purpose of frequency-selectively amplifying an optical sideband, which may have a typical bandwidth of a few hundred MHz as is determined by the speed of microwave modulation. In this case, it is required that the locking range is sufficiently large, i.e., at the few-hundred-MHz level, in order to prevent signal distortion induced by spectral non-uniform amplification throughout the entire sideband. According to Eq. 2.12, to provide a sufficiently large locking range one could, in principle, increase the injected power. Therefore, it is essential to investigate the increase of locking range with injected power in a quantitative experiment.

Our own experimental results on the first injection locking of a hybrid semiconductor laser with feedback from a waveguide circuit will be presented in Chapter 4. There we demonstrate that, the investigated type of hybrid laser can be locked over a large frequency range of about 500 MHz, limited only

by the available injected power from the master laser. The described injection locking experiments can be seen as an important step towards on-chip phase control of entire arrays of hybrid lasers, as is of central importance for the aimed OBFN application in microwave photonics.

2.5 Conclusion

In in this chapter we have first elaborated on several central design aspects for the realization of hybrid lasers with widely wavelength-tunable, single frequency output of narrow spectral linewidth. Regarding the latter, we expect an extremely narrow intrinsic laser linewidth at the sub-kilohertz level, when choosing the envisioned set of parameters, specifically, a power coupling coefficient of $K=0.1$ for three sequential MRRs ($S_1 = 99 \mu m$, $S_2 = 102 \mu m$ and $S_3 = 1485 \mu m$) and a reflectivity of 0.5 for the adjustable loop mirror. Secondly, we have briefly recalled the principle of injection locking, as a preparation for exploring the potential of utilizing hybrid lasers for providing phase controlled local carriers, which is important, e.g., for application in optical beam forming networks [41, 43] or carrier recovery in coherent optical receivers [58].

Bibliography

- [1] S. Zhang, P. Y. Kam, C. Yu, and J. Chen, “Laser linewidth tolerance of decision-aided maximum likelihood phase estimation in coherent optical M-ary PSK and QAM systems,” *IEEE Photon. Technol. Lett.* **21**, 1075–1077 (2009).
- [2] J. E. Koroshetz, “Fiber lasers for lidar,” in “Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference,” (Optical Society of America, 2005), p. OFJ4.
- [3] C. E. Wieman and L. Hollberg, “Using diode lasers for atomic physics,” *Rev. Sci. Instrum.* **62**, 1–20 (1991).
- [4] L. He, Ş. Özdemir, J. Zhu, W. Kim, and L. Yang, “Detecting single viruses and nanoparticles using whispering gallery microlasers,” *Nat. Nanotechnol.* **6**, 428–432 (2011).
- [5] M. Faugeron, M. Tran, O. Parillaud, and M. Chtioui, “High-power tunable dilute mode DFB laser with low RIN and narrow linewidth,” *IEEE Photon. Technol. Lett.* **25**, 7–10 (2013).
- [6] Y. A. Akulova, G. A. Fish, P.-C. Koh, C. L. Schow, P. Kozodoy, A. P. Dahl, S. Nakagawa, M. C. Larson, M. P. Mack, T. A. Strand, C. W. Coldren, E. Hegblom, S. K. Penniman, T. Wipiejewski, and L. A. Coldren, “Widely tunable electroabsorption-modulated sampled-grating DBR laser transmitter,” *IEEE J. Sel. Top. Quantum Electron.* **8**, 1349–1357 (2002).
- [7] C. Henry, “Theory of the linewidth of semiconductor lasers,” *IEEE J. Quantum Electron.* **18**, 259–264 (1982).
- [8] S. Latkowski, A. Hänsel, N. Bhattacharya, T. de Vries, L. Augustin, K. Williams, M. Smit, and E. Bente, “Novel widely tunable monolithically integrated laser source,” *IEEE Photon. J.* **7**, 1–9 (2015).
- [9] S. Latkowski, A. Hänsel, P. J. van Veldhoven, D. D’Agostino, H. Rabbani-Haghighi, B. Docter, N. Bhattacharya, P. J. A. Thijs, H. P. M. M. Ambrosius, M. K. Smit, K. A. Williams, and E. A. J. M. Bente, “Monolithically integrated widely tunable laser source operating at 2 μm ,” *Optica* **3**, 1412–1417 (2016).

- [10] S. Saito and Y. Yamamoto, "Direct observation of lorentzian lineshape of semiconductor laser and linewidth reduction with external grating feedback," *Electron. Lett.* **17**, 325–327 (1981).
- [11] W. D. R. Wyatt, "10 kHz linewidth 1.5 μm InGaAsP external cavity laser with 55 nm tuning range," *Electron. Lett.* **19**, 110–112(2) (1983).
- [12] S. D. Saliba and R. E. Scholten, "Linewidths below 100 kHz with external cavity diode lasers," *Appl. Opt.* **48**, 6961–6966 (2009).
- [13] A. L. Schawlow and C. H. Townes, "Infrared and optical masers," *Phys. Rev.* **112**, 1940–1949 (1958).
- [14] M. W. Fleming and A. Mooradian, "Fundamental line broadening of single-mode (GaAl)As diode lasers," *Appl. Phys. Lett.* **38**, 511–513 (1981).
- [15] J. Buus, M.-C. Amann, and D. J. Blumenthal, *Tunable laser diodes and related optical sources* (John Wiley & Sons, Hoboken, N.J, 2005).
- [16] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," *IEEE J. Quantum Electron.* **16**, 347–355 (1980).
- [17] M. Fleming and A. Mooradian, "Spectral characteristics of external-cavity controlled semiconductor lasers," *IEEE J. Quantum Electron.* **17**, 44–59 (1981).
- [18] K. Kikuchi and T. Okoshi, "Simple formula giving spectrum-narrowing ratio of semiconductor-laser output obtained by optical feedback," *Electron. Lett.* **18**, 10–12(2) (1982).
- [19] L. Goldberg, H. F. Taylor, A. Dandridge, J. F. Weller, and R. O. Miles, "Spectral characteristics of semiconductor lasers with optical feedback," *IEEE Trans. Microw. Theory Techn.* **30**, 401–410 (1982).
- [20] S. Saito, O. Nilsson, and Y. Yamamoto, "Oscillation center frequency tuning, quantum FM noise, and direct frequency characteristics in external grating loaded semiconductor lasers," *IEEE J. Quantum Electron.* **18**, 961–970 (1982).
- [21] Y. C. Chen, "Phase noise characteristics of single mode semiconductor lasers with optical feedback," *Appl. Phys. Lett.* **44**, 10–12 (1984).
- [22] E. Patzak, A. Sugimura, S. Saito, T. Mukai, and H. Olesen, "Semiconductor laser linewidth in optical feedback configurations," *Electron. Lett.* **19**, 1026 – 1027 (1983).
- [23] G. Agrawal, "Line narrowing in a single-mode injection laser due to external optical feedback," *IEEE J. Quantum Electron.* **20**, 468–471 (1984).

- [24] P. Spano, S. Piazzolla, and M. Tamburrini, "Theory of noise in semiconductor lasers in the presence of optical feedback," *IEEE J. Quantum Electron.* **20**, 350–357 (1984).
- [25] R. Wyatt, "Spectral linewidth of external cavity semiconductor lasers with strong, frequency-selective feedback," *Electron. Lett.* **21**, 658 – 659 (1985).
- [26] R. Tkach and A. Chraplyvy, "Regimes of feedback effects in 1.5 μm distributed feedback lasers," *J. Lightw. Technol.* **4**, 1655–1661 (1986).
- [27] H. Sato and J. Ohya, "Theory of spectral linewidth of external cavity semiconductor lasers," *IEEE J. Quantum Electron.* **22**, 1060–1063 (1986).
- [28] R. Kazarinov and C. Henry, "The relation of line narrowing and chirp reduction resulting from the coupling of a semiconductor laser to passive resonator," *IEEE J. Quantum Electron.* **23**, 1401–1409 (1987).
- [29] B. Dahmani, L. Hollberg, and R. Drullinger, "Frequency stabilization of semiconductor lasers by resonant optical feedback," *Opt. Lett.* **12**, 876–878 (1987).
- [30] N. Schunk and K. Petermann, "Numerical analysis of the feedback regimes for a single-mode semiconductor laser with external feedback," *IEEE J. Quantum Electron.* **24**, 1242–1247 (1988).
- [31] G. P. Agrawal and C. H. Henry, "Modulation performance of a semiconductor laser coupled to an external high-Q resonator," *IEEE J. Quantum Electron.* **24**, 134–142 (1988).
- [32] H. Li and N. B. Abraham, "Power spectrum of frequency noise of semiconductor lasers with optical feedback from a high-finesse resonator," *Appl. Phys. Lett.* **53**, 2257–2259 (1988).
- [33] H. Li and N. B. Abraham, "Analysis of the noise spectra of a laser diode with optical feedback from a high-finesse resonator," *IEEE J. Quantum Electron.* **25**, 1782–1793 (1989).
- [34] P. Laurent, A. Clairon, and C. Breant, "Frequency noise analysis of optically self-locked diode lasers," *IEEE J. Quantum Electron.* **25**, 1131–1142 (1989).
- [35] M. Ohtsu, M. Murata, and M. Kouroggi, "FM noise reduction and subkilohertz linewidth of an algaas laser by negative electrical feedback," *IEEE J. Quantum Electron.* **26**, 231–241 (1990).
- [36] D. R. Hjelme, A. R. Mickelson, and R. G. Beausoleil, "Semiconductor laser stabilization by external optical feedback," *IEEE J. Quantum Electron.* **27**, 352–372 (1991).

- [37] L. N. Langley, J. Mørk, and K. A. Shore, “Dynamical and noise properties of laser diodes subject to strong optical feedback,” *Opt. Lett.* **19**, 2137–2139 (1994).
- [38] J. Sigg, “Effects of optical feedback on the light-current characteristics of semiconductor lasers,” *IEEE J. Quantum Electron.* **29**, 1262–1270 (1993).
- [39] B. Liu, A. Shakouri, and J. E. Bowers, “Passive microring-resonator-coupled lasers,” *Appl. Phys. Lett.* **79**, 3561–3563 (2001).
- [40] K. Wörhoff, R. Heideman, A. Leinse, and M. Hoekman, “Triplex: A versatile dielectric photonic platform,” *Adv. Opt. Techn.* **4**, 189–207 (2015).
- [41] L. Zhuang, C. G. H. Roeloffzen, A. Meijerink, M. Burla, D. A. I. Marpaung, A. Leinse, M. Hoekman, R. G. Heideman, and W. van Etten, “Novel ring resonator-based integrated photonic beamformer for broadband phased array receive antennas -part II: Experimental prototype,” *J. Lightw. Technol.* **28**, 19–31 (2010).
- [42] D. Marpaung, C. Roeloffzen, R. Heideman, A. Leinse, S. Sales, and J. Capmany, “Integrated microwave photonics,” *Laser Photon. Rev.* **7**, 506–538 (2013).
- [43] C. G. H. Roeloffzen, L. Zhuang, C. Taddei, A. Leinse, R. G. Heideman, P. W. L. van Dijk, R. M. Oldenbeuving, D. A. I. Marpaung, M. Burla, and K. J. Boller, “Silicon nitride microwave photonic circuits,” *Opt. Express* **21**, 22937–22961 (2013).
- [44] D. Marcuse, “Reflection loss of laser mode from tilted end mirror,” *J. Lightw. Technol.* **7**, 336–339 (1989).
- [45] A. Yariv, “Universal relations for coupling of optical power between microresonators and dielectric waveguides,” *Electron. Lett.* **36**, 321–322 (2000).
- [46] L. Jin, M. Li, and J.-J. He, “Highly-sensitive silicon-on-insulator sensor based on two cascaded micro-ring resonators with vernier effect,” *Opt. Commun.* **284**, 156 – 159 (2011).
- [47] G. Griffel, “Vernier effect in asymmetrical ring resonator arrays,” *IEEE Photon. Technol. Lett.* **12**, 1642–1644 (2000).
- [48] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and K.-J. Boller, “25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity,” *Laser. Phys. Lett.* **10**, 015804 (2013).
- [49] R. M. Oldenbeuving, “Spectral control of diode lasers using external waveguide circuits,” Ph.D. thesis, Universiteit Twente, Enschede (2013).

- [50] B. Liu, A. Shakouri, and J. Bowers, “Wide tunable double ring resonator coupled lasers,” *IEEE Photon. Technol. Lett.* **14**, 600–602 (2002).
- [51] R. Adler, “A study of locking phenomena in oscillators,” *Proc. IRE* **34**, 351–357 (1946).
- [52] H. L. Stover and W. H. Steier, “Locking of laser oscillators by light injection,” *Appl. Phys. Lett.* **8**, 91–93 (1966).
- [53] R. Lang, “Injection locking properties of a semiconductor laser,” *IEEE J. Quantum Electron.* **18**, 976–983 (1982).
- [54] F. Mogensen, H. Olesen, and G. Jacobsen, “Locking conditions and stability properties for a semiconductor laser with external light injection,” *IEEE J. Quantum Electron.* **21**, 784–793 (1985).
- [55] U. Gliese, E. L. Christensen, and K. E. Stubkjaer, “Laser linewidth requirements and improvements for coherent optical beam forming networks in satellites,” *J. Lightw. Technol.* **9**, 779–790 (1991).
- [56] A. Meijerink, C. G. H. Roeloffzen, R. Meijerink, L. Zhuang, D. A. I. Marpaung, M. J. Bantum, M. Burla, J. Verpoorte, P. Jorna, A. Hulzinga, and W. van Etten, “Novel ring resonator-based integrated photonic beam-former for broadband phased array receive antennas -part I: Design and performance analysis,” *J. Lightw. Technol.* **28**, 3–18 (2010).
- [57] A. Siegman, *Lasers*, University Science Books (University Science Books, 1986).
- [58] Z. Liu, et al. “Homodyne OFDM with optical injection locking for carrier recovery,” *J. Lightw. Technol.* **33**, 34–41 (2015).

3

A hybrid semiconductor-glass waveguide laser with maximized feedback from two microring resonators

We report on a novel type of laser in which a semiconductor optical amplifier (SOA) receives frequency-selective feedback from a glass-waveguide circuit. The laser we present here is based on InP for operation in the $1.55\ \mu\text{m}$ wavelength range. The $\text{Si}_3\text{N}_4/\text{SiO}_2$ glass waveguide circuit comprises two sequential high-Q ring resonators. Adiabatic tapering is used for maximizing the feedback. The laser shows single-frequency oscillation with a record-narrow spectral linewidth of 24 kHz at an output power of 5.7 mW. The hybrid laser can be tuned over a broad range of 46.8 nm (1531 nm to 1577.8 nm). Such InP-glass hybrid lasers can be of great interest in dense wavelength division multiplexing (DWDM) and as phase reference in optical beam-forming networks (OBFN). The type of laser demonstrated here is also of general importance because it may be applied over a huge wavelength range including the visible, limited only by the transparency of glass (400 nm to $2.35\ \mu\text{m}$).¹

¹This Chapter is based on the following published work "A hybrid semiconductor-glass waveguide laser," SPIE Proceedings 9135, 91351B. (2014)

3.1 Introduction

New developments in laser technology are of both fundamental and technological interest and enable numerous applications. Of special interest are tunable lasers with narrow spectral linewidth, for which external cavity diode lasers (ECDLs) are important candidates. However, in such lasers the external frequency-selective feedback is usually achieved with bulk optical components, which renders such lasers unsuitable for many applications where small size is required. Furthermore, the mechanical tuning scheme limits the switching time between different wavelengths to tens of ms [1, 2], while a design with bulk components is prone to acoustic perturbations. These issues can be addressed with monolithic integration such as found in distributed Bragg reflector (DBR) lasers and distributed feedback (DFB) lasers. But the spectral linewidth so far achieved with DFB and DBR lasers is typically in the order of MHz, along with a small tuning range around a few nm [3, 4].

In this work we report on a novel type of laser in which components with complementary (active versus passive) properties are combined. Wide tunability and a record narrow linewidth are demonstrated with this type of laser while the footprint is kept small (a few mm). The construction of the laser is depicted in Fig. 3.1. The light generated by a solitary semiconductor optical amplifier (SOA) is controlled by frequency selective feedback from a glass-waveguide circuit which incorporates two microring resonators (MRRs). The control yields single-frequency oscillation and a wide wavelength tunability. Choosing MRRs with high quality factors enhances the frequency selectivity. Choosing glass waveguides with low loss enables an increasing of the feedback path lengths for narrowing the spectral laser linewidth. The shown type of laser may be straightforwardly extended to operate over a wide spectral region including the entire visible range, due to the wide transparency range of glass waveguides (400 nm to $2.35\text{ }\mu\text{m}$) [5], when making use of amplifiers from different semiconductor materials, such as GaN, GaAs or InGaAsSb/AlGaAsSb. Compared to initial our results [6], using an improved design with tapered glass waveguides, we demonstrate here a factor of ten increase in output power and an enlarged spectral coverage.

3.2 Structure and operation principle

As is shown in Fig. 3.1, the hybrid laser features an active-passive structure, comprising a solitary InP SOA chip and a dedicate glass waveguide circuit. To more detail, one of the facets of the amplifier chip is equipped with a high reflection (HR) coating, while the other facet (facing the glass chip) is anti-reflection (AR) coated, to suppress lasing within the gain chip. To further decrease residual feedback from the AR facet, the waveguide of the gain chip is

Figure 3.1: Schematic illustration of the hybrid semiconductor-glass waveguide laser

tilted at 5 degrees² with respect to the facet normal. Wire-bonding is used for current injection while the gain chip is mounted on a Si heatsink for the purpose of temperature stabilization. The chip is butt-coupled to the external glass waveguide circuit, the key component of which is a mirror-like circuitry (MRR mirror) composed of two sequential MRRs with slightly different radii. Due to the Vernier effect, a much larger free spectral range (FSR) can be achieved than with a single MRR [7, 8]. A large FSR is preferable for wide range tuning while maintaining single-mode operation. Lasing wavelength selection can be accomplished through thermally tuning the optical length of the MRRs via chromium heaters deposited on top of the resonators. The large index contrast ($\Delta n = 0.5$) of $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguides brings a considerable decrease in size compared to that, e.g., achieved with silica on silicon [5]. Additionally, propagation losses are low due to the smooth $\text{Si}_3\text{N}_4/\text{SiO}_2$ interfaces that can be provided with these amorphous materials. For example, propagation losses of typically 0.06-0.08 dB/cm can be achieved across the entire telecommunication C-band [9], which are nearly two orders of magnitude lower than the commonly obtained 3 dB/cm with Si/SiO₂ waveguides [10–13]. Also $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguides with a

²The tilt angle of the RSOAs may vary throughout this thesis, because all InP chips used were prototypes with various different combinations of angle, length and back facet reflectivity. In Chapter 5 we used a relatively long RSOA chip (2 mm) in order to increase the tolerance to potential losses, as will be presented later. In Chapter 7 we used a RSOA chip with moderate length (0.7 mm) that has a high back-facet reflectivity (90%) in order to decrease the cavity loss. The latter two types of RSOA chips were available only with an angle of 9 degrees.

record low loss of 0.007 dB/cm has been reported recently [14]. It can be clearly seen that advantages associated with the utilization of $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguides over other types of waveguides are prominent.

Another key issue of combining a solitary laser with an external waveguide is mode matching between the two. Undesired loss occurs when the mode profile in the gain waveguide differs from that in the passive waveguide. This is detrimental because it lowers the output power and increases the laser linewidth as well [6]. To address this, a taper section has been implemented in the external waveguide circuit. The technique applied for tapering are described to more detail in Ref [15]. Based on the design parameters chosen for reliable fabrication we determine a high coupling efficiency of 80%, which decreases undesired losses to about 20%.

3.3 Experimental results

In this section the properties of the hybrid laser are discussed in detail. The radii of the two MRRs are 49.5 μm and 54 μm respectively. The waveguide consists of two 790-nm-wide, 220-nm-thick Si_3N_4 stripes with SiO_2 as an intermediate layer (300 nm) and cladding. Via such a cross section the group refractive index of the waveguide is designed as 1.78, resulting in a calculated total FSR of 47.7 nm. The output of the hybrid laser is collected using a polarization maintaining (PM) fiber and then fed into a high resolution (0.01 nm) optical spectrum analyzer (OSA).

3.3.1 MRR mirror properties

A broadband optical source (superluminescent diode) emitting light from 1500 nm to 1600 nm is used to measure the reflectivity of the MRR mirror as a function of wavelength. These measurements are done to confirm the successful fabrication of the design. In Fig. 3.2 we present a typical example of both a calculated and a measured reflectivity spectrum. The measured spectrum is normalized to its peak reflectivity which is 48%. It can be seen that the spectra, after normalization, are in good agreement with each other. The double-ring arrangement provides a relatively large free spectral range (FSR) of 46.4nm. This is promising in terms of wide tunability across the entire bandwidth of the gain chip while maintaining a single-wavelength output. The relatively small spectral width of the central maximum (0.19 nm) and the low reflectivity of the first side peak (22%) are desirable for single-mode operation.

3.3.2 Emission spectrum

Figure 3.3 shows the output spectrum of the hybrid laser when operating at a driving current of 90 mA which is far above the threshold (5 mA). The output power is 5.7 mW of which 2 mW is coupled into the fiber for spectral analysis.

Figure 3.2: Calculated (blue) and measured (red) reflectivity as a function of wavelength of the double microring resonator mirror

It can be seen that the side mode suppression ratio (SMSR) is higher than 50 dB which suffices in almost all of the applications where there is a high demand for spectral purity [16, 17].

In order to measure the tuning range of the hybrid laser, a continuously increasing voltage is applied to the heater of one of the MRRs. This resulted in stepwise tuning via mode hops of the the wavelength with the FSR of the other MRR. Wavelengths larger than 1561.7 nm are obtained by heating the MRR with the larger radius (54 μm) while shorter wavelengths are achieved by tuning the smaller MRR (49.4 μm) at a driving current of 70 mA. Figure 3.4 shows that the hybrid laser can be tuned over a broad range starting from 1531 nm, towards 1577.8 nm, amounting to 46.8 nm, which is approximately 1.5-times larger than the telecommunication C-band (35 nm). The power variations (due to mode hops) throughout the tuning range might be reduced with maximizing the output power via the heater voltages after each mode hop. We note that the measured tuning range matches well with the FSR found in Fig. 3.2 as expected.

3.3.3 Linewidth measurement

To resolve the linewidth of the hybrid laser beyond the resolution of the OSA we employ delayed self-heterodyne detection. A 30 km long fiber is used to provide a delay longer than the coherence time of the laser. Considering the refractive index of the fiber, this length should be sufficiently long to measure

Figure 3.3: Single-wavelength laser spectrum obtained at a driving current of 90 mA, the measured side mode suppression ratio (SMSR) is larger than 50 dB.

Figure 3.4: Superimposed output spectra of the hybrid laser obtained at driving current of 70 mA.

Figure 3.5: Measured spectrum of the beat signal shows a FWHM spectral width of 48 kHz, corresponding to a 3-dB laser linewidth of 24 kHz.

laser linewidths down to 10 kHz. A subsequent acousto-optic modulator shifts the light frequency by 80 MHz for generating a non-zero-frequency beating. The beat signal is detected with a photo diode connected to a radio frequency (RF) analyzer. The RF spectrum shown in Fig.3.5 is obtained under the same condition as for recording the data in Fig.3.3. The full width at half maximum (FWHM) bandwidth of the RF spectrum is 48 kHz. This corresponds to a 24 kHz 3-dB laser linewidth³. The measured linewidth is surprisingly narrow considering the short physical length of the laser of about 4 mm. This can be largely ascribed to the low-loss feedback waveguide circuit, the long effective length of the MRRs and their high frequency selectivity. As a comparison, achieving similarly narrow linewidths with standard external cavity diode lasers using, e.g., a bulk optical grating, requires a free-space cavity length in the order of ten centimeters or more [18]. Such free-space, bulk-optical cavity, due to susceptibility to acoustic perturbations and thermal drift, then usually requires an additional active frequency stabilization [2]. On the other hand when considering integrated Bragg gratings (monolithic DBR or DFB laser) the effective length of the grating is usually shorter than its physical length [19], which gives rise to a typical linewidth in the order of 1 MHz.

³We note that the center part of the laser emission spectrum is usually broadened due to technical noise at low noise frequencies. This means that the 3-dB linewidth is larger than the fundamental (intrinsic) laser linewidth. A detailed discussion about intrinsic linewidth retrieving based on laser frequency noise measurements can be found in Chapter 7.

3.4 Conclusion

A hybrid semiconductor-glass waveguide laser has been presented and its main properties have been investigated. By maximizing the coupling between the semiconductor and Si_3N_4 glass waveguides via tapering, a maximum of 5.7 mW output power was achieved with a SMSR larger than 50 dB. The laser exhibits a broad tuning range of 46.8 nm while the spectral linewidth is as narrow as 24 kHz. This is the smallest linewidth obtained so far for any hybrid-integrated diode laser, including work based on feedback from Si waveguide MRR circuits [11–13]. Seen the low losses of glass waveguides, a further narrowing of the linewidth into the sub-KHz range might be realized with further improved mode matching together with increasing the effective length the MRRs via smaller coupling [6]. The wide freedom of choice in selecting any desired semiconductor gain material within the transparency range of glass appears of interest for exploring the described laser also in other wavelength ranges, such as for applications in gas sensing or precision metrology.

Bibliography

- [1] E. Bruce, “Tunable lasers,” *IEEE Spectrum* **39**, 35–39 (Feb 2002).
- [2] S. D. Saliba, and R. E. Scholten, “Linewidths below 100 kHz with external cavity diode lasers,” *Appl. Opt.* **48**, 6961–6966 (Dec 2009).
- [3] P. Signoret, M. Myara, J. P. Turrenc, B. Orsal, M.-H. Monier, J. Jacquet, P. Leboudec, and F. Marin, “Bragg section effects on linewidth and line-shape in 1.55 μm DBR tunable laser diodes,” *IEEE Photon. Technol. Lett.* **16**, 1429–1431 (June 2004).
- [4] M. Faugeron, M. Tran, O. Parillaud, M. Chtioui, Y. Robert, E. Vinet, A. Enard, J. Jacquet, and F. van Dijk, “High-power tunable dilute mode DFB laser with low RIN and narrow linewidth,” *IEEE Photon. Technol. Lett.* **25**, 7–10 (Jan 2013).
- [5] A. Leinse, R. G. Heideman, M. Hoekman, F. Schreuder, F. Falke, C. G. H. Roeloffzen, L. Zhuang, M. Burla, D. Marpaung, D. H. Geuzebroek, R. Dekker, E. J. Klein, P. W. L. van Dijk, and R. M. Oldenbeuving, “Triplex waveguide platform: low-loss technology over a wide wavelength range,” *Proc. SPIE* **8767**, 87670E–87670E–13 (2013).
- [6] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and , K.-J. Boller, “25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity,” *Laser. Phys. Lett.* **10**(1), 015804 (2013).
- [7] D. Rabus, Z. Bian, and , A. Shakouri, “A GaInAsP-InP double-ring resonator coupled laser,” *IEEE Photon. Technol. Lett.* **17**, 1770–1772 (Sept 2005).
- [8] Y. Chung, D.-G. Kim, and N. Dagli, “Widely tunable coupled-ring reflector laser diode,” *IEEE Photon. Technol. Lett.* **17**, 1773–1775 (Sept 2005).
- [9] F. Morichetti, A. Melloni, M. Martinelli, R. G. Heideman,, A. Leinse, D. H. Geuzebroek, and A. Borreman, “Box-shaped dielectric waveguides: A new concept in integrated optics?,” *J. Lightw. Technol.* **25**, 2579–2589 (Sept 2007).
- [10] Y. Vlasov, and S. McNab, “Losses in single-mode silicon-on-insulator strip waveguides and bends,” *Opt. Express* **12**, 1622–1631 (Apr 2004).

- [11] J. C. Hulme, J. K. Doylend, and J. E. Bowers, “Widely tunable vernier ring laser on hybrid silicon,” *Opt. Express* **21**, 19718–19722 (Aug 2013).
- [12] K. Suzuki, T. Kita, and H. Yamada, “Wavelength tunable laser diodes with Si-wire waveguide ring resonator wavelength filters,” *Proc. SPIE* **7943**, 79431G–79431G–7 (2011).
- [13] K. Nemoto, T. Kita, and H. Yamada, “Narrow-spectral-linewidth wavelength-tunable laser diode with Si wire waveguide ring resonators,” *Appl. Phys. Express* **5**(8), 082701 (2012).
- [14] J. Bauters, M. J. R. Heck, D. John, M.-C. Tien, W. Li, J. s. Barton, D. Blumenthal, J. E. Bowers, A. Leinse, and R. G. Heideman, “Ultra-low-loss single-mode Si₃N₄ waveguides with 0.7 dB/m propagation loss,” *37th European Conference and Exposition on Optical Communications*, paper Th.12.LeSaleve.3 (2011).
- [15] K. Wörhoff, R. Heideman, A. Leinse, and M. Hoekman, “Triplex: A versatile dielectric photonic platform,” *Adv. Opt. Techn.* **4**, 189–207 (2015).
- [16] A. Nakamura, “LGLC tunable laser with highly stable smsr against large filter deviation for full C-band operation,” in [*Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*], *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, OTh3I.6, Optical Society of America (2013).
- [17] J. Jin, L. Wang, T. Yu, Y. Wang, and J.-J. He, “Widely wavelength switchable V-coupled-cavity semiconductor laser with ~ 40 dB side-mode suppression ratio,” *Opt. Lett.* **36**, 4230–4232 (Nov 2011).
- [18] R. A. Linke, and K. J. Pollock. “Linewidth versus length dependence for an external cavity laser,” *Proc. 10th IEEE International Semiconductor Laser Conference* (1986).
- [19] B. Liu, A. Shakouri, and J. E. Bowers, “Passive microring-resonator-coupled lasers,” *Appl. Phys. Lett.* **79**, 3561–3563 (Nov 2001).

4

Q -factor measurements through injection locking of a semiconductor-glass hybrid laser with unknown intracavity losses

The injection locking properties of a newly developed waveguide based external cavity semiconductor laser have been investigated. Using the injection locking properties to measure the Q -factor of complex optical cavities with unknown internal losses, has been demonstrated for the first time. ¹

¹This Chapter is based on the following published work "Q-factor measurements through injection locking of a semiconductor-glass hybrid laser with unknown intracavity losses," Optics Letters **39**(7), 1748 (2014).

4.1 Introduction

Injection locking of lasers is a powerful method for all-optical control of the frequency and phase of laser oscillators with superior precision [1, 2]. Semiconductor lasers are a very important target for injection locking, as evidenced by a wide range of fundamental physics applications. These include the generation of non-classical, sub-Poissonian states of light [3, 4], or highly frequency selective amplification in precision metrology based on optical frequency combs [5]. Injection-locking of semiconductor lasers is also of great technological importance in integrated optical systems. Examples are the generation of ultrawide tunable radiation (microwave to terahertz) [6], phase-locking of entire arrays of lasers [7], phase control of terahertz lasers [8], applications in coherent communications systems [9], and microwave photonics [10].

Integration of hybrid devices, which can combine lasers, splitters, modulators, and detectors on the same substrate, are interesting for a range of applications [11]. Of particular interest is the integration of optical components with complementary (i.e. active vs. passive) properties [12] because this can strongly enhance the spectral and temporal control of the generated light, such as via integrated high Q resonators and delay lines. An example is the integration of InP semiconductor optical amplifiers (SOAs) with spectrally selective Si waveguide resonators for external feedback. This approach yielded integrated external cavity diode lasers with wide spectral tuning [13] and narrow spectral bandwidth [14]. The narrowest spectral bandwidth obtained so far with such waveguide based external cavity semiconductor lasers was achieved with using, for the first time, a glass-based waveguide circuit to form a semiconductor-glass hybrid laser. The narrow spectral bandwidth was the result of using feedback from a low-loss glass ($\text{Si}_3\text{N}_4/\text{SiO}_2$) waveguide circuit containing two microring resonators (MRRs). We found, interestingly, that the laser had a spectral bandwidth as low as 25 kHz [15]. Nevertheless the full potential of such lasers is far from being explored.

The low reported spectral bandwidth is likely to be due to the low losses obtained from the glass waveguides [16, 17]. These losses make ultra-low spectral bandwidths in the sub-kHz-range appear feasible if the quality factor (Q -factor) of the hybrid laser cavity can be increased. This could be achieved by reducing the coupling loss at the interface between the SOA and the waveguide feedback chip, for example. Increasing the Q -factor also yields an inversely proportional narrowing of the locking range [18], which enhances the frequency selectivity of a hybrid laser. Frequency selective amplification is of great interest for the amplification of single lines in optical frequency combs, or narrow sidebands, as is required for phased array antenna applications [19]. This reasoning, however, can be reversed: the inversely proportional relationship between the Q -factor and locking range also enables a direct measurement of the Q -factor of the hybrid laser cavity. This is important because measuring the roundtrip losses in such laser is even more difficult than determining the losses in a solitary diode laser [20]. The hybrid laser is based on a complex cavity, consisting of a low- Q

semiconductor gain section and dedicated high- Q waveguide circuitry. In this case, a conventional cavity ring-down measurement cannot be easily conducted [21]. In addition, the need for another probe laser with a frequency that is on resonance with the hybrid laser cavity renders this method prohibitive. An alternative solution might involve measuring the losses originating from numerous mechanisms in a hybrid device. This would require measuring internal losses in the active region [20], propagation loss in the waveguide, and bending losses within each MRR [22], as well as *a priori* unknown feedback and coupling loss at the interface between the SOA and the waveguide chip [23]. This would be time consuming, and large uncertainties would arise due to differences, associated with fabrication and processing variability, between samples used for each measurement.

Here we demonstrate the first injection locking of a semiconductor-glass waveguide hybrid laser and characterize its basic parameters. Locking is performed by injecting an RF sideband from a second hybrid laser. The locking range, measured vs. the injected power, is in agreement with previously estimated values for the Q -factor of the hybrid laser cavity and, thereby, confirms the high potential of such lasers as new class of integrated-optics oscillators with ultra-low bandwidth. The locking demonstrated here also provides a new tool for measuring the cavity Q -factor of such lasers in operation and, thereby, allows the quality of chip-to-chip coupling to be assessed. The availability of such a tool lies at the heart of hybrid photonic integration involving optical amplification, because measurements of chip-to-chip coupling performance is necessary to guide loss reduction strategies, such as waveguide tapering for spotsize conversion [24].

4.2 Theoretical background

To recall the essential properties of injection locking: the output from a first laser, called the master laser (ML), is injected into a second laser, called the slave laser (SL). If the detuning of the ML frequency, ν_{ML} , from the free-running SL frequency, ν_{SL} , is smaller than the so-called locking range, i.e., $\Delta\nu_{lk} > |\nu_{ML} - \nu_{SL}|$, the SL starts oscillating at the injected ML frequency rather than at ν_{SL} .

The full locking range, which is twice the so-called locking half-range, is given by: [18]

$$\Delta\nu_{lk} = \frac{\nu_{SL}}{Q} \sqrt{\frac{P_i}{P_{SL}}}, \quad (4.1)$$

where Q is the quality factor of the slave laser's resonator, P_{SL} is the free running output power, and P_i is the injected power. The latter includes transmission and mode matching losses and is, thus, only a fraction of the ML total output power.

This expression would underestimate the locking range by a factor of $(1 + \alpha^2)^{1/2}$ if applied to a solitary diode laser, [25], where α is the linewidth enhancement or Henry factor [26]. In a hybrid laser, however, only a small fraction of the cavity, $f_c < 1$ is fabricated from semiconductor material. In our case, the light only spends $f_c = 0.15$ of the roundtrip time in the semiconductor material, and α is between 3 and 4, according to the manufacturer (Fraunhofer Heinrich-Hertz-Institut, Berlin). Using these considerations, we estimate that the broadening of the locking range is limited to $(1 + (f_c \alpha)^2)^{1/2}$, which is in the range of 1.1–1.17 for the lasers described here.

Eq.(4.1) can be used to determine the effective Q -factor of the hybrid cavity by varying the injected power and measuring the locking range. The schematic structure of the two lasers used is the same as shown in Chapter 3 (Fig. 3.1). Both the ML and SL are the same as that described in detail in Ref. [15]. In brief, the lasers are based on InP SOAs with a measured output power of 7.4 mW (at drive current 90 mA) at a wavelength of around 1.55 μm . The gain waveguide is tilted at 5 degrees with respect to the anti-reflection coated output facet. The frequency selective waveguide feedback circuits are fabricated using $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguide technology with a box-shaped waveguide cross section [16]. Light coupled into the input/output waveguide travels via a Y-junction through two sequential MRRs (radius of 50 and 55 μm) before traveling back into the SOA. The input-output facet the waveguide is tilted and anti-reflection coated to minimize coupling losses. Heaters are placed on top of the MRRs to thermally tune the two MRR's resonance frequencies. Output from the lasers is obtained after a second Y-junction behind the MRRs.

4.3 Experimental results and discussion

The injection locking experimental setup is shown in Fig. 4.1. The light from the ML is coupled into a single-mode fiber and amplified by an Erbium doped fiber amplifier (EDFA, Firmstein Technologies PR25R), followed by a 90/10 splitter. The higher power portion is used to provide the reference signal for heterodyne detection, while the lower power signal is used for injection locking. The injection signal is passed through a Mach-Zehnder optical modulator (Avanex PowerLog FA 20), which is driven by a signal generator (Agilent Technologies E8267D) that is capable of sweeping the modulation frequency, Ω , from 0 to 20 GHz. After modulation, about 15% of the optical power is contained in the first $(\nu_{ML} - \Omega)$ sideband. To prevent feedback from the SL into the ML, the modulated signal is passed through an optical isolator (IO-H-1550FC Thorlabs). Thereafter, the injection signal is amplified by two EDFAs (Alcatel 1686WM). The injected power is controlled via a variable attenuator (Ando AQ3105), and the light is injected into the SL via a 50/50 coupler.

This coupler is also the output port of the SL. The output of the SL exits the coupler, and is amplified by an EDFA (Firmstein Technologies PR25R). Following amplification, the SL output is mixed with the reference using a sec-

Figure 4.1: Schematic of the injection locking setup. The master laser is marked as ML, slave: SL, optical modulator: MOD., optical isolator: $\rightarrow$, optical attenuator: Att., couplers: 50/50 and 90/10, optical spectrum analyzer: OSA, photodiode: PD, and RF spectrum analyzer: RF. Measurements of the injected ML power and the SL output power are performed at the location marked with the arrow.

and 50/50 coupler. Half of the light is detected at one port of the 50/50 coupler using a photodiode (Discovery Semi DSC 30S) with a bandwidth of 20 GHz. The beat frequency is recorded using an RF spectrum analyzer (Agilent Signal Analyzer MXA N9020A, maximum range 10 Hz to 26.5 GHz). The light from the second output of the 50/50 coupler is directed to an optical spectrum analyzer (Ando AQ6317, spectral resolution 3 GHz).

The two lasers were coarsely tuned until their frequencies were within 20 GHz of each other, as measured by the optical spectrum analyzer. The modulation frequency was then swept so that the frequency of the light injected into the SL was precisely controlled compared to the precision achieved via thermally tuning the ML. The frequency range over which the ML could successfully injection lock the SL was recorded for different injected powers.

To calibrate the power of the injected sideband, we determined the ML power at the output of the 50/50-coupler in front of the SL, which is marked with an arrow in Fig. 4.1. We measured a ML power of 2.69 mW with the attenuator set to 0 dB, and 15% of this amount is transferred to the upper first-order sideband, which corresponds to a sideband power of 403.5 μ W. At the same position, the output power of the slave laser was measured to be $P_{SL} = 20.9 \mu$ W. The mode field diameter of the single mode fiber is specified to be $10.5 \pm 0.8 \mu$ m (P1-1550PM-FC-2) and that of the waveguide chip is measured to be 1 μ m in both directions, yielding a calculated coupling efficiency of 3.56×10^{-2} with uncertainties of -13% and $+17\%$. This allows us to determine the ratio of P_i and P_{SL} in Eq. 4.1. Using the calculated coupling efficiency, the maximum injected sideband power from the ML was calculated to be $P_i =$

Figure 4.2: RF beat spectra of the injected and the SL frequency, recorded for different detunings of the injected ML sideband. Locking is indicated by a single beat frequency ((b)–(e)). No locking is indicated by the presence of several beat frequencies, generated by the different frequencies of the sideband, reference and SL ((a) and (f)). The shown spectra are obtained with an injected power of $14.38 \mu\text{W}$. The shown spectra are all centered at 11.24 GHz .

$14.38 \mu\text{W}$ at 0 dB of attenuation.

A set of typical RF spectra is shown in Fig. 4.2, recorded for different values of the modulation frequency. The presence of injection locking is determined by inspecting the spectra for the number of frequencies of beat notes. If the SL was successfully locked to the ML, a single beat frequency between the reference and locked sideband was observed (see Fig. 4.2(b)–(e)). If the SL was not locked while the frequency of the ML frequency was close to the edge of the locking range, multiple sidebands were observed (see Fig. 4.2(a), and (f)). The origin of these sideband is well understood [27]. The injected light, when tuned outside the locking range, does not extinguish the SL frequency, but causes a frequency modulation of the SL frequency, at the SL-ML difference frequency.

Fig. 4.3 shows the main results, which is the measured injection locking range as a function of the injected ML sideband power. The injected powers for which locking was observed range from 6.42 – $14.38 \mu\text{W}$. The vertical error bars indicate the experimental uncertainty.

The data is plotted on a double-logarithmic scale in order to investigate whether they follow a linear function with a slope of $-1/2$ as predicted by Eq. 4.1. The solid line shows a least-square fit of Eq.(4.1) to the data, with

Figure 4.3: Injection locking range of the hybrid laser vs. the injected sideband power, on a double-logarithmic scale. The output power of the locked SL-hybrid laser is 0.587 mW. The red circles depict the experimental data. The solid line is a least-squares fit of Eq. 4.1 with Q as the only free parameter.

Q the only free parameter. The best fit value for Q was found to be $(6.2 \pm 1.6) \times 10^4$. The uncertainty comes from two sources: the uncertainty in the locking range, which contributes 1.0×10^4 , and might be decreased substantially by using an optimized choice of RF spectrum analyzer and RF modulator sweep times. We address the remaining 0.6×10^4 error to the input power measurements. Taking into account the influence of the Henry factor (10–17%), the Q is found to be in the range of 4.1×10^4 to 8.6×10^4 . We note that this value is of the same order as previous estimates of the Q ($Q = 1.6 \times 10^4$) based on an estimated 13.5 ps photon lifetime in the hybrid laser cavity) [15].

4.4 Conclusion

Here we have investigated injection locking of a novel type of hybrid laser based on semiconductor gain and glass waveguide feedback. Integrated optical lasers lend themselves to injection locking because they are largely immune to mechanical perturbations and drifts of mode-matching conditions. This ease of injection locking allows it to be used as a method to quantify the effective Q -factor of integrated optical cavities with unknown internal losses. This tool may also be used to inspect the intracavity losses of standard monolithic diode lasers, such as Fabry-Perot and distributed feedback lasers.

Bibliography

- [1] H. L. Stover, “Locking of laser oscillators by light injection,” *Appl. Phys. Lett.* **8**, 91 (1966).
- [2] C. J. Buczek, R. J. Freiberg, and M. L. Skolnick, “Laser injection locking,” *Proc. IEEE* **61**, 1411–1431 (1973).
- [3] H. Wang, M. J. Freeman, and D. G. Steel, “Squeezed light from injection-locked quantum well lasers,” *Phys. Rev. Lett.* **71**, 3951–3954 (1993).
- [4] S. Kasapi, S. Lathi, and Y. Yamamoto, “Amplitude-squeezed, frequency-modulated, tunable, diode-laser-based source for sub-shot-noise FM spectroscopy,” *Opt. Lett.* **22**, 478–480 (1997).
- [5] T. Fortier, Y. Le Coq, J. Stalnaker, D. Ortega, S. Diddams, C. Oates, and L. Hollberg, “Kilohertz-Resolution Spectroscopy of Cold Atoms with an Optical Frequency Comb,” *Phys. Rev. Lett.* **97**, 163905 (2006).
- [6] G. J. Schneider, J. A. Murakowski, C. A. Schuetz, S. Shi, and D. W. Prather, “Radiofrequency signal-generation system with over seven octaves of continuous tuning,” *Nat. Photon.* **7**, 118–122 (2013).
- [7] L. Goldberg, H. F. Taylor, J. F. Weller, and D. M. Bloom, “Microwave signal generation with injection-locked laser diodes,” *Electron. Lett.* **19**, 491–493 (1983).
- [8] D. Oustinov, N. Jukam, R. Rungsawang, J. Madéo, S. Barbieri, P. Filloux, C. Sirtori, X. Marcadet, J. Tignon, and S. Dhillon, “Phase seeding of a terahertz quantum cascade laser,” *Nat. Commun.* **1**, 1–6 (2010).
- [9] T. Jung, J.-L. Shen, D. T. K. Tong, S. Murthy, M. C. Wu, T. Tanbun-Ek, W. Wang, R. Lodenkamper, R. Davis, L. J. Lembo, and J. C. Brock, “CW injection locking of a mode-locked semiconductor laser as a local oscillator comb for channelizing broad-band RF signals,” *IEEE T. Microw. Theory* **47**, 1225–1233 (1999).
- [10] J. Capmany and D. Novak, “Microwave photonics combines two worlds,” *Nat. Photon.* **1**, 319–330 (2007).

- [11] Y. Urino, T. Shimizu, M. Okano, N. Hatori, M. Ishizaka, T. Yamamoto, T. Baba, T. Akagawa, S. Akiyama, T. Usuki, D. Okamoto, M. Miura, M. Noguchi, J. Fujikata, D. Shimura, H. Okayama, T. Tsuchizawa, T. Watanabe, K. Yamada, S. Itabashi, E. Saito, T. Nakamura, and Y. Arakawa, "First demonstration of high density optical interconnects integrated with lasers, optical modulators, and photodetectors on single silicon substrate," *Opt. Express* **19**, B159 (2011).
- [12] Y. Wakayama, T. Kita, and H. Yamada, "Optical Crossing and Integration Using Hybrid Si-Wire/Silica Waveguides," *Jpn. J. Appl. Phys* **50**, 04DG20 (2011).
- [13] S. Tanaka, S.-H. Jeong, S. Sekiguchi, T. Kurahashi, Y. Tanaka, and K. Morito, "High-output-power, single-wavelength silicon hybrid laser using precise flip-chip bonding technology," *Opt. Express* **20**, 28057–28069 (2012).
- [14] K. Nemoto, T. Kita, and H. Yamada, "Narrow-Spectral-Linewidth Wavelength-Tunable Laser Diode with Si Wire Waveguide Ring Resonators," *Appl. Phys. Express* **5**, 082701 (2012).
- [15] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and K.-J. Boller, "25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity," *Laser Phys. Lett.* **10**, 015804 (2012).
- [16] F. Morichetti, , A. Melloni, M. Martinelli, R. G. Heideman, A. Leinse, D. H. Geuzebroek, and A. Borreman, "Box-shaped dielectric waveguides: A new concept in integrated optics?," *J. Lightwave Technol.* **25**, 2579–2589 (2007).
- [17] J. F. Bauters, M. J. R. Heck, D. D. John, J. S. Barton, C. M. Bruinink, A. Leinse, R. G. Heideman, D. J. Blumenthal, and J. E. Bowers, "Planar waveguides with less than 0.1 dB/m propagation loss fabricated with wafer bonding," *Opt. Express* **19**, 24090–24101 (2011).
- [18] R. Adler, "A study of locking phenomena in oscillators," *Proc. IRE* **34**, 351–357 (1946).
- [19] A. Meijerink, C. G. H. Roeloffzen, R. Meijerink, L. Zhuang, D. A. I. Marpaung, M. J. Bentum, M. Burla, J. Verpoorte, P. Jorna, A. Hulzinga, and W. van Etten, "Novel ring resonator-based integrated photonic beam-former for broadband phased array receive antennas—Part I: Design and performance analysis," *J. Lightwave Technol.* **28**, 3–18 (2010).
- [20] P. A. Andrekson, N. A. Olsson, T. Tanbun-Ek, R. A. Logan, D. Coblentz, and H. Temkin, "Novel technique for determining internal loss of individual semiconductor lasers," *Electron. Lett.* **28**, 171–172 (1992).

-
- [21] S. L. Logunov, “Cavity ringdown detection of losses in thin films in the telecommunication wavelength window,” *Appl. Opt.* **40**, 1570–1573 (2001).
 - [22] Y. Vlasov and S. McNab, “Losses in single-mode silicon-on-insulator strip waveguides and bends,” *Opt. Express* **12**, 1622–1631 (2004).
 - [23] Y. Barbarin, E. Bente, C. Marquet, E. Leclerc, J. Binsma, and M. K. Smit, “Measurement of reflectivity of butt-joint active-passive interfaces in integrated extended cavity lasers,” *IEEE Photon. Technol. Lett.* **17**, 2265–2267 (2005).
 - [24] T. Mizuno, T. Kitoh, M. Itoh, T. Saida, T. Shibata, and Y. Hibino, “Optical Spotsize Converter Using Narrow Laterally Tapered Waveguide for Planar Lightwave Circuits,” *J. Lightwave. Technol.* **22**, 833 (2004).
 - [25] F. Mogensen, H. Olesen, and G. Jacobsen, “Locking conditions and stability properties for a semiconductor laser with external light injection,” *IEEE J. Quantum Electron.* **21**, 784–793 (1985).
 - [26] C. Henry, “Theory of the linewidth of semiconductor lasers,” *IEEE J. Quantum Electron.* **18**, 259–264 (1982).
 - [27] A. E. Siegman, *Lasers* (University Science Books, 1986), 1st ed.

5

Optically integrated InP-Si₃N₄ hybrid laser

We describe the first demonstration and characterization of an optically integrated InP-Si₃N₄ hybrid laser. The laser is formed by integration of an InP based reflective semiconductor optical amplifier (RSOA) with a Si₃N₄ based feedback waveguide circuit. The circuit comprises a frequency selective and tunable Vernier mirror composed of two microring resonators (MRRs) with slightly different radii. A wide tuning range of more than 43 nm is achieved via the thermo-optic effect. The typical side mode suppression ratio (SMSR) is 35 dB. The narrowest linewidth achieved is about 90 kHz, and the relative intensity noise is less than -135 dBc/Hz.¹

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5.1 Introduction

There has been an ever-increasing demand for higher bandwidth in fiber-optic communications. Such demand has driven the need for integrated semiconductor laser sources with narrow linewidths that can be applied in dense wavelength division multiplexing (DWDM) using advanced modulation formats, such as quadrature amplitude modulation (QAM) [1]. Besides fiber-optic telecommunications, applications that benefit from such lasers are optical beamforming networks [2], light detection and ranging (LIDAR) [3], spectroscopy [4], optical sensing [5] or space-based laser cooling [6] and atomic clocks [7] in global positioning systems (GPS). Especially when looking for narrow spectral bandwidth, monolithic semiconductor lasers, where all the components of the laser are made of the same materials, approach their limits. This is the reason why so-called hybrid lasers are currently gaining considerable interest. In such lasers, a semiconductor amplifier made of active material providing optical gain is optically coupled to an integrated optical waveguide circuit fabricated from a different passive material (without optical gain). Specifically, replacing any passive but otherwise relatively lossy section of a semiconductor waveguide resonator by low-loss passive waveguides enables reducing the total cavity loss and increasing the cavity length, which is known to decrease the Schawlow-Townes linewidth of the laser [8].

The hybrid laser schemes investigated so far can be divided into three types: a) evanescently coupled III/V on Si lasers [9]; b) lasers which utilize a vertical taper to realize an adiabatic conversion of the optical mode from a III-V gain waveguide into passive waveguides [10–12]; and c) reflective semiconductor optical amplifiers (RSOAs) butt-coupled to external waveguide circuits, realized with various passive waveguide platforms such as Si [13, 14], SiON [15], polymer [16] and Si₃N₄ [17]. While evanescently and adiabatically coupled lasers might be integrated via bonding techniques, they require sophisticated fabrication technology which essentially introduces III-V material in CMOS processing lines, which is generally not supported in current foundries. Moreover, the passive material used so far has exclusively been limited to Si, and thus to certain infrared ranges including the telecom range while, but excluding applications in the visible. The third type, however, is quite different in that it relieves the difficulties in fabrication and broadens the choice of materials. The RSOA and external waveguide circuitry can be fabricated separately, for achieving high performance with independently optimizing each component.

Previously, we had reported the first demonstration of a semiconductor-Si₃N₄ hybrid laser. In this experiment, the InP RSOA and Si₃N₄ waveguide chips were not yet integrated (firmly and permanently coupled to each other), but the chips were mounted on separate alignment stages and it remained possible to optimize the optical coupling via manual readjustments. Frequency selection is achieved using a Vernier mirror based on two microring resonators (MRRs) [17, 18]. A wide tuning range covering the entire telecom C-band was achieved. The emerging Si₃N₄ waveguide platform is of special importance be-

cause it can offer some fundamental and technological advantages over other passive waveguide platforms: a) compared to silica that has only a low index contrast ($\Delta n \approx 10^{-2}$ [19]), the index contrast is very high, $\Delta n \approx 0.5$, rendering a small footprint achievable even with long optical lengths; b) Si_3N_4 waveguides provide a very large transparency range, from 400 nm to 2400 nm [20], which means that a large varieties of semiconductor materials other than InP might be used, to form hybrid lasers working at other wavelengths including the visible range; c) very low linear propagation loss in the order of 0.1 dB/cm [21] when using a double-stripe cross-section and record-low loss of less than 0.001 dB/cm with a single-stripe cross-section [22]; d) its low nonlinearity, which prevents two-photon absorption [23]; e) its maturity in terms of design, tunability [24] and programmability [25], which enables access to complex functionalities on the same photonic chip.

The aforementioned advantages of a hybrid InP- Si_3N_4 laser call for a feasible approach to integrate such lasers, which is the key for applications. Examples are flip-chip bonding [26–28] and a recently reported 3D integration utilizing a total internal reflection (TIR) turning mirror within the RSOA [29]. However, those approaches require a highly specific design of the RSOA, ruling out the possibility of utilizing off-the-shelf, standard gain chips that are easily available at most desired wavelengths and powers.

In this chapter we demonstrate an optically integrated InP- Si_3N_4 laser for the first time. A first challenge in this, when using standard, non-customized RSOA chips and basic, non-tapered waveguides, is that even with perfect alignment the optical mode mismatch can be large and cause coupling loss at the 90% level [17]. Tapered waveguides would increase the optical coupling but different tapers are required for different types of RSOAs which deviate significantly in their mode field diameters (MFD). Secondly, the typical limit in alignment accuracy is in the order of 0.1 μm which introduces unforeseeable loss particularly at small and well-matched mode field diameters. These effects greatly influence the achievable output power via some unpredictable increase in laser threshold, in addition to threshold variations due to the spectrally varying transmission of the output mirror which is a major aspect of laser cavity designs [14]. Ruling out these shortcomings and uncertainties and improving accuracy in positioning and fixation is certainly possible to an appreciable extent but it would lead to smaller tolerances and thus higher risk and costs in optical integration.

In this work, the goal is to demonstrate a viable way of integrating a hybrid laser that offers useful output power at the mW-level and still provides a large tolerance to the named losses, although this would sacrifice wall plug efficiency and increases the spectral linewidth of the laser [8]. To secure a strong loss margin, we use an RSOA with a rather large length to provide high gain. Numerical modeling of the output power versus coupling loss is carried out to quantify our assumption of the loss margin, while comparison with experimental output data can be used to determine the amount of losses present. After integration of the hybrid laser, its spectral linewidth and other important properties such

as the side mode suppression ratio (SMSR) and relative intensity noise (RIN) are presented.

5.2 Device description and operation principle

Figure 5.1: Schematic drawing of the hybrid laser (not to scale). R_1 is the reflectivity of the high reflection (HR) coated amplifier back facet, R_2 is the overall reflectivity of the Vernier mirror, L is the total length of the feedback circuit and β is the power coupling efficiency between the anti-reflection (AR) coated diode waveguide and the Si₃N₄ waveguide.

The basic waveguide layout of the hybrid laser under investigation is shown in Fig. 5.1. The laser comprises an InP based RSOA and a Si₃N₄ waveguide circuit. The RSOA (obtained from the Fraunhofer Heinrich-Hertz-Institute, Berlin) possesses a relatively long length of 2 mm, in order to provide a high single-pass gain for compensating potential high losses in the hybrid laser cavity. The RSOA has a HR coated back-facet with a reflectivity of $R_1=90\%$ and an AR coating of the front-facet optimized for a refractive index of 1.5, close to the effective index of the external Si₃N₄ waveguide which was used in this work (1.535). The diode waveguide is angled with regard to the front facet by 9° to further reduce perturbing back reflection. This was successfully achieved, because the output spectra as presented later, appear free of a 0.16-nm modulation that would correspond to the optical roundtrip length of the diode; the MFD is specified to be $4.2\ \mu\text{m}$ in the horizontal direction and $1.95\ \mu\text{m}$ in the vertical direction. These values for the MFD are large when compared with other commercially available RSOA chips and also compared with the MFD of the Si₃N₄ waveguide used here ($1.62\ \mu\text{m}$ in the horizontal direction and $1.72\ \mu\text{m}$ in the vertical direction). Although this mismatch will lead to increased roundtrip losses of the hybrid laser, the purpose here is to improve the tolerance *vs* misalignment. The calculated coupling loss between the two chips as a function of transverse misalignment is shown in Fig. 5.2. It can be seen that the coupling loss increases by 1 dB with a misalignment of $1.6\ \mu\text{m}$ in the horizontal direction or $1.3\ \mu\text{m}$ in the vertical direction. Given that state-of-the-art precision stages that we use here provide 100 nm resolution, a sufficiently large misalignment tolerance should be present. The RSOA chip is butt-coupled to the Si₃N₄ waveguide circuit, which carries a circuitry composed of two cascaded

(Vernier) MRRs that work as highly frequency selective feedback elements for imposing single-frequency operation at a narrow spectral bandwidth. The two slightly different radii of the MRRs and their power coupling coefficients are selected such that a) the total free spectral range (FSR) of the Vernier mirror exceeds the gain bandwidth of the RSOA, and b) that the spectral side peaks of the Vernier mirror reflectivity are suppressed to avoid lasing at undesired side modes [17].

Figure 5.2: The calculated coupling loss between the InP RSOA chip and the Si_3N_4 chip as a function of transverse misalignment, while the longitudinal gap size is assumed to be zero. It can be seen that the optimum coupling loss is about 2.6 dB. The 1-dB misalignment tolerance reaches $1.6\ \mu\text{m}$ in horizontal direction and $1.3\ \mu\text{m}$ in vertical direction.

Figure 5.3: The amplified spontaneous emission (ASE) spectrum (red curve) of the RSOA at 80 mA driving current is displayed together with the spectral reflectivity (blue curve) of the Vernier mirror when using a superluminescent diode (SLD) as the light source. Both spectra are normalized to their corresponding maxima.

For checking the fulfillment of these conditions we measured the amplified spontaneous emission (ASE) spectrum of the RSOA and the reflection spectrum

of various Vernier mirrors. An example of an ASE spectrum is shown in Fig. 2, recorded at a driving current of 80 mA. The reflectivity of the Vernier mirror selected for laser feedback (MRR radii of 49.5 and 54.0 μm , power coupling coefficients set to 0.3, total circuit length $L=3.5$ mm) was measured with a broadband (3 dB spectral width of 50 nm) superluminescent diode (SLD) and is plotted in Fig. 5.3 as well. It can be seen that the RSOA provides optical gain over more than 35 nm bandwidth, covering the telecom C-band and that the Vernier mirror exceeds this bandwidth with a total free spectral range (FSR) of 46.4 nm and high side peak suppression.

5.3 Modeling of the output power versus coupling efficiency β

In order to retrieve important parameters that are needed for modeling the output power of the hybrid laser under various coupling efficiencies, β , first the RSOA output power (as cleaved, before the deposition of HR and AR coatings) *vs* driving current (LI curve) was recorded in solitary operation, i.e., before integration with the Si₃N₄ circuit. From the LI curve that showed a threshold current of 50 mA and slope efficiency of about 13.5 W/A, we calculated a gain-factor g_0 of about 2500 cm^{-1} and an internal loss coefficient of about 13 cm^{-1} , using a rate equation (RE) model [30] when the tilting induced reflectivity (16.5%) as defined in Eq. 2.9 is taken into account [31]. g_0 is the current-independent gain-factor that scales in the gain coefficient, g , as follows: $g = g_0 \ln N/N_{tr}$ where N is the carrier density which depends on driving current and N_{tr} is the transparency carrier density.

Figure 5.4: Numerically calculated LI curves at different optical coupling efficiencies β .

To verify that the chosen high-gain RSOA provides a high tolerance with regard also to higher losses between the InP and the Si_3N_4 interface, and for a later comparison with the experimental output power in order to evaluate the value for β that was actually achieved, we calculated the LI characteristics of the hybrid laser for different values of the coupling efficiency. Using the RE model, a wide range from weak coupling ($\beta=0.1$), medium ($\beta=0.5$) to perfect coupling ($\beta=1$), was considered in the calculations whereas the RSOA back reflection was taken as equal to the specified value, $R_1=90\%$, and the effective Vernier feedback as $R_2=90\%$. The calculated power *vs* driving current at various values of β is shown in Fig. 5.4. It can be seen that the slope efficiency only varies by a factor of two although the coupling loss varies by a factor of ten, from $\beta=0.1$ to 1. This differs significantly from the calculated result in [26], where a much shorter ($600\text{ }\mu\text{m}$) RSOA was used. An explanation can be that in their case the coupling loss is dominating the roundtrip loss, such that the change of slope efficiency is comparable to the change of β . In our case it can be seen that the hybrid laser should, although at high currents, provide an output in the 10 mW-range, even if the coupling becomes very small ($\beta=0.1$). Recalling that $\beta=0.1$ means a power loss of 20 dB per roundtrip shows that a high-gain RSOA indeed introduces a huge tolerance in terms of β . The latter proved important for successful laser operation with the integration procedure described as follows, which has not been evaluated so far. We note that the previously investigated version of the laser was still based on manually aligning the two chips with precision stages during characterization of the laser output.

5.4 Integration processes

A close-up and microscope photograph of the integrated laser is shown in Fig. 5.5. The RSOA chip and the chip with the feedback circuit were fixed on separate submounts and held by two precision translation stages. The electric contact pads of the MRRs were wire-bonded to a fan-out printed circuit board (PCB) which is connected to a dedicated controlling board. Low currents were injected in the InP RSOA via probe needles to generate an ASE output for next alignment steps. The output waveguide facet of the feedback chip was first aligned and assembled with a high numerical aperture (NA) polarization maintaining (PM) fiber. The specified $1/e$ mode field diameter (MFD) of the fiber is $6\text{ }\mu\text{m}$ in both directions, which is close to the MFD of the output waveguide (about $5\text{ }\mu\text{m}$ in both directions). A small amount of optically transparent UV curable glue was applied to the InP- Si_3N_4 interface. As a next step the InP RSOA and Si_3N_4 circuit were aligned relative to each other using translational stages while the fiber-coupled output ASE power of the hybrid laser is monitored and maximized as a signature for best optical coupling, i.e., a maximized value for β . UV light was used to cure the adhesive after the optimum alignment was obtained, thereby fixing the two components at best optical alignment. As the second step after curing of the UV glue, the

Figure 5.5: (a) Photograph of the integrated hybrid laser; (b) Microscope image of the Vernier mirror

InP-Si₃N₄ hybrid laser assembly was taken off the alignment stages and fixed on top of a copper heat sink using thermal paste, which allows driving currents of up to 200 mA before thermal effects set in.

5.5 Characteristics of the integrated hybrid laser and discussion

We measured the output characteristics of the integrated hybrid laser to evaluate whether laser oscillation is achieved after integration. In brief, as will be discussed below, we achieved single-mode laser oscillation with mW-level output power with wide tunability, narrow linewidths, good side-mode suppression ratio and low intensity noise.

5.5.1 Output power *vs* driving current

Figure 5.6: Measured output power *vs* driving current of the hybrid laser.

In the experiments performed at room temperature, the laser showed a threshold current of approximately 70 mA and an output power of 1.7 mW, obtained at the maximum applicable driving current of 200 mA, as is shown in Fig. 5.6. These results match well with the calculated LI curve at $\beta=0.5$ in Fig. 5.4. Calculations revealed that this value is close to what is obtained from calculation of the RSOA-Si₃N₄ field overlap integral alone ($\beta=0.6$). This indicates that the alignment and integration precision have not been the major limiting factor. The wall plug efficiency achieved here (0.85%) is comparable with our previous work [17], where an efficiency of 0.96% was achieved. As a consequence a further increase in the mode matching appears promising for increasing the output power in a next step.

5.5.2 Wavelength tuning

Figure 5.7: (a) Superimposed spectra when coarsely tuning over a 43 nm wide range as observed when thermally tuning only one of the two MRRs. (b) Superimposed spectra when fine-tuning over a range of 0.8 nm via tuning both MRRs simultaneously, achieving a stepwise sweeping of the wavelength at the FSR of the whole laser cavity.

The laser output wavelength was tuned via phase shifters on top of the MRRs. Here, we have used thermal tuning based on two resistive heaters (one for each MRR) using a maximum power of about 250 mW. It should be noted that in this waveguide platform piezo-tuning has been demonstrated as well [32] which can strongly reduce the required power. Fig. 5.7 shows both coarse and fine tuning. It can be seen that the hybrid laser offers a broad tuning range of more than 43 nm. To more detail, Fig. 5.7 (a) shows the case when only one of the two MRRs was tuned. This gives rise to discrete changes of the laser wavelength at a stepsize of the FSR of the other MRR (in this case $\Delta\lambda=4$ nm). We note that this measurement was solely intended to determine the maximum tuning range (yielding a value of 43.2 nm). A detailed analysis of the displayed output power vs wavelength remained difficult due to the manual tuning procedure and limitations to the heater current (damage). For tuning, the heating current was manually increased until a mode hop occurred. Then some adjustment of the heating current was used to roughly maximize the output power at that wavelength, thereafter proceeding to the next mode hop. The wavelength in the middle of the tuning range (near 1560 nm), where the output power was 6 dB less, was actually achieved with the maximum allowable heating current, where a fine adjustment was not possible anymore. Fig. 5.7 (b) shows the case when both MRRs were tuned simultaneously, which allows for a much finer tuning stepsize of $\Delta\lambda=0.09$ nm. The latter value corresponds to the FSR of the entire laser cavity, i.e., in this tuning mode the laser performs axial mode hops. A finer tuning might possibly be achieved either with a finely controlled change of the diode driving current or, alternatively, with implementing an additional phase tuning section in the Si₃N₄ waveguide circuit.

5.5.3 Side mode suppression ratio

Figure 5.8: (a) Single mode output spectrum measured at a resolution of 1 nm, at a driving current of 90 mA. (b) The same spectrum recorded with higher resolution (RES) around the laser wavelength. It is noted that the SMSR (35 dB) is well-resolved at resolutions better than 0.02 nm.

In order to characterize the hybrid laser's side-mode suppression ratio (SMSR), we investigated the output spectrum of the laser over a wide range around the central emission wavelength. To ensure a well-resolved SMSR we performed the measurement *vs* increasing resolution of the used optical spectrum analyzer (OSA) (ANDO, AQ6317). Fig. 5.8 (a) shows, as an overview, the measured typical laser spectrum over a range of 100 nm centered at 1550 nm with a coarse resolution of 1 nm. A single peak of laser output is observed on top of some background that originates from ASE emission and is filtered by the transmission spectrum of the Vernier mirror. Fig. 5.8 (b) displays a zoom-in view of the same spectrum with four values of stepwise increased resolution, from 0.1 nm to 0.01 nm. It can be seen that the recorded spectra start to become identical towards increased resolution, i.e., at 0.02 nm and 0.01 nm. The SMSR amounts to 35 dB with regard to the nearest side mode and to values between 45 and 55 dB with regard to the other side modes, clearly indicating single-mode oscillation.

5.5.4 Spectral linewidth

The spectral linewidth of the integrated hybrid laser output was too narrow to be resolved with the resolution of the OSA. For providing a higher resolution, we applied delayed self-heterodyne (DSH) detection [33], as is shown in Fig. 5.9. (a). A 6 km long fiber delay line forms the first arm of a Mach-Zehnder interferometer while an acoustic-optical modulator is placed in the other arm to induce a frequency shift of 80 MHz. The optical (short-term, instantaneous) linewidth of the laser can be retrieved by analyzing the RF beat power spectrum which is recorded by an electrical spectrum analyzer (ESA). In order to

rule out spectral broadening of the laser output via pickup noise in the diode laser driving current, the laser was operated with an ultra-low noise battery current source.

Figure 5.9: ((a) Schematic of the delayed self-heterodyne (DSH) detection setup for linewidth measurement; (b) Laser linewidth measured at various wavelength within the tuning range; (c) Recorded beat signal (black) at a driving current of 196 mA and a laser output wavelength of 1578.12 nm. The red fit curve represents a Voigt profile of which the Lorentzian component corresponds to an instantaneous (intrinsic) laser linewidth of 87 kHz.

We measured the linewidth at different driving currents and different laser wavelengths, since the linewidth is power dependent and wavelength dependent, due to a wavelength dependence of the linewidth enhancement factor and the laser threshold [34]. This is shown in Fig 5.9. (b) that displays the variation in linewidth as recorded in search of the lowest possible value. Fig 5.9. (c) shows the beat spectrum recorded at a driving current of 196 mA and a laser output wavelength of 1578.12 nm, for that lowest value which occurred. To extract the instantaneous linewidth [35] we fitted a Voigt profile to the spectrum. The fit yields a linewidth of 87 kHz.

The total quality factor of the Vernier filter, defined as the ratio of center wavelength to the bandwidth of the filter, as measured with a second sample of the feedback chip was 7750. Inserting into Henry's formula [8] (modified for external cavity diode lasers [36]) the experimental parameters and loss parameters derived with the mean-field model [30] we find a linewidth between 8

and 28 kHz, depending on the alpha-factor (4 to 8 [37], respectively). This is smaller than the measured linewidths, but may be due to other uncertainties, specifically the unknown spontaneous emission factor in [8], the wavelength-dependent output coupling or the validity of the mean-field approximation in [8].

The measured linewidth value is about 4-times higher than our previously reported value of 24 kHz for a non-integrated laser [18] with a tapered Si_3N_4 waveguide for an optimized mode matching. The larger linewidth in the present experiment can be qualitatively understood to a first part from a higher coupling loss. Secondly, due to the increased length of the RSOA used here one expects increased roundtrip losses and also a stronger influence of the linewidth enhancement factor [8]. Nevertheless, the measured linewidth compares favorably with the approximate 1-MHz linewidth of typical monolithic DBR and DFB laser sources [38, 40].

5.5.5 Relative intensity noise

Figure 5.10: Measured relative intensity noise (RIN) spectrum.

To characterize the stability of the output intensity, we measured the relative intensity noise (RIN) spectrum of the hybrid laser. A fast photodiode with 20 GHz bandwidth was used for light detection and the RF signal was fed into an ESA. Fig. 5.10 presents a typical example of the measured RIN spectrum, recorded at 170 mA driving current, and a video bandwidth (VBW) of 100 kHz and a resolution bandwidth (RBW) of 10 kHz. It can be seen that the RIN is below a value of -135 dBc/Hz over the DC-to-20 GHz range accessible to us. This RIN level is clearly higher than the -150-dBc/Hz-levels that can be reached with DFB and DBR lasers. We address this to our operation relatively close to threshold (170 mA pump current *vs* 70 mA threshold current), while lower RIN is typically achieved much higher above threshold [39]. Two noise peaks

at 9.6 GHz and 11 GHz, via comparison with the measured optical spectrum, can be ascribed to a beating of adjacent modes, possibly in connection with a non-uniform mode spacing induced by group delay dispersion near the MRR resonances [41].

5.6 Conclusion

In this paper, an integrated InP-Si₃N₄ hybrid laser is demonstrated and characterized for the first time. The results from characterization of the laser confirm both the flexibility and viability of our laser integration approach, which is of high relevance for the potential application of such Si₃N₄-based hybrid lasers. In terms of improvement, there are two possible routes, which is best explained by looking at Fig. 5.4. By gradually improving alignment precision and implementing tapers for improved mode matching, one might attain the same amount of output power in combination with a further decreased linewidth at the 20-kHz-level [17, 18], if using a shorter RSOA, specified with a lower maximum current. A shorter RSOA enables a lower electric power consumption with less heat generation, which is an important requirement for many applications. Alternatively it might be useful to maintain using a long RSOA with high gain if an improved cooling can be provided. Given the fact that the pump current is limited to about 200 mA (about 1.9 times above threshold) while the maximum allowed pump current is 1400 mA (about 19 times above threshold), we expect that a factor of about ten increase in the output power might be achieved at high driving currents. Considering that the linewidth reduces inversely proportionally with increasing output power [42, 43], a linewidth reduction by a factor of ten might be possible, yielding linewidths at the ten-kHz level.²

5.7 Acknowledgment

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²We note that so far our linewidth predictions are based on mean-field approximation and without considering the role of amplified spontaneous emission. In the following chapter we will present a more detailed linewidth analysis based on a spatially resolved model, which takes into account also the influence of amplified spontaneous emission.

Bibliography

- [1] S. Zhang, P. Y. Kam, C. Yu, and J. Chen, “Laser linewidth tolerance of decision-aided maximum likelihood phase estimation in coherent optical M-ary PSK and QAM systems,” *IEEE Photon. Technol. Lett.*, vol. 21, no. 15, pp. 1075–1077, Aug 2009.
- [2] L. Zhuang, C. G. H. Roeloffzen, A. Meijerink, M. Burla, D. A. I. Marpaung, A. Leinse, M. Hoekman, R. G. Heideman, and W. van Etten, “Novel ring resonator-based integrated photonic beamformer for broadband phased array receive antennas—part II: Experimental prototype,” *J. Lightwave Technol.*, vol. 28, no. 1, pp. 19–31, Jan 2010.
- [3] J. E. Koroshetz, “Fiber lasers for lidar,” in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*. Optical Society of America, 2005, p. OFJ4.
- [4] C. E. Wieman and L. Hollberg, “Using diode lasers for atomic physics,” *Rev. Sci. Instrum.*, vol. 62, no. 1, pp. 1–20, 1991.
- [5] L. He, Ş. K. Özdemir, J. Zhu, W. Kim, and L. Yang, “Detecting single viruses and nanoparticles using whispering gallery microlasers,” *Nat. Nanotechnol.*, vol. 6, no. 7, pp. 428–432, 2011.
- [6] A. Hemmerich, D. McIntyre, D. Schropp, D. Meschede, and T. Hänsch, “Optically stabilized narrow linewidth semiconductor laser for high resolution spectroscopy,” *Opt. Commun.*, vol. 75, no. 2, pp. 118 – 122, 1990.
- [7] Y. Jiang, A. Ludlow, N. Lemke, R. Fox, J. Sherman, L.-S. Ma, and C. Oates, “Making optical atomic clocks more stable with 10^{-16} -level laser stabilization,” *Nat. Photonics*, vol. 5, no. 3, pp. 158–161, 2011.
- [8] C. Henry, “Theory of the linewidth of semiconductor lasers,” *IEEE J. Quantum Electron.*, vol. 18, no. 2, pp. 259–264, Feb 1982.
- [9] C. Santis, S. Steger, Y. Vilenchik, A. Vasilyev, and A. Yariv, “High-coherence semiconductor lasers based on integral high-Q resonators in hybrid Si/III-V platforms,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 111, no. 8, pp. 2879–2884, 2014.

- [10] J. C. Hulme, J. K. Doyle, and J. E. Bowers, "Widely tunable Vernier ring laser on hybrid silicon," *Opt. Express*, vol. 21, no. 17, pp. 19718–19722, Aug 2013.
- [11] G. H. Duan, C. Jany, A. L. Liepvre, A. Accard, M. Lamponi, D. Make, P. Kaspar, G. Levaufre, N. Girard, F. Lelarge, J. M. Fedeli, A. Descos, B. B. Bakir, S. Messaoudene, D. Bordel, S. Menezo, G. de Valicourt, S. Keyvaninia, G. Roelkens, D. V. Thourhout, D. J. Thomson, F. Y. Gardes, and G. T. Reed, "Hybrid III–V on silicon lasers for photonic integrated circuits on silicon," *IEEE J. Sel. Top. Quantum Electron.*, vol. 20, no. 4, pp. 158–170, July 2014.
- [12] S. Keyvaninia, G. Roelkens, D. V. Thourhout, C. Jany, M. Lamponi, A. L. Liepvre, F. Lelarge, D. Make, G.-H. Duan, D. Bordel, and J.-M. Fedeli, "Demonstration of a heterogeneously integrated III-V/SOI single wavelength tunable laser," *Opt. Express*, vol. 21, no. 3, pp. 3784–3792, Feb 2013.
- [13] T. Kita, R. Tang, and H. Yamada, "Compact silicon photonic wavelength-tunable laser diode with ultra-wide wavelength tuning range," *Appl. Phys. Lett.*, vol. 106, no. 11, 2015.
- [14] A. J. Zilkie, P. Seddighian, B. J. Bijlani, W. Qian, D. C. Lee, S. Fatholouloumi, J. Fong, R. Shafiha, D. Feng, B. J. Luff, X. Zheng, J. E. Cunningham, A. V. Krishnamoorthy, and M. Asghari, "Power-efficient III-V/Silicon external cavity DBR lasers," *Opt. Express*, vol. 20, no. 21, pp. 23 456–23 462, Oct 2012.
- [15] T. Matsumoto, A. Suzuki, M. Takahashi, S. Watanabe, S. Ishii, K. Suzuki, T. Kaneko, H. Yamazaki, and N. Sakuma, "Narrow spectral linewidth full band tunable laser based on waveguide ring resonators with low power consumption," in *Optical Fiber Communication Conference*. Optical Society of America, 2010, p. OThQ5.
- [16] D. de Felipe, Z. Zhang, W. Brinker, M. Kleinert, A. M. Novo, C. Zawadzki, M. Moehrl, and N. Keil, "Polymer-based external cavity lasers: Tuning efficiency, reliability, and polarization diversity," *IEEE Photon. Technol. Lett.*, vol. 26, no. 14, pp. 1391–1394, July 2014.
- [17] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and K.-J. Boller, "25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity," *Laser Phys. Lett.*, vol. 10, no. 1, p. 015804, 2013.
- [18] Y. Fan, R. M. Oldenbeuving, E. J. Klein, C. J. Lee, H. Song, M. R. H. Khan, H. L. Offerhaus, P. J. M. van der Slot, and K.-J. Boller, "A hybrid semiconductor-glass waveguide laser," in *Proc. SPIE*, vol. 9135, 2014, pp. 91 351B–91 351B–6.

- [19] H. Ou, “Different index contrast silica-on-silicon waveguides by PECVD,” *Electron. Lett.*, vol. 39, pp. 212–213(1), January 2003.
- [20] K. Wörhoff, R. Heideman, A. Leinse, and M. Hoekman, “Triplex: A versatile dielectric photonic platform,” *Adv. Opt. Technol.*, vol. 4, no. 2, pp. 189–207, 2015.
- [21] L. Zhuang, D. Marpaung, M. Burla, W. Beeker, A. Leinse, and C. Roeloffzen, “Low-loss, high-index-contrast $\text{Si}_3\text{N}_4/\text{SiO}_2$ optical waveguides for optical delay lines in microwave photonics signal processing,” *Opt. Express*, vol. 19, no. 23, pp. 23 162–23 170, Nov 2011.
- [22] J. F. Bauters, M. J. R. Heck, D. D. John, J. S. Barton, C. M. Bruinink, A. Leinse, R. G. Heideman, D. J. Blumenthal, and J. E. Bowers, “Planar waveguides with less than 0.1 dB/m propagation loss fabricated with wafer bonding,” *Opt. Express*, vol. 19, no. 24, pp. 24 090–24 101, Nov 2011.
- [23] J. P. Epping, T. Hellwig, M. Hoekman, R. Mateman, A. Leinse, R. G. Heideman, A. van Rees, P. J. van der Slot, C. J. Lee, C. Fallnich, and K.-J. Boller, “On-chip visible-to-infrared supercontinuum generation with more than 495 THz spectral bandwidth,” *Opt. Express*, vol. 23, no. 15, pp. 19 596–19 604, Jul 2015.
- [24] C. G. H. Roeloffzen, L. Zhuang, C. Taddei, A. Leinse, R. G. Heideman, P. W. L. van Dijk, R. M. Oldenbeuving, D. A. I. Marpaung, M. Burla, and K.-J. Boller, “Silicon nitride microwave photonic circuits,” *Opt. Express*, vol. 21, no. 19, pp. 22 937–22 961, Sep 2013.
- [25] L. Zhuang, C. G. H. Roeloffzen, M. Hoekman, K.-J. Boller, and A. J. Lowery, “Programmable photonic signal processor chip for radiofrequency applications,” *Optica*, vol. 2, no. 10, pp. 854–859, Oct 2015.
- [26] S. Tanaka, S.-H. Jeong, S. Sekiguchi, T. Kurahashi, Y. Tanaka, and K. Morito, “High-output-power, single-wavelength silicon hybrid laser using precise flip-chip bonding technology,” *Opt. Express*, vol. 20, no. 27, pp. 28 057–28 069, Dec 2012.
- [27] N. Fujioka, T. Chu, and M. Ishizaka, “Compact and low power consumption hybrid integrated wavelength tunable laser module using silicon waveguide resonators,” *J. of Lightwave Technol.*, vol. 28, no. 21, pp. 3115–3120, Nov 2010.
- [28] K. Sato, N. Kobayashi, M. Namiwaka, K. Yamamoto, S. Watanabe, T. Kita, H. Yamada, and H. Yamazaki, “Demonstration of silicon photonic hybrid ring-filter external cavity wavelength tunable lasers,” in *Optical Communication (ECOC), 2015 European Conference on*, Sept 2015, pp. 1–3.

- [29] B. Song, C. Stagaescu, S. Ristic, A. Behfar, and J. Klamkin, "3D integrated hybrid silicon laser," *Opt. Express*, vol. 24, no. 10, pp. 10 435–10 444, May 2016.
- [30] L. A. Coldren, S. W. Corzine, and M. L. Mašanović, *A Phenomenological Approach to Diode Lasers*. John Wiley & Sons, Inc., 2012, pp. 45–90.
- [31] D. Marcuse, "Reflection loss of laser mode from tilted end mirror," *J. Lightwave Technol.*, vol. 7, no. 2, pp. 336–339, Feb 1989.
- [32] N. Hosseini, R. Dekker, M. Hoekman, M. Dekkers, J. Bos, A. Leinse, and R. Heideman, "Stress-optic modulator in triplex platform using a piezoelectric lead zirconate titanate (PZT) thin film," *Opt. Express*, vol. 23, no. 11, pp. 14 018–14 026, Jun 2015.
- [33] A. N. T. Okoshi, K. Kikuchi, "Novel method for high resolution measurement of laser output spectrum," *Electron. Lett.*, vol. 16, pp. 630–631(1), July 1980.
- [34] M. Osinski and J. Buus, "Linewidth broadening factor in semiconductor lasers—an overview," *IEEE J. Quantum Electron.*, vol. 23, no. 1, pp. 9–29, Jan 1987.
- [35] L. B. Mercer, "1/f frequency noise effects on self-heterodyne linewidth measurements," *J. of Lightwave Technol.*, vol. 9, no. 4, pp. 485–493, Apr 1991.
- [36] M. Fleming and A. Mooradian, "Spectral characteristics of external-cavity controlled semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 17, no. 1, pp. 44–59, Jan 1981.
- [37] S. D. Saliba and R. E. Scholten, "Linewidths below 100 kHz with external cavity diode lasers," *Appl. Opt.*, vol. 48, no. 36, pp. 6961–6966, July 2014.
- [38] A. J. Ward, D. J. Robbins, G. Busico, E. Barton, L. Ponnampalam, J. P. Duck, N. D. Whitbread, P. J. Williams, D. C. J. Reid, A. C. Carter, and M. J. Wale, "Widely tunable DS-DBR laser with monolithically integrated SOA: design and performance," *IEEE J. Sel. Top. Quantum Electron.*, vol. 11, no. 1, pp. 149–156, Jan 2005.
- [39] M. Faugeron, M. Tranand, O. Parillaud, M. Chtioui, Y. Robert, E. Vinet, A. Enard, J. Jacquet and F. Van Dijk, "High-power tunable dilute mode DFB laser with low RIN and narrow linewidth," *IEEE Photon. Technol. Lett.*, vol. 25, no. 1, pp. 7–10, Jan 2013.
- [40] Y. A. Akulova, G. A. Fish, P.-C. Koh, C. L. Schow, P. Kozodoy, A. P. Dahl, S. Nakagawa, M. C. Larson, M. P. Mack, T. A. Strand, C. W. Coldren, E. Hegblom, S. K. Penniman, T. Wipiejewski, and L. A. Coldren, "Widely tunable electroabsorption-modulated sampled-grating DBR laser

- transmitter,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 8, no. 6, pp. 1349–1357, Nov 2002.
- [41] Z. Bian, B. Liu, and A. Shakouri, “InP-based passive ring-resonator-coupled lasers,” *IEEE J. Quantum Electron.*, vol. 39, no. 7, pp. 859–865, July 2003.
- [42] K. Dridi, A. Benhsaien, J. Zhang, and T. J. Hall, “Narrow linewidth 1550 nm corrugated ridge waveguide DFB lasers,” *IEEE Photon. Technol. Lett.*, vol. 26, no. 12, pp. 1192–1195, June 2014.
- [43] T. Kita, K. Nemoto, and H. Yamada, “Silicon photonic wavelength-tunable laser diode with asymmetric Mach-Zehnder interferometer,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 20, no. 4, pp. 344–349, July 2014.

6

Spectral linewidth analysis of semiconductor hybrid lasers with feedback from an external waveguide resonator circuit

We present a comprehensive analysis of a semiconductor hybrid laser exploiting spectral control from a photonic waveguide circuit used as a frequency-selective external feedback resonator. Based on an advanced spatially resolved transmission line model (TLM), we have investigated the output power characteristics and the laser spectral linewidth. We find that, if the feedback becomes weaker, the spectral linewidth is larger than predicted by previous models that are based on a modified mean-field approximation, even if these take a strong spatial variation of the gain into account. The observed excess linewidth is caused by additional index fluctuations associated with strong spatial gain variations.

6.1 Introduction

Widely tunable, narrow linewidth diode lasers have found a wide range of important applications, from terrestrial applications such as fiber-optic communications [1] or optical sensing [2], to space-based applications such as laser cooling [3] and atomic clocks [4] in global positioning systems (GPS). In the evolution of such applications, monolithic single-frequency diode laser sources, specifically distributed feedback (DFB) lasers and distributed Bragg reflector (DBR) lasers, approach their limits due to a relatively small tuning range [5] and large linewidths at the MHz level [6], the latter caused by their short photon lifetime in the laser cavity. In comparison, so-called hybrid diode waveguide lasers, can offer much longer photon lifetimes, accordingly narrower linewidths, in addition to wider tunability and thus have been subject of recent, extensive research. The concept of such hybrid lasers is based on optically coupling a semiconductor gain medium to a low-loss passive waveguide circuit that provides a significantly extended resonator length and a highly frequency selective feedback. The benefits to be gained with low-loss waveguide feedback circuits are that: a) flexible filtering schemes can be applied which allow for wide wavelength tunability, b) narrow linewidths can be achieved due to increased photon lifetime that is associated with an extended cavity length [7], and that such lasers are ideal for integrating into subsequent waveguide circuitry fabricated on the same waveguide chip.

Making use of high-quality intra-cavity microring resonators (MRRs) in the feedback circuit has introduced a new paradigm on how to pursue chip-based narrow linewidth semiconductor laser sources. As opposed to Bragg gratings, the fabrication of MRRs does not demand complicated lithography processes and can provide lower losses. A related important merit of using low-loss MRRs is that they effectively extend the optical length of the laser resonator by an appreciable factor, due to the multiple roundtrips in the MRR [8]. This length extension contributes again to a narrowing of the laser linewidth.

The tuning property of such hybrid lasers are generally well-understood. However, the laser linewidth remains challenging to predict due to the increased complexity of the cavity design which is ruled by a larger set of experimental parameters. So far, for a coarse estimation of the linewidths of such lasers [9], it is common practice to employ Henry's theory which is using the mean-field approximation (MFA) corrected with the so-called linewidth enhancement factor, α [7]. However, this is rather incomplete since the effect of linewidth narrowing or broadening induced by the spectral selectivity and dispersion of the external feedback [10] is not taken into account.

Being aware of these shortcomings, refined models were developed [10] and used for comparison with experimental linewidth data, and qualitative agreement was found [11]. However, still these theories are based upon the mean-field approximation (MFA) in the gain section. Specifically for hybrid lasers this renders the applicability of these models questionable or insufficiently accurate. The reason is that hybrid lasers, depending on the strength of the feedback,

may show strong spatial variations of the intensity in the semiconductor gain element which introduces strong variations of the carrier density as well. We note that in monolithic diode lasers with a single cavity of short length such spatial effects [12] and nonlinear gain effects [13] cause an increase of the laser linewidths as compared to mean-field models.

In this work, we present the first modeling of external cavity diode lasers that takes into account the complex feedback obtained with waveguide resonator circuits such as in [11] and [14] and that simultaneously takes into account the detailed spatial variation of the diode-internal intensity and carrier density, such as in [12] and [13]. The goal of our detailed modeling is to enable a comparison with the existing simplified theories and, thereby, check their validity under different conditions. To this end, we make use of a commercially available, advanced transmission line model (TLM) [15] which involves spatially resolved rate equations for the complex-valued electric field and spatially resolved rate equations for the carrier density and index variations [16, 17] in the section of the laser cavity that contains the semiconductor optical amplifier. The remaining, external part of the cavity that comprises the linear optical waveguide feedback and spectral filtering circuit is modeled as a complex-valued frequency depending scattering matrix. A first test of this model has been described in our previous conference publication [18], showing satisfying agreement within a factor of about 1.5 in the 20-50 kHz range, with experimental data obtained with a relatively short InP-Si₃N₄ waveguide hybrid laser with feedback from two MRRs, and with a fixed optical coupling strength. In order to cover different regimes of interest, specifically, for a prediction of optimum cavity parameters that yield a narrow laser linewidth, here we systematically vary this power coupling strength, β , between the InP gain section and the Si₃N₄ waveguide chip. This variation brings the diode internal field and carrier distribution from spatially high uniformity ($\beta \approx 1$ and strong feedback from the waveguide resonators, where the MFA remains justified) towards a strong spatial variation ($\beta \approx 0$ or weak resonator feedback) where a detailed modeling has not been performed so far. The drive current of the diode amplifier is used as an adjustable input parameter because also in a typical experimental investigation the electric drive current can be varied most easily. For each setting of the chip-to-chip coupling efficiency we calculate the power spectral density of the frequency noise from which we derive a value for the laser linewidth, to compare with values obtained with a modified MF theory.

6.2 Operation principle

The hybrid laser that we model comprises a semiconductor active gain chip coupled to a passive external cavity as shown in Fig. 6.1. For definiteness, as required in a numerical model, and to guide our experimental efforts, we chose a typical InP diode as amplifier while the feedback is provided via a Si₃N₄

waveguide waveguide chip.

Figure 6.1: Schematic representation of the hybrid laser with an active gain section with length L_1 coupled, with power coupling coefficient β , to a passive waveguide section with physical length L_2 (excluding the MRRs). The left facet of the laser diode is highly reflective, R_1 , and the right facet is anti-reflective coated combined with a tilt angle of 5° , resulting in a extremely low facet reflectivity ($R_2 \approx 0$). The two MRRs provides an effective power reflectivity R_3 which is frequency dependent.

The laser diode gain chip has one high-reflectivity facet with power-reflectivity R_1 and one low reflective facet, R_2 . The overall feedback provided by the Si₃N₄ waveguide chip circuitry is lumped into a frequency dependent power reflectivity, $R_{eff}(\omega)$, which comprises both propagation through the passive bus waveguides and reflection from two microring resonators (MRRs) of slightly different free spectral range (FSR). The latter provides a so-called Vernier mirror on the waveguide chip, and act as wavelength-selective reflective filters that can be tuned via the thermo-optic effect, e.g., by heating of the rings. Further details about MRR Vernier filters can be found in [19–21].

Radiation generated by spontaneous and stimulated emission in the amplifier chip enters the Si₃N₄ waveguide chip with a power coupling coefficient, β , that depends on the overlap (matching) of the mode profiles in the gain waveguide and Si₃N₄ waveguide [22].

In the Si₃N₄ chip, light is first split by a symmetric 50/50 bidirectional coupler, and then guided sequentially through the two cascaded MRRs. Before returning towards the laser diode, a certain frequency dependent fraction of the light passes by the resonators is outcoupled towards the end facet of the waveguide chip. For the hybrid laser to oscillate at the frequency of a specific longitudinal mode of the entire cavity, that frequency must also be supported by the gain spectrum of the specific semiconductor material used, and coincide

with the transmission spectra of both MRRs. In order to combine the laser output from the throughputs of both microring resonators, a second symmetric 50/50 bidirectional coupler is implemented.

6.3 Revisiting laser linewidth theories

The currently most complete analytical theory [10] for external cavity diode lasers with spectrally filtered feedback suggests that the linewidth of the hybrid laser, $\Delta\nu$, can be calculated along the following lines: first, recalling from Chapter 2, the hybrid laser is modeled in the same manner as a solitary Fabry-Perot laser with a frequency-independent real-valued back facet field amplitude reflectivity of $r_1 = \sqrt{R_1}$. The front facet is given a complex-valued amplitude reflectivity, $r_{eff}(\omega) = r(\omega)\exp(-j*\varphi_{eff}(\omega))$. The real-valued amplitude factor in this expression, $r(\omega)$, lumps the overall strength field feedback from the external resonator (R_3 , the power coupling efficiency, β , and any additional loss that occurs in the external feedback path). The frequency dependent phase, $\varphi_{eff}(\omega)$, takes any optical delay into account that the feedback may contain. Specifically, this phase is frequency dependent because it depends on the detuning from the resonance frequency of the Vernier filter and on other optical parameters of the external feedback path, such as the length of the waveguide to and from the MRRs. After lumping the external feedback into $r_{eff}(\omega)$ for the front facet, $\Delta\nu$ is given by:

$$\Delta\nu = \frac{\Delta\nu_{ST}}{F^2}, \quad (6.1)$$

In this equation, $\Delta\nu_{ST}$ is the Schawlow-Townes linewidth of the equivalent Fabry-Perot solitary diode laser:

$$\Delta\nu_{ST} = \frac{1}{4\pi} \frac{v_g^2 h \nu n_{sp} \gamma_{tot} \gamma_m (1 + \alpha^2)}{P_0 \left(1 + \frac{r_1}{r(\omega)} \frac{1 - r(\omega)^2}{1 - R_1} \right)}, \quad (6.2)$$

i.e., of a diode laser having the length of the amplifier section (L_1) and having real-valued field reflectivities r_1 and $r(\omega)$.

In Eq. 6.2, $v_g = c/n_{g1}$ is the group velocity in the diode, $\gamma_m = 1/(2L_1) \ln(1/(R_1 r^2(\omega)))$ is distributed mirror loss, γ_{tot} is the total loss (mirror loss plus diode internal loss), n_{sp} is the spontaneous emission factor, ν is the laser emission frequency, h is the Plank constant, P_0 is the output power from the back diode facet, and α is Henry's linewidth enhancement factor.

The denominator in Eq. 6.1 is a linewidth reduction factor,

$$F = 1 + A + B, \quad (6.3)$$

where

$$A = \frac{1}{\tau_{LD}} \left(\frac{d}{d\omega} \phi_{eff}(\omega) \right), \quad (6.4)$$

$$B = \frac{\alpha}{\tau_{LD}} \left(\frac{d}{d\omega} \ln r(\omega) \right). \quad (6.5)$$

In Eqs. 6.4 and 6.5, $\tau_{LD} = 2n_{g1}L_1/c$ is the roundtrip time in the solitary diode. The term A can be physically interpreted as the ratio between the external cavity optical length and the solitary diode optical length, which describes a linewidth reduction resulting solely from the extension of the cavity length. As described above, $\phi_{eff}(\omega)$ contains simple propagation in the waveguides to and from the MRRs. I also contains (via a maximum of $\frac{d}{d\omega}\phi_{eff}(\omega)$ at the peak of the filter resonance) the cavity length enhancement by multiple passes through the MRRs. The term B describes an additional linewidth reduction that occurs only at the rising slope of the spectral peak of the MRR Vernier filtered feedback, where $(\frac{d}{d\omega} \ln r(\omega))$ is positive.

The problem with the Schawlow-Townes expression in Eq. 6.2 and as indicated already in Chapter 2, is that it is based on the standard mean-field approach, which treats any mirror loss lumped as uniformly distributed along the cavity. However, such treatment is only valid for diode lasers that have symmetric and relatively high reflectivities ($r_1 \approx r_2 \approx 1$) such that the diode internal intensity is approximately uniform (spatially homogeneous). It should be noted that only with such uniform intensity, the carrier density is uniform as well, which is required to justify a uniform gain-index coupling in the form of a simple space-independent α -factor in Eq. 6.2. Hybrid lasers, specifically, do not generally fulfill these assumptions because the chip-to-chip coupling efficiency, β , might be rather low (at the 10% level without adiabatic tapering [20]), because the circuit reflectivity might be low and because the back facet reflectivity might also be very low, for instance, for the purpose of extracting more usable output power [23]. In these situations, the reflectivities of the equivalent FP solitary laser may become highly asymmetric, the α factor may strongly vary throughout the amplifier, which can increase the laser linewidth to beyond what is predicted in Eq. 6.1.

The criticality of the mean-field approximation had been realized by several independent researchers. Specifically, lumping strongly asymmetric and low facet reflectivities in the Schawlow-Townes expression in Eq. 6.2 underestimates the coupling of amplified spontaneous emission into the main laser mode [24–26], because low facet reflectivities result in a large single pass gain. To take these effects into account to some extent, it was suggested to modify Eq. 6.1 with another multiplicative factor, F_R , called spontaneous emission enhancement factor, given by:

$$F_R = \left[\frac{(r_1 + r_2)(1 - r_1 r_2)}{2r_1 r_2 \ln(r_1 r_2)} \right]^2, \quad (6.6)$$

where in the case of an external cavity hybrid laser r_2 is substituted by $r(\omega)$ (modified mean-field model).

However, even through modifying Eq. 6.1 with F_R takes additional noise by locally less depleted gain into account, this still does not address the associated index-effect that would be described by an increased α -factor. What is required is to conduct also detailed calculations which include the spatially varying index effect in the laser linewidth.

6.4 Spatially resolved modeling of a hybrid laser

6.4.1 Implementation of transmission line model

In order to include all the spatial variations of the gain and index in a more detailed and more accurate linewidth analysis, we have chosen to apply an advanced transmission line model (TLM) for the gain section. Summarized, the implementation of the TLM [16],[17] is a time-domain model that iterates optical fields travelling back and forth along the semiconductor amplifier to generate optical waveforms at the facets. Both the time and space coordinates are taken as discrete variables. Figure 6.2 shows the structure of the TLM implemented. The active gain section is divided into multiple longitudinal TLM sections and when sufficiently thin, each section can be treated as homogeneous. For an efficient implementation, the TLM sections were chosen to have a length that is equal to the distance the light propagates within a model time step, $\Delta z = c\Delta t/n_{g1}$. For each section there is a so-called *scattering node* that represents, e.g., the electric field, carrier density, gain, loss and noise being present at that local section. Within each section, uncorrelated spontaneous emission noise is added as Langevin noise sources [7] for both forward and backward fields. The spectral shape of the spontaneous emission is determined by the gain spectrum, and the power spectral density is proportional on the local carrier density. The passive external resonator section is modeled in the frequency domain based on the scattering-matrix method [27] which makes use of well-known analytical solutions of the involved basic optical components, such as linear propagation waveguide sections, Y-junctions, microring resonators. Fourier transform is performed in order to switch between the time-domain calculation and frequency domain calculation. The laser parameters introduced into the TLM are summarized in Tab. 6.1 (diode parameters) and Tab. 6.2 (feedback parameters). The used values for these parameters are based on the experimental setup that was presented in Chapter 3 and built-in library of the modules that are used in the model.

The goal is to model the propagation and amplification of waves at frequencies of hundreds of THz, however, this would require numerically unfeasible sampling rates of a petahertz if trying to resolve each optical cycle to full de-

Figure 6.2: In the transmission line model applied here, the semiconductor gain medium is divided in sections. The passive external resonator section is modeled in the frequency domain based on the scattering-matrix method. $r_{eff}(\omega)$ is complex-valued and frequency dependent to include all frequency dependencies and phase shifts.

tail. We follow an alternative solution where the waves are modeled as a fixed, known carrier wave frequency multiplied with a somewhat slower varying envelope. This approximation is justified here due to the small spectral content of the field of single frequency lasers with low background across a limited relative bandwidth. In all of our modeling the center frequency was set to $f_0=193.1$ THz, which is equivalent to an output wavelength around 1550 nm. Each calculation run includes a large number of iterations, called scattering steps, taking place depending on the sample rate and the time window settings. Multiple runs can be carried out subsequently, each one taking as the initial values the last results of the former run. For the continuous-wave, steady-state laser modeled here, the initial runs containing laser startup and transients can be discarded and multiple runs of steady-state calculations can be used for averaging of the frequency noise spectra. The configuration parameters for numerical modeling are given in Tab. 6.3.

In order to illustrate what external feedback, $r_{eff}(\omega)$, we use in the numerical model, we plot in Fig. 6.3 (a) the magnitude of r_{eff} , $r(\omega) = |r_{eff}|$, as obtained with the parameters in Tab. 6.2 for three different values of β ($\beta=0.1, 0.5$ and 1). In Fig. 6.3 (b) we plot the values for A, B and F, assuming a typical α value of 3. As the laser will operate at a frequency around the Vernier peak frequency (f_0), the horizontal axis is normalized to show the light frequency as a detuning with respect to f_0 . It can be seen in Fig. 6.3 (a) that the feedback from the MRRs generates a spectral feedback maximum at zero detuning, whereas the height of the maximum decreases in proportion with β . The linewidth reduction terms A and B, which are associated with a spectrally varying phase ($\phi_{eff}(\omega)$) and amplitude ($r(\omega)$) of the feedback, and the resulting total linewidth reduction, F, are plotted in Fig. 6.3 (b). For the calculation

of B we assumed a typical value for the α -factor ($\alpha = 3$). It can be seen that MRR spectrally filtered feedback causes a): a linewidth reduction brought by an enhanced cavity length due to multiple roundtrips (see peak of A at zero detuning); b): a linewidth reduction in the lower-frequency wing of the filter resonance (see asymmetric peak in B).

Figure 6.3: (a) Calculated amplitude reflectivity as a function of frequency detuning (with respect to the Vernier peak frequency) for three different values of β ; (b) Calculated A, B and F coefficients as a function of frequency detuning.

In the following section, we present typical results obtained from the numerical transmission line model and compare them with what is predicted with the modified mean-field model as given by Eqs. 6.1 to 6.6. In brief, it shows that the two models agree well with each other, however, that the mean-field model underestimates the linewidth at weak coupling between the two chips.

6.4.2 Output power and laser emission frequency

With the TL model, the output power (P_0) from the diode back facet and laser emission frequency (Δf , relative to f_0) was calculated for a range of coupling coefficients, from $\beta = 0.1$ to 1.0 in steps of 0.1, and for various different drive currents (I) up to 100 mA. Examples of typical results are presented in Fig. 6.4 (P vs I) and in Fig. 6.5 (Δf vs I), for three different coupling efficiencies, $\beta=1, 0.7, 0.3$. It can be seen in Fig. 6.4 that the output power follows an approximately linear growth with the current interrupted by discontinuous hops, and that the overall power level drops as β decreases. Discontinuities are also seen in the output frequency (Fig. 6.5) and these occur at the same current values as in Fig. 6.4. Variations of the output frequency of lasers in Fig. 6.5 are actually well known. They represent so-called mode hopping of the laser frequency to that of a neighboring longitudinal mode of the overall hybrid laser cavity. The frequency change of such hop is given by the free spectral range (longitudinal

mode spacing) of the hybrid laser cavity which is here about 15 GHz.

It can also be seen that in between mode hops the frequency increases linearly with the drive current (such as the output power did). This might be understood follows: at higher drive currents, higher output powers and photon densities are reached. This results in a lower differential gain parameter and thus a higher carrier density for balancing the same threshold gain. A higher carrier density results in a lower refractive index [28], which leads to an increased laser frequency.

Figure 6.4: Calculated output power vs drive current for three different values of β . The curves resemble the typical output power characteristic of diode lasers and the observed discontinuities are due to mode hopping. The values of the output power within the gray area (between 20 mA to 60 mA drive currents) were chosen for calculations of the linewidth (Fig. 6.7 and 6.8).

6.4.3 Frequency noise spectra and laser spectral linewidth

In order to calculate the laser spectral linewidth in a computationally feasible way, we calculate the power spectral density (PSD) of the frequency noise instead of directly resolving the full width at half maximum of the laser field power spectrum, because the latter requires kHz-level resolution and consequently prohibitively long calculation time. The PSD is obtained via squaring the Fourier transform of the temporally varying (instantaneous) laser frequency. The fundamental (quantum) noise limited spectral linewidth can be retrieved from the limit value of the PSD towards zero value of noise frequency, i.e., from the PSD in the flat, low-frequency part of the noise spectrum [29]. Two examples of such frequency noise spectra are shown in Fig. 6.6, calculated for the same value of chip-to-chip coupling ($\beta=0.7$) but for two different drive currents

Figure 6.5: Calculated laser frequency detuning from the Vernier peak frequency (f_0) vs drive current for three different values of β . The frequency tuning and mod hops vs increasing drive currents are caused by index changes within the gain section.

(20 mA and 60 mA). In both spectra, two peaks can be seen. The first, shallower and broader peak corresponds to damped relaxation oscillations (between 2 and 3 GHz). The second, higher and narrower peak corresponds to beating between adjacent longitudinal modes (at about 15 GHz) respectively. It can be seen that the average PSD value at low frequencies (below 1 GHz) decreases from about $10.25 \times 10^3 \text{ Hz}^2/\text{Hz}$ at 20 mA to about $2.36 \times 10^3 \text{ Hz}^2/\text{Hz}$ at 60 mA, indicating (via multiplication by π) a linewidth reduction from about 32.2 kHz to about 7.4 kHz.

In order to conduct a first, qualitative comparison between the linewidth values from the transmission line model and the values obtained with the modified mean-field model, the linewidth for $\beta=0.7$ is plotted as a function of the inverse output power, $1/P$, in Fig. 6.7. The motivation for plotting the linewidth vs $1/P$ is that Eq. 6.2 predicts a $1/P$ dependence. The symbols represent values calculated with the transmission line model and the error bars represent the standard deviation of the PSD at low frequency frequencies from the average PSD in that range. The dashed line is a least mean square fit with a straight line as expected from Eq. 6.1. The numerical data clearly confirm the expected overall trend of linewidth narrowing with increasing output power, i.e., towards smaller values of $1/P$ on the horizontal axis. All other linewidth data calculated for other values of β (not shown here) displayed the same power dependence as long as no mode hop was present within the inspected range of power variation.

Figure 6.6: Two examples of the calculated power spectral density (PSD) of frequency noise for $\beta=0.7$ at 20 mA and 60 mA drive current. For each PSD curve, two spectral peaks can be seen, which correspond to relaxation oscillations (between 2 and 3 GHz) and beating between two adjacent longitudinal modes (at about 15 GHz) respectively. The laser spectral linewidth is retrieved via multiplying the mean values of the PSD at low frequencies by π , in this case obtaining about 32.2 kHz at 20 mA and 7.4 kHz at 60 mA.

Figure 6.7: Characterization of the laser spectral linewidth plotted vs $1/P$ for $\beta=0.7$, as an example. The symbols represent the values calculated with the transmission line model and the error bars represent the standard deviation from reading out PSD levels at low noise frequency. The dashed line is a linear least mean square fit. The good agreement confirms the expected linewidth narrowing inversely with increasing output power.

6.4.4 Comparison between numerical results and analytical results

To carry out a quantitative comparison between the numerical results and the values predicted by the mean-field theory, it is crucial to determine from the transmission line model the effective value of the linewidth enhancement factor, α , because, different from the analytical theory, such linewidth enhancement factor cannot be inserted a priori as parameter in the numerical model. Instead, the numerical model calculates explicitly the local carrier density, $N(z)$, from which it explicitly calculates the local refractive index, $n(z)$. This means that, in the numerical model being much closer to a complete description, there is no generally valid α -factor. Instead the gain-index coupling is a local, space dependent parameter of which some overall, effective (space averaged) α -factor may be derived that depends on the specific carrier and intensity distribution in the gain section. However, if the steady-state carrier density along the diode section is computed as a function of current at different values of β , this enables a calibration of the effective value of α as compared to the mean-field model, where α is inversely proportional to the carrier density.

We have carried out the named calibration as follows: at first, an operation point is identified in terms of drive current that gives rise to steady-state

operation and that satisfies the mean-field approximation. Here we chose $\beta = 1$ because then $r(\omega)$ is close to unity as well (see Fig. 6.3 (a)), such as is also r_1 ($r_1 = 0.92$). As a result, the carrier density, N_0 , shows a negligible spatial variation. Secondly, Eq. 6.1 is fitted to the linewidth obtained from the transmission line model, where α is the only fit parameter. For a drive current of 20 mA, this yields an α -value of 3.4, which we denote as α_0 . In a third step, we obtain α -values for lower values of β via multiplying α_0 by N/N_0 where N is the spatially averaged carrier density, regardless of how strong the spatial variation is. As the last step, the theoretical linewidth value obtained with Eqs. 6.1 to 6.6 is calculated ($\Delta\nu$), where the α -value from the previous step is inserted.

In Fig. 6.8 (a), the ratio between the linewidth from the transmission line model and from the modified mean-field model, denoted as $\Delta\nu_{TL}/\Delta\nu$, is plotted as a function of $r(\omega)$ across the inspected range of β (0.1 to 1) and across the inspected range of drive currents (20 mA to 60 mA). It can be seen in Fig. 6.8 that at $r(\omega) \approx 1$ this ratio is approximately unity (at the calibration point as expected) but that it deviates increasingly from unity as the effective reflectivity decreases. The vertical spread of data points can be associated with uncertainties in linewidth retrieval from frequency noise spectra. Nevertheless, clearly an overall increasing trend of the ratio towards small values of $r(\omega)$ can be seen. This trend of increasing error in the analytical model is even more obvious also in Fig. 6.8 (b) where we have plotted the linewidth ratio for each β .

Figure 6.8: (a) Ratio between laser spectral linewidths obtained with the transmission line model and the modified mean-field model for the full range of β (0.1 to 1) and drive currents (20 mA to 60 mA). Due to the different laser output frequencies, $|r(\omega)|$ varies as drive current for each value of β ; (b) Average ratio over the full range of drive currents for each β (from 0.1 to 1). A clear upward trend is seen as β approaches smaller values.

6.5 Conclusion

Our theoretical modeling provides for the first time a comprehensive comparison between the current, analytical linewidth theory (a modified-field model) and numerical calculations based on an advanced, spatial resolving transmission line model for hybrid diode lasers with frequency-selective feedback. It is found that with a weak optical coupling between the diode amplifier and the feedback (here a waveguide circuit on a chip), the modified mean-field model tends to underestimate the laser spectral linewidth. This underestimation becomes more apparent with decreasing coupling. We address the discrepancy between the transmission line and mean-field model mainly to an inadequacy of the mean-field model in scaling the effect of a locally varying gain-index coupling into a single number for the α -linewidth enhancement factor.

While the direct implications of strong spatial gain variations may be well-included in the mean-field model via a spontaneous emission enhancement factor, this does not account for the associated variation in index. Our numerical modeling reveals that these index effects can be seen as an effective α -factor that increases the laser linewidth with decreasing feedback strength.

Our findings have the following implications for predicting the spectral linewidth of hybrid lasers in order to find a proper design of the waveguide feedback circuit parameters before fabrication and hybrid integration:

1. For a proper prediction of the laser linewidth in the case of strong feedback (β close to unity), it is fully sufficient to use the current, modified mean-field theory as guidance. The laser linewidth will decrease as expected with increasing output power, with increasing mode coupling efficiency, and by implementing feedback circuits with low loss and a large linewidth reduction term (F^2 in Eq. 6.3);
2. For hybrid lasers with weak coupling ($\beta \leq 0.1$) where a strong spatial variation in the carrier density is present, the analytical theory should be tackled with more caution. Namely one should be aware that the presence of a strong spatial variation in carrier density will broaden the linewidth with an additional index related effect. For instance, at a weak coupling of $\beta = 0.1$ (which is still fully sufficient for laser operation due to the huge gain provided by diode amplifiers) the linewidth will be larger by a factor of about 2. Following this trend, higher values than that may be expected with a further lowering of coupling.

Examples of the second situation are hybrid lasers where the feedback mode is not well matched to the diode waveguide mode, or when the feedback waveguide circuit itself is providing high losses, such as would typically occur with feedback from waveguide circuits fabricated from Si. Also other types of diode lasers show a strong variation of the carrier density and should thus exhibit linewidth larger than expected. These are diode lasers that are deliberately

equipped with a low reflectivity of the back facet (at the few percent level or below) [23] as is often chosen for increasing the usable output power, or heterogeneous integrated hybrid DFB lasers [30] that might show strong spatial carrier density variations such as though spatial hole burning [12].

6.6 Appendix: numerical parameters

Table 6.1: Semiconductor chip parameters

Symbol	Value	Description
λ	1552.6 nm	Operating wavelength
g_0	1800 cm^{-1}	Gain coefficient
N_{tr}	$1.5 \cdot 10^{18} \text{ cm}^{-3}$	Transparency carrier density
ϵ	$1 \cdot 10^{-17} \text{ cm}^3$	Gain compression factor
η_i	1	Internal efficiency
A	0	Linear recombination coefficient
B	$1.0 \cdot 10^{-10} \text{ cm}^3/\text{s}$	Bimolecular recombination coefficient
C	$1.3 \cdot 10^{-29} \text{ cm}^6/\text{s}$	Auger recombination coefficient
n_{g1}	3.6	Group index of laser diode material
L_1	$400 \mu\text{m}$	Length of active layer
d_{MQW}	40 nm	Thickness of multi quantum wells
w	$2.5 \mu\text{m}$	Width of active layer
R_1	0.85	Left facet power reflection
R_2	0	Right facet power reflection
α_i	1607 m^{-1}	Internal loss coefficient of the laser diode
n_{sp}	2.0	Spontaneous emission coefficient at threshold
Γ	0.07	Optical confinement factor of the MQW area

Table 6.2: *Feedback waveguide chip parameters*

Symbol	Value	Description
S_1	$49.5 \mu m$	Radius of the first microring resonator
S_2	$54.0 \mu m$	Radius of the second microring resonator
α_2	60 dB/m	Waveguide attenuation
κ^2	0.2	Power coupling coefficient for both MRRs
L_2	$3500 \mu m$	Bus waveguide length
n_{eff2}	1.54	Effective index
n_{g2}	1.7147	Group index

Table 6.3: *Configuration parameters used for numerical modeling*

Symbol	Value	Description
BW	10.24 THz	Sampling rate
T	25.6 ns	Time window for each calculation
Ave	10	Number of average for each PSD spectra

Bibliography

- [1] S. Zhang, P. Y. Kam, C. Yu, and J. Chen, “Laser linewidth tolerance of decision-aided maximum likelihood phase estimation in coherent optical M-ary PSK and QAM systems,” *IEEE Photon. Technol. Lett.* **21**, 1075–1077 (2009).
- [2] L. He, Ş. Özdemir, J. Zhu, W. Kim, and L. Yang, “Detecting single viruses and nanoparticles using whispering gallery microlasers,” *Nat. Nanotechnol.* **6**, 428–432 (2011).
- [3] A. Hemmerich, D. McIntyre, D. Schropp, D. Meschede, and T. Hänsch, “Optically stabilized narrow linewidth semiconductor laser for high resolution spectroscopy,” *Opt. Commun.* **75**, 118 – 122 (1990).
- [4] Y. Jiang, A. Ludlow, N. Lemke, R. Fox, J. Sherman, L.-S. Ma, and C. Oates, “Making optical atomic clocks more stable with 10^{-16} -level laser stabilization,” *Nat. Photon.* **5**, 158–161 (2011).
- [5] M. Faugeron, M. Tran, O. Parillaud, and M. Chtioui, “High-power tunable dilute mode DFB laser with low RIN and narrow linewidth,” *IEEE Photon. Technol. Lett.* **25**, 7–10 (2013).
- [6] Y. A. Akulova, G. A. Fish, P.-C. Koh, C. L. Schow, P. Kozodoy, A. P. Dahl, S. Nakagawa, M. C. Larson, M. P. Mack, T. A. Strand, C. W. Coldren, E. Hegblom, S. K. Penniman, T. Wipiejewski, and L. A. Coldren, “Widely tunable electroabsorption-modulated sampled-grating DBR laser transmitter,” *IEEE J. Sel. Top. Quantum Electron.* **8**, 1349–1357 (2002).
- [7] C. Henry, “Theory of the linewidth of semiconductor lasers,” *IEEE J. Quantum Electron.* **18**, 259–264 (1982).
- [8] B. Liu, A. Shakouri, and J. E. Bowers, “Passive microring-resonator-coupled lasers,” *Appl. Phys. Lett.* **79**, 3561–3563 (2001).
- [9] T. Kita, K. Nemoto, and H. Yamada, “Silicon photonic wavelength-tunable laser diode with asymmetric Mach-Zehnder interferometer,” *IEEE J. Sel. Top. Quantum Electron.* **20**, 344–349 (2014).
- [10] R. Kazarinov and C. Henry, “The relation of line narrowing and chirp reduction resulting from the coupling of a semiconductor laser to passive resonator,” *IEEE J. Quantum Electron.* **23**, 1401–1409 (1987).

- [11] T. Komljenovic, S. Srinivasan, E. Norberg, M. Davenport, G. Fish, and J. E. Bowers, "Widely tunable narrow-linewidth monolithically integrated external-cavity semiconductor lasers," *IEEE J. Sel. Top. Quantum Electron.* **21**, 214–222 (2015).
- [12] M. Wu, Y. Lo, and S. Wang, "Linewidth broadening due to longitudinal spatial hole burning in a long distributed feedback laser," *Appl. Phys. Lett.* **52**, 1119–1121 (1988).
- [13] F. Girardin, G.-H. Duan, and P. Gallion, "Linewidth rebroadening due to nonlinear gain and index induced by carrier heating in strained quantum-well lasers," *IEEE Photon. Technol. Lett.* **8**, 334–336 (1996).
- [14] S. Srinivasan, M. Davenport, T. Komljenovic, J. Hulme, D. T. Spencer, and J. E. Bowers, "Coupled-ring-resonator-mirror-based heterogeneous III-V silicon tunable laser," *IEEE Photon. J.* **7**, 1–8 (2015).
- [15] VPI GmbH, "VPIphotonics" (2017), <http://www.vpiphotonics.com/>.
- [16] A. Lowery, "New dynamic semiconductor laser model based on the transmission-line modelling method," *IEE PROC-J* **134**, 281 (1987).
- [17] W. Hoefer, "The transmission-line matrix method - theory and applications," *IEEE Trans. Microw. Theory Techn.* **33**, 882–893 (1985).
- [18] Y. Fan, R. M. Oldenbeuving, P. J.M. van der Slot, and K.-J. Boller, "A semiconductor-glass waveguide hybrid laser with ultra-long cavity length," in "Proceeding of the 20th Annual Symposium of the IEEE Photonics Society Benelux," (2016), pp. 121 – 124.
- [19] T. Chu, N. Fujioka, and M. Ishizaka, "Compact, lower-power-consumption wavelength tunable laser fabricated with silicon photonic wire waveguide micro-ring resonators," *Opt. Express* **17**, 14063–14068 (2009).
- [20] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and K.-J. Boller, "25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity," *Laser Phys. Lett.* **10**, 015804 (2013).
- [21] J. C. Hulme, J. K. Doylend, and J. E. Bowers, "Widely tunable vernier ring laser on hybrid silicon," *Opt. Express* **21**, 19718–19722 (2013).
- [22] A. Yariv, "Coupled-mode theory for guided-wave optics," *IEEE J. Quantum Electron.* **9**, 919–933 (1973).
- [23] R. Tang, T. Kita, and H. Yamada, "Narrow-spectral-linewidth silicon photonic wavelength-tunable laser with highly asymmetric Mach-Zehnder interferometer," *Opt. Lett.* **40**, 1504–1507 (2015).

- [24] C. Henry, “Theory of spontaneous emission noise in open resonators and its application to lasers and optical amplifiers,” *J. Lightw. Technol.* **4**, 288–297 (1986).
- [25] G. Bjork and O. Nilsson, “A tool to calculate the linewidth of complicated semiconductor lasers,” *IEEE J. Quantum Electron.* **23**, 1303–1313 (1987).
- [26] K. Ujihara, “Phase noise in a laser with output coupling,” *IEEE J. Quantum Electron.* **20**, 814–818 (1984).
- [27] S. F. Mingaleev and K. Busch, “Scattering matrix approach to large-scale photonic crystal circuits,” *Opt. lett.* **28**, 619–621 (2003).
- [28] B. Bennett, R. A. Soref, and J. del Alamo, “Carrier-induced change in refractive index of InP, GaAs and InGaAsP,” *IEEE J. Quantum Electron.* **26**, 113–122 (1990).
- [29] G. Di Domenico, S. Schilt, P. Thomann, “Simple approach to the relation between laser frequency noise and laser line shape,” *Appl. Opt.* **49**, 4801–4807 (2010).
- [30] C. T. Santis, S. T. Steger, Y. Vilenchik, A. Vasilyev, and A. Yariv, “High-coherence semiconductor lasers based on integral high-Q resonators in hybrid Si/III-V platforms,” *Proc. Natl. Acad. Sci. U.S.A.* **111**, 2879–2884 (2014).

7

290 Hz intrinsic linewidth of a chip-based widely tunable InP-Si₃N₄ hybrid laser

We report the realization of an InP-Si₃N₄ chip-based hybrid laser with an ultra-narrow spectral linewidth of 290 Hz. The laser is constructed by butt-coupling of an InP reflective semiconductor amplifier (RSOA) and a low-loss frequency selective Si₃N₄ waveguide feedback circuit. The feedback circuit incorporates three high-Q microring resonators which increases the effective roundtrip length of the laser cavity to a high value of about 30 cm. The laser has a low threshold current of about 22 mA and offers a high output power of 13 mW at a driving current of 200 mA. A wide wavelength tunability covering the entire bandwidth of the RSOA (from 1500 nm to 1581 nm, 81 nm coverage) is achieved. A record-low intrinsic spectral linewidth of about 290 Hz is obtained. The demonstrated narrow linewidth is the lowest value of any chip-based diode laser up to date and, therefore, marks a new paradigm for semiconductor lasers with ultra-high coherence.

7.1 Introduction

There has been an ever-increasing demand for higher data rates in fiber-optic communications. Such demand has driven the need for integrated semiconductor laser sources with narrow quantum linewidths that can be applied in dense wavelength division multiplexing (DWDM) using advanced modulation formats, such as quadrature amplitude modulation (QAM) [1]. Besides fiber-optic telecommunications, applications that benefit from such lasers are optical beamforming networks [2], light detection and ranging (LIDAR) [3], spectroscopy [4], optical sensing [5] or space-based laser cooling [6] and atomic clocks [7] in global positioning systems (GPS). Especially when looking for narrow spectral linewidth, monolithic semiconductor lasers, such as distributed feedback (DFB) lasers and distributed Bragg reflector (DBR) lasers, where all the components of the laser are made of the same materials, approach their limits. Such lasers typically exhibit linewidths at the MHz level, which is fundamentally limited by high cavity losses and short cavity lengths.

The spectral linewidth of diode lasers can be approximately predicted via the well-known Schawlow-Townes formula [8]:

$$\Delta\nu_{LD} = (1 + \alpha^2) (\Delta\nu_c)^2 \frac{\pi h\nu}{P} n_{sp}, \quad (7.1)$$

where $\Delta\nu_{LD}$ is the fundamental (intrinsic, quantum) laser linewidth, α is the linewidth enhancement factor that is a specific feature for semiconductor lasers, $\Delta\nu_c$ is the cold cavity bandwidth of the laser diode resonator which decreases with increasing cavity length, and which increases with higher loss. $h\nu$ is the photon energy, P is the total output power, and n_{sp} is the spontaneous emission factor, which typically assumes values on the order of 2 [8].

Great efforts are made in order to narrow the spectral linewidths of semiconductor lasers, using external feedback from bulk optical components and active frequency stabilization with large servo bandwidths. Such methods have achieved linewidths at the Hz-level since long [9–11]. However, the utilization of bulk optics in those laser systems rules out the possibility of realizing such lasers in a chip-sized fashion. As a result, external cavity diode lasers, such as with grating feedback remain prone to mechanical vibrations and render themselves unstable, which requires sophisticated frequency stabilization in combination with a bulk-stabilized (shielded and heavy) design.

To remove these limitations, it is of highest interest to realize external feedback with optically long waveguide circuits on a chip. The optically long cavity would then provide a narrow intrinsic linewidth whereas the inherent passive stability of integrated optic waveguide circuits removes the need for large physical size, weight and acoustic shielding.

This is the reason why so-called hybrid lasers, which enable straightforward fundamental linewidth narrowing via integrated optics, are currently gaining considerable importance. In such lasers, a semiconductor amplifier made of

active material providing optical gain receives feedback from an integrated optical waveguide circuit fabricated from a different passive material (without optical gain). Specifically, replacing any passive but otherwise lossy section of a semiconductor waveguide resonator by low-loss passive waveguides allows for reducing the total cavity loss and extending the cavity length. This reduces the cold cavity bandwidth in Eq. 7.1 and thereby narrows the laser spectral linewidth.

One of the currently promising hybrid laser approaches focuses on reducing the total cavity loss, via evanescently coupling III-V semiconductor to a passive, low-loss Si resonator [12]. A fundamental linewidth as low as 1 kHz has been reported via such de-localizing of the optical mode away from the high-loss active semiconductor material [13]. However, such an approach involves highly material specific and technologically complicated fabrication processes that are not supported by most of the current foundries. Furthermore, the wavelength of such lasers is pre-determined by the compatibility of material properties. Another disadvantage is that such lasers cannot be tuned over wide ranges. These two advantages may limit usability for many applications.

Another promising approach of which we make use is based on extending the total cavity length via equipping a reflective semiconductor optical amplifier (RSOA) with an external waveguide feedback circuit that contains frequency-selective elements for intra-cavity filtering and wavelength tuning. The desire for a long cavity length together with a wide tuning range has strongly stimulated the choice of low-loss microring resonators (MRRs) for intra-cavity filtering. The advantage of utilizing such MRRs, as compared to Bragg gratings as in DFB and DBR lasers, is that a wavelength tuning across wide ranges can be easily achieved with the so-called Vernier effect [14, 15]. Another important advantage is that the effective length of a low-loss MRR can be much larger than its circumference, by an enhancement factor $E=(1-K)/K$ [16] where K is the power coupling coefficient, which contributes to linewidth narrowing according to Eq. 7.1. To date, there have been numerous demonstrations of hybrid lasers with external MRRs, realized in various material platforms such as Si [17–19], SiON [20], SiO₂ [21] and Si₃N₄ [14, 22], with reported spectral linewidths ranging from 2 kHz [21] to about 300 kHz [18] and with typical tuning ranges of a few tens of nanometers.

Recently we have reported the first demonstration of an RSOA butt-coupled semiconductor-Si₃N₄ hybrid laser where frequency selection is achieved using a Vernier mirror based on two microring resonators (MRRs) [14, 22]. Using an InP based RSOA, carefully positioned next to the Si₃N₄ chip with alignment stages, a wide tuning range covering the entire telecom C-band was achieved. The emerging Si₃N₄ waveguide platform is of special importance because it can offer some fundamental and technological advantages over other passive waveguide platforms: a) compared to silica that has only a low index contrast ($\Delta n \approx 10^{-2}$ [23]), the index contrast is very high, $\Delta n \approx 0.5$, rendering a small footprint achievable even with long optical feedback resonator; b) Si₃N₄ waveguides provide a very large transparency range, from 400 nm to 2400 nm [24],

which means that a large variety of semiconductor materials other than InP might be used equally well, to form hybrid lasers emitting at other wavelengths including the visible range; c) Si₃N₄ waveguides support extremely low linear propagation loss from 0.001 dB/cm [25] to 0.1 dB/cm [26], depending on the chosen waveguide core cross-section; d) the nonlinearity of Si₃N₄ is low, which prevents two-photon absorption [27]; e) Si₃N₄ waveguides offer unprecedented maturity in terms of design, tunability [28] and programmability [29], which enables access to complex functionalities on the same photonic chip; f) adiabatic tapers can be realized that enable tailoring of the mode field diameter [24]. The latter is important to reduce the mode matching losses in the diode-waveguide coupling, which is crucial for the performance of such lasers. When aiming at narrower linewidths of well below 1 kHz, a significant extension of the cavity length is desired in combination with a strong refinement of intra-cavity filtering to maintain single-frequency oscillation.

In this work, we present the first experimental realization of a sub-kHz hybrid diode laser based on optical chips. The laser is an InP-Si₃N₄ hybrid laser with a long cavity based on spectrally filtered feedback from three microring resonators (MRRs). The laser exhibits a record-narrow spectral linewidth of 290 Hz and also a record-wide wavelength tuning range of 81 nm. Two MRRs are used as a coarse Vernier filter that provide a wide wavelength tuning range covering the entire RSOA gain bandwidth. The third MRR is given a high quality factor ($Q \approx 300,000$) which is used for further refining the frequency selectivity. The second purpose of the MRRs is that they enhance the roundtrip effective length of the laser cavity to a high value of 30 cm. Realizing strong feedback with such a long cavity on a chip is possible due to the low propagation loss Si₃N₄ waveguides together with low-loss mode matching with the amplifier waveguide based on mature tapering techniques [24].

7.2 Laser cavity design

The detailed optical circuit diagram of the hybrid laser is shown in Fig. 7.1. The cross section of the waveguides (Fig. 7.1 (a)) is formed by two stripes of Si₃N₄ ($n \approx 2$) surrounded with SiO₂ as an intermediate layer and cladding ($n \approx 1.45$). This geometry is chosen for single transverse mode guiding at 1550 nm, allows for a small minimum bending radius (100 μm) for TE polarization, and provides low loss (less than 0.1 dB/cm, based on scattered light measurement using an infrared camera). The effective group index of this waveguide profile is 1.715.

The hybrid laser shown in Fig. 7.1.(b) comprises an InP based reflective (double pass) semiconductor optical amplifier (RSOA) and the Si₃N₄ waveguide feedback circuit. The RSOA (prototype obtained from the Fraunhofer Heinrich-Hertz-Institute, Berlin) possesses a length of 700 μm . The RSOA has a high reflection (HR) coated back-facet with a reflectivity of $R_1=90\%$. To reduce perturbing back reflections [30] and to lower the coupling loss to the

Figure 7.1: Schematic drawing of the hybrid laser (not to scale). R_1 is the reflectivity of the high reflection (HR) coated amplifier back facet, R_2 is the overall reflectivity of the Vernier mirror, L is the total length of the feedback circuit and β is the power coupling efficiency between the anti-reflection (AR) coated diode waveguide and the Si_3N_4 waveguide.

Si_3N_4 waveguide chip, the front facet carries an anti-reflection (AR) coating, optimized for a refractive index of 1.5 which is close to the effective index of the tapered input end of the external Si_3N_4 waveguide used (1.454). To further reduce perturbing back reflections, the diode waveguide is angled with regard to the front facet by 9° . The mode field diameter (MFD) is specified to be 3.5 μm both in both transverse directions.

7.2.1 Coupling between InP chip and Si_3N_4 chip

In order to maximize the coupling efficiency between the InP chip and the Si_3N_4 chip, an adiabatic taper is implemented in the Si_3N_4 chip. To quantify the expected coupling efficiency and sensitivity to transverse misalignment, we calculated the mode overlap integral *vs* the offset in both transverse directions, Δx and Δy (Fig. 7.2). As can be seen, the chosen tapering provides a theoretical coupling efficiency of higher than 93% (loss smaller than 0.3 dB). As was described above, such a high coupling efficiency, i.e., small loss contribution to the overall roundtrip cavity loss is important for high output power and narrow spectral linewidth. Fig. 7.2 also shows that such a taper results in a relatively large misalignment tolerance, e.g., the coupling is still at about 90% with a misalignment of 0.4 μm . Given that state-of-the-art precision stages provide a resolution of about 0.1 μm , it should be feasible to reach a coupling loss of less than 0.5 dB reproducibly.

Figure 7.2: Calculated mode overlap as a function of transverse offset.

7.2.2 Intra-cavity spectral filtering

The transmission function through the three-MMR waveguide filter shown in Fig. 7.1 was calculated as described in Chapter 2 and is plotted Fig.2.4, using the parameters that were specified for fabrication of the chip. The radii of the ring resonators are 99 μm , 102 μm and 1485 μm , and all power coupling coefficients are chosen as $K=0.1$. The motivation for choosing these specific values is detailed as well in Chapter 2, which is a long laser resonator roundtrip length (about 30 cm) and simultaneously restricting laser oscillation to a single resonator mode.

7.2.3 Adjustable loop mirror

In all lasers the achievable laser output power and optimum output coupling strongly depends on the output mirror transmission (active loss) in relation to other loss (passive loss). Generally, if the passive losses in the amplifier are high or there are high losses due to a non-unity back reflectivity, it is desired to provide also a relatively high output coupling in order to obtain an efficient power extraction [31]. However, a high output coupling increases the total roundtrip loss which broadens the laser linewidth in return [8]. Therefore, when aiming at narrowest linewidth a trade-off is imposed on the optimum output coupling which is difficult to determine beforehand. To address this issue experimentally, we have implemented an adjustable loop mirror in the laser cavity, as is shown in Fig. 7.1 (b). The mirror is composed of a balanced Mach-Zehnder

Figure 7.3: Calculated power reflectivity/transmissivity of the adjustable loop mirror. The power coupling coefficients of both directional couplers are set to 0.5. It can be seen that through a phase change of $\pi/2$, reflectivities (transmissivities) ranging from 0 (1) to 1 (0) can be accessed.

interferometer (MZI) with two directional couplers where one of the couplers is closed by a waveguide loop. The reflectivity and output coupling is adjusted via a tunable phase shift, Φ , in one arm of the MZI. Using a scattering matrix method, the power reflectivity/transmissivity of the adjustable loop mirror as a function of Φ is calculated (see Fig. 7.3). Throughout the experiments the reflectivity was adjusted to a value of about 0.5.

7.3 Characteristics of the integrated hybrid laser and discussion

In the following sections, the experimental equipment, experimental procedures and the results obtained with the hybrid laser will be presented.

7.3.1 Laser alignment

The hybrid laser prepared and setup as follows: both facets of the Si_3N_4 waveguide chip were polished for providing a smooth surface for better butt-coupling. The chip is then bonded using thermally conducting double-sided tape to a standard waveguide mount that is clamped on a metal block. The RSOA chip and an output fiber are manually aligned to the input end and output end of the Si_3N_4 waveguide chip, respectively, via two six-axis precision stages (Thorlabs, MAX601/M). In order to reduce back reflections, index matching gel was applied between the Si_3N_4 chip and the fiber. For temperature controlling, the RSOA is placed on top of a laser diode mount (Thorlabs,

HLD001) incorporating a thermo-electric cooler with a thin layer of thermally conducting paste applied in between the two, and the temperature is kept at 25 degrees C using a temperature controller (Thorlabs, TED200C). The temperature of the Si₃N₄ chip remained at the ambient temperature due to contact with the metal block. For driving the RSOA, a standard current source (Thorlabs, LDC210B) and two probe needles are used. The latter also clamp the RSOA chip on its mount. For driving the heaters for laser wavelength tuning, several standard DC voltage power supplies and probe stages (Microtech, DPP105-AI-S) are used. For avoiding perturbing back reflections, the output fiber is connected to a fiber optical isolator before sending for power and spectral analysis.

7.3.2 Laser output spectrum

In the experiments, the laser showed a low threshold current of approximately 22 mA and an high fiber-coupled output power of 13 mW, obtained at a current of 200 mA. The corresponding wall-plug efficiency is about 5% which compares well with what has been reported from other hybrid lasers that were optimized for high efficiency [31–33].

To verify that the laser oscillates at a single wavelength, we have measured the laser output spectrum using an optical spectrum analyzer (OSA) (ANDO, AQ6317). Fig. 7.4 shows a typical laser output spectrum, obtained at a driving current of 200 mA and recorded across a spectral range from 1500 nm to 1600 nm, with a resolution of 0.05 nm. It can be seen that the side mode suppression ratio is as high as 60 dB. This clearly proves single-mode oscillation. The spectrum shows a slightly asymmetric ASE background near the main longitudinal mode, which can be understood by asymmetric nonlinear gain saturation [34].

7.3.3 Laser wavelength tuning

The laser output wavelength was tuned via phase shifters on top of the MRRs based on three resistive heaters (one for each MRR) using a maximum power of about 270 mW.

For coarse wavelength tuning, the heater current of one of the small MRRs was manually increased. This gives rise to discrete wavelength changes at a stepsize which corresponds to approximately the FSR of the other small MRR. After the output power is maximized at a desired wavelength by tuning MRR1 or MRR2, the heating current of the other small MRR is adjusted to improve the spectral alignment of all three MRRs. The latter can be seen as a maximum output power achieved *vs* heating current. Figure 7.5 shows an example of superimposed laser spectra, with the laser tuned to 39 different wavelengths. It can be seen that the hybrid laser offers a broad tuning range of more than 80 nm, covering the entire gain bandwidth of the InP RSOA. This value, being a few nm larger than the current record obtained with much more

Figure 7.4: Laser output power spectrum of the hybrid laser on a logarithmic scale, obtained at a driving current of 200 mA and recorded at a resolution of 0.05 nm of the OSA. The measured side-mode suppression ratio is about 60 dB.

Figure 7.5: Superimposed laser output spectra when coarsely tuned over a 81 nm wide range as observed when thermally tuning one of the two MRRs. The laser was operated at a driving current of 70 mA and the spectra were recorded with an OSA resolution of 0.1 nm. The power variations among different laser output wavelength is mainly ascribed to a manual tuning procedure that we carried out.

compact monolithic lasers (74.3 nm) [36], is the widest tunability among hybrid lasers on a chip. During the described coarse tuning small power variations were observed as can be seen in Fig. 7.5. These are due to imperfect spectral alignment of the three MRRs. If the three MRRs are tuned in a synchronized manner, and if adjusting a phase-shift section accordingly that is implemented on the Si₃N₄ chip as well, it should be possible to tune the laser wavelength to any pre-defined value within the tuning range. This is required in most applications, such as tuning to the ITU telecom C-band wavelength grid [37]. The observed tuning range is in good agreement with the calculated total FSR (74.3 nm) of the Vernier filter. The observed amount of 6 nm extra tuning range might be explained with a noticeable dispersion of the group index in the feedback circuitry across the huge spectral range.

7.3.4 Spectral linewidth of the laser

In order to investigate the spectral linewidth of the laser, we measure its frequency noise using an asymmetric Mach-Zehnder interferometer (AMZI) that acts as a frequency discriminator [38]. The optical path difference between the two arms is 5.4 m. An acoustic-optic modulator in one of the arms induces a frequency shift of 40 MHz for an easier measurability of beat signals. The optical signal behind the AMZI is fed into a balanced detector and the electrical signal containing frequencies close to 40 MHz is sampled in the time domain using an analog-to-digital converter (ADC). The obtained time traces are stored on a computer and then analyzed for the power spectral density (PSD) of the laser frequency noise.

The motivation for applying such spectrally resolved noise measurement is that it can discriminate between noise contributions from different physical origins. Typically, such frequency noise measurement can inherently separate so-called technical noise, from fundamental noise. Technical noise is contributed by various kinds of environmental perturbations, e.g., pick up noise, thermal noise, acoustic noise or current noise from power supplies. Technical frequency noise can usually be identified via its decrease *vs* increasing noise frequency or as distinct, isolated noise peaks. Technical noise may be removed with appropriate method, such as cooling, acoustic isolation or electromagnetic shielding. Fundamental noise in lasers, also called intrinsic noise, is caused by the quantum nature of light, which shows as spontaneous emission into the investigated optical mode. Quantum noise, due to its physical origin, is independent of the RF noise frequency, thus it is also called white frequency noise. Correspondingly, at sufficiently high noise frequencies, quantum noise dominates the frequency noise spectrum of lasers, forming the ultimate (quantum) limit of the spectral purity of laser light. Quantitatively, the fundamental spectral linewidth limit (Schawlow-Townes, quantum limit) of a technically ideal laser, as given in Eq. 7.1, can be obtained by multiplying the PSD value of the double-sided band white noise level with a factor of 2π [12, 39–41].

We measured the PSD at various different driving currents and laser wave-

Figure 7.6: Measured power spectral density of the frequency noise of the hybrid laser at two driving currents (50 mA, blue; 120 mA, red). The intrinsic laser linewidth is retrieved via multiplying PSD value of the white frequency noise by 2π .

lengths, since the linewidth is power dependent and wavelength dependent. The latter is due to a wavelength dependence of the linewidth enhancement factor (α in Eq. 7.1) and the laser threshold [42]. Fig. 7.6 shows two examples of measured frequency noise spectra, obtained at a laser output wavelength of 1567 nm and two different driving currents of 50 mA and 120 mA. It can be seen that technical frequency noise is present at low frequencies, decaying towards a noise frequency of about 1 MHz. At higher frequencies (shaded area), white frequency noise dominates the spectrum, as expected. The average PSD in this range amounts to $125 \text{ Hz}^2/\text{Hz}$ and $46 \text{ Hz}^2/\text{Hz}$ for a driving current of 50 mA and 120 mA, respectively. The latter noise density is equivalent to an intrinsic laser linewidth of 290 Hz.

To the best of our knowledge, the measured value of 290 Hz represents the narrowest fundamental linewidth that has ever been achieved with a chip-based diode laser so far. This includes all previous types of external cavity lasers using photonic integrated circuits and heterogeneous integrated hybrid DFB laser [12], as is shown in Fig. 7.7 (see references in the caption). This includes also optically pumped solid-state waveguide lasers [43], fiber lasers [44–46] as well as hybrid semiconductor-fiber lasers [47], the latter even equipped with a longer roundtrip cavity length (70 cm). We ascribe the obtained 290 Hz narrow linewidth to a well-balanced choice of laser parameters, specifically, an efficient InP-Si₃N₄ coupling, a long cavity length enabled by a low-loss waveguide platform and highly frequency-selective intra-cavity filtering with high-Q MRRs.

Further reduction of frequency noise at low noise frequencies will require

Figure 7.7: Reported linewidths of hybrid lasers for references [12, 14, 15, 18–22, 48–57]

a long-term, permanent fixation of the two chips with respect to each other (i.e. optical integration [15] with the precision as named above). Extending the long-term stability of the laser with optical integration would enable also a long term stabilization of the laser, e.g., to an absolute reference (e.g. a Doppler-free absorption line of C₂O₂).

7.4 Further linewidth narrowing

In order to estimate the possibility of realizing a fundamental laser linewidth that is even narrower than what we have experimentally realized so far, it is instructive to calculate how the spectral linewidth scales with a further increased external feedback path length and depending on the waveguide loss, based on the demonstrated laser cavity design in this chapter. To this end, we have used Eqs. 6.1 to 6.6 from the previous chapter to calculate the laser linewidth as a function of the single-pass external cavity length L_2 (including the contribution from the intra-cavity microring resonators). The calculation was carried out for a set of different loss values (α_2). The other parameters used in the calculations were taken to be feasible (realistic) as follows: linewidth enhancement factor, $\alpha = 5$; back facet reflectivity of the RSOA chip, $R_1 = 0.9$; internal waveguide loss of the RSOA chip, $\alpha_1 = 13 \text{ cm}^{-1}$; group index of the RSOA chip, $n_{g1} = 3.6$; length of the RSOA chip, $L_1 = 0.7 \text{ mm}$; power coupling efficiency between the two chips, $\beta = 0.9$; group index of the Si₃N₄ chip, $n_{g1} = 1.715$; power reflectivity of the loop mirror, $R_3 = 0.5$; output power from the back facet of the RSOA, $P_0 = 1 \text{ mW}$. Note that for simplicity we have assumed a zero value for the second linewidth narrowing term, B, as this narrowing is available at a certain detuning from the Vernier peak frequency.

The calculated results are summarized in Fig. 7.8. As can be seen, generally the laser linewidth decreases with increased L_2 , and the linewidths are approximately the same at low values of L_2 , i.e., smaller than 1 cm, independent on the waveguide loss, α_2 . However, at larger values of L_2 , the calculated linewidths show noticeable differences at different values of waveguide loss (α_2) and the linewidths saturate at certain levels (do not become smaller) as L_2 increases. The saturation is reached at shorter values of L_2 for higher values of α_2 , which can be understood by the increased spontaneous emission enhancement factor resulting from higher levels of total external cavity losses. When aiming at the range of one-Hertz level linewidths as indicated by the horizontal dashed line, Fig. 7.8 shows a possible realization via lowering the waveguide loss to 0.1 dB/m which is feasible [25] and via extending the cavity length to about one meter. Such a long cavity length might be achieved, e.g., via decreasing the power coupling coefficient of the microring resonator with the largest radius (1485 μm) to a low value of 0.01.

Figure 7.8: Calculated laser spectral linewidth as a function of external cavity length (which includes the effective length of microring resonators). The assumed values are as follows: 1 mW of output power, a mode coupling efficiency of 0.9 between the two chips, a diode back facet reflectivity of 0.9 and an external reflectivity of 0.5 of the loop mirror. We have used Eqs. 6.1 to 6.6 from the previous chapter, based on the equivalent Fabry-Perot laser model where the second linewidth reduction term, B , is omitted for simplicity. The linewidth calculation is carried out for a set of loss values of the Si_3N_4 waveguides, α_2 . As can be seen, with the loss reduced to 0.1 dB/m and at an external cavity length, L_2 , of the feedback, it appears feasible that the linewidth of the hybrid laser can be narrowed down to the one-Hz-level.

7.5 Conclusion

In this chapter we have presented a hybrid InP-Si₃N₄ with a very long cavity length (30 cm roundtrip) on a chip. A high fiber-coupled output power of 13 mW is achieved and the laser wavelength can be tuned over a record-wide spectral range of 81 nm, covering the entire gain bandwidth, from 1500 nm to 1581 nm. A record-narrow intrinsic linewidth of 290 Hz is experimentally demonstrated. These results are of high promise for the potential use of such lasers in many applications. Further narrowing of the laser linewidth might be possible, e.g., by reducing the power coupling coefficients of the MRRs or by adding more MRRs or waveguide length. Another option might be using Si₃N₄ waveguide circuits with a single-stripe cross-section that offers ultra-low propagation loss in the order of 0.1 dB/m [25]. This should allow for cavity lengths at the level of a meter and linewidth at the Hertz-level.

Bibliography

- [1] S. Zhang, P. Y. Kam, C. Yu, and J. Chen, “Laser linewidth tolerance of decision-aided maximum likelihood phase estimation in coherent optical M-ary PSK and QAM systems,” *IEEE Photon. Technol. Lett.* **21**, 1075–1077 (2009).
- [2] L. Zhuang, C. G. H. Roeloffzen, A. Meijerink, M. Burla, D. A. I. Marpaung, A. Leinse, M. Hoekman, R. G. Heideman, and W. van Etten, “Novel ring resonator-based integrated photonic beamformer for broadband phased array receive antennas—part II: Experimental prototype,” *J. Lightwave Technol.* **28**, 19–31 (2010).
- [3] J. E. Koroshetz, “Fiber lasers for lidar,” in “Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference,” (Optical Society of America, 2005), p. OFJ4.
- [4] C. E. Wieman and L. Hollberg, “Using diode lasers for atomic physics,” *Rev. Sci. Instrum.* **62**, 1–20 (1991).
- [5] L. He, Ş. Özdemir, J. Zhu, W. Kim, and L. Yang, “Detecting single viruses and nanoparticles using whispering gallery microlasers,” *Nat. Nanotechnol.* **6**, 428–432 (2011).
- [6] A. Hemmerich, D. McIntyre, D. Schropp, D. Meschede, and T. Hänsch, “Optically stabilized narrow linewidth semiconductor laser for high resolution spectroscopy,” *Opt. Commun.* **75**, 118 – 122 (1990).
- [7] Y. Jiang, A. Ludlow, N. Lemke, R. Fox, J. Sherman, L.-S. Ma, and C. Oates, “Making optical atomic clocks more stable with 10^{-16} -level laser stabilization,” *Nat. Photon.* **5**, 158–161 (2011).
- [8] C. Henry, “Theory of the linewidth of semiconductor lasers,” *IEEE J. Quantum Electron.* **18**, 259–264 (1982).
- [9] B. Dahmani, L. Hollberg, and R. Drullinger, “Frequency stabilization of semiconductor lasers by resonant optical feedback,” *Opt. Lett.* **12**, 876–878 (1987).
- [10] H. Stoehr, F. Mensing, J. Helmcke, and U. Sterr, “Diode laser with 1 Hz linewidth,” *Opt. Lett.* **31**, 736–738 (2006).

- [11] J. Alnis, A. Matveev, N. Kolachevsky, T. Udem, and T. W. Hänsch, “Sub-hertz linewidth diode lasers by stabilization to vibrationally and thermally compensated ultralow-expansion glass fabry-pérot cavities,” *Phys. Rev. A* **77**, 053809 (2008).
- [12] C. T. Santis, S. T. Steger, Y. Vilenchik, A. Vasilyev, and A. Yariv, “High-coherence semiconductor lasers based on integral high-Q resonators in hybrid Si/III-V platforms,” *Proc. Natl. Acad. Sci. U.S.A.* **111**, 2879–2884 (2014).
- [13] C. Santis, Y. Vilenchik, A. Yariv, N. Satyan, and G. Rakuljic, “Sub-khz quantum linewidth semiconductor laser on silicon chip,” in “CLEO: 2015 Postdeadline Paper Digest,” (Optical Society of America, 2015), p. JTh5A.7.
- [14] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and K.-J. Boller, “25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity,” *Laser. Phys. Lett.* **10**, 015804 (2013).
- [15] Y. Fan, J. P. Epping, R. M. Oldenbeuving, C. G. H. Roeloffzen, M. Hoekman, R. Dekker, R. G. Heideman, P. J. M. van der Slot, and K.-J. Boller, “Optically integrated InP-Si₃N₄ hybrid laser,” *IEEE Photon. J.* **8**, 1–11 (2016).
- [16] B. Liu, A. Shakouri, and J. E. Bowers, “Passive microring-resonator-coupled lasers,” *Appl. Phys. Lett.* **79**, 3561–3563 (2001).
- [17] T. Kita, R. Tang, and H. Yamada, “Compact silicon photonic wavelength-tunable laser diode with ultra-wide wavelength tuning range,” *Appl. Phys. Lett.* **106**, 111104 (2015).
- [18] J. C. Hulme, J. K. Doylend, and J. E. Bowers, “Widely tunable Vernier ring laser on hybrid silicon,” *Opt. Express* **21**, 19718–19722 (2013).
- [19] N. Kobayashi, K. Sato, M. Namiwaka, K. Yamamoto, S. Watanabe, T. Kita, H. Yamada, and H. Yamazaki, “Silicon photonic hybrid ring-filter external cavity wavelength tunable lasers,” *J. Lightw. Technol.* **33**, 1241–1246 (2015).
- [20] T. Matsumoto, A. Suzuki, M. Takahashi, S. Watanabe, S. Ishii, K. Suzuki, T. Kaneko, H. Yamazaki, and N. Sakuma, “Narrow spectral linewidth full band tunable laser based on waveguide ring resonators with low power consumption,” in “Optical Fiber Communication Conference,” (Optical Society of America, 2010), p. OThQ5.
- [21] H. Debregeas, C. Ferrari, M. A. Cappuzzo, F. Klemens, R. Keller, F. Pardo, C. Bolle, C. Xie, and M. P. Earnshaw, “2kHz linewidth C-band tunable laser by hybrid integration of reflective SOA and SiO₂ PLC

- external cavity,” in “2014 International Semiconductor Laser Conference,” (2014), pp. 50–51.
- [22] Y. Fan, R. M. Oldenbeuving, E. J. Klein, C. J. Lee, H. Song, M. R. H. Khan, H. L. Offerhaus, P. J. M. van der Slot, and K.-J. Boller, “A hybrid semiconductor-glass waveguide laser,” in “Proc. SPIE,” , vol. 9135 (2014), vol. 9135, pp. 91351B–91351B–6.
- [23] H. Ou, “Different index contrast silica-on-silicon waveguides by PECVD,” *Electron. Lett.* **39**, 212–213(1) (2003).
- [24] K. Wörhoff, R. Heideman, A. Leinse, and M. Hoekman, “Triplex: A versatile dielectric photonic platform,” *Adv. Opt. Techn.* **4**, 189–207 (2015).
- [25] J. F. Bauters, M. J. R. Heck, D. D. John, J. S. Barton, C. M. Bruinink, A. Leinse, R. G. Heideman, D. J. Blumenthal, and J. E. Bowers, “Planar waveguides with less than 0.1 dB/m propagation loss fabricated with wafer bonding,” *Opt. Express* **19**, 24090–24101 (2011).
- [26] L. Zhuang, D. Marpaung, M. Burla, W. Beeker, A. Leinse, and C. Roeloffzen, “Low-loss, high-index-contrast $\text{Si}_3\text{N}_4/\text{SiO}_2$ optical waveguides for optical delay lines in microwave photonics signal processing,” *Opt. Express* **19**, 23162–23170 (2011).
- [27] J. P. Epping, T. Hellwig, M. Hoekman, R. Mateman, A. Leinse, R. G. Heideman, A. van Rees, P. J. van der Slot, C. J. Lee, C. Fallnich, and K.-J. Boller, “On-chip visible-to-infrared supercontinuum generation with more than 495 THz spectral bandwidth,” *Opt. Express* **23**, 19596–19604 (2015).
- [28] C. G. H. Roeloffzen, L. Zhuang, C. Taddei, A. Leinse, R. G. Heideman, P. W. L. van Dijk, R. M. Oldenbeuving, D. A. I. Marpaung, M. Burla, and K.-J. Boller, “Silicon nitride microwave photonic circuits,” *Opt. Express* **21**, 22937–22961 (2013).
- [29] L. Zhuang, C. G. H. Roeloffzen, M. Hoekman, K.-J. Boller, and A. J. Lowery, “Programmable photonic signal processor chip for radiofrequency applications,” *Optica* **2**, 854–859 (2015).
- [30] R. Tkach and A. Chraplyvy, “Regimes of feedback effects in 1.5- μm distributed feedback lasers,” *J. Lightw. Technol.* **4**, 1655–1661 (1986).
- [31] A. J. Zilkie, P. Seddighian, B. J. Bijlani, W. Qian, D. C. Lee, S. Fatholouloumi, J. Fong, R. Shafiha, D. Feng, B. J. Luff, X. Zheng, J. E. Cunningham, A. V. Krishnamoorthy, and M. Asghari, “Power-efficient III-V/Silicon external cavity DBR lasers,” *Opt. Express* **20**, 23456–23462 (2012).

- [32] S. Tanaka, S.-H. Jeong, S. Sekiguchi, T. Kurahashi, Y. Tanaka, and K. Morito, “High-output-power, single-wavelength silicon hybrid laser using precise flip-chip bonding technology,” *Opt. Express* **20**, 28057–28069 (2012).
- [33] J. H. Lee, I. Shubin, J. Yao, J. Bickford, Y. Luo, S. Lin, S. S. Djordjevic, H. D. Thacker, J. E. Cunningham, K. Raj, X. Zheng, and A. V. Krishnamoorthy, “High power and widely tunable Si hybrid external-cavity laser for power efficient Si photonics WDM links,” *Opt. Express* **22**, 7678–7685 (2014).
- [34] C. Becher, E. Gehrig, and K.-J. Boller, “Spectrally asymmetric mode correlation and intensity noise in pump-noise-suppressed laser diodes,” *Phys. Rev. A* **57**, 3952–3960 (1998).
- [35] N. Hosseini, R. Dekker, M. Hoekman, M. Dekkers, J. Bos, A. Leinse, and R. Heideman, “Stress-optic modulator in triplex platform using a piezoelectric lead zirconate titanate (PZT) thin film,” *Opt. Express* **23**, 14018–14026 (2015).
- [36] S. Latkowski, A. Hänsel, N. Bhattacharya, T. de Vries, L. Augustin, K. Williams, M. Smit, and E. Bente, “Novel widely tunable monolithically integrated laser source,” *IEEE Photon. J.* **7**, 1–9 (2015).
- [37] R. G.694.1., “Spectral grids for WDM applications: DWDM frequency grid,” International Telecommunications Union, Tech. Rep (2012).
- [38] O. Llopis, P. H. Merrer, H. Brahimi, K. Saleh, and P. Lacroix, “Phase noise measurement of a narrow linewidth cw laser using delay line approaches,” *Opt. Lett.* **36**, 2713–2715 (2011).
- [39] G. M. Stéphan, T. T. Tam, S. Blin, P. Besnard, and M. Têtu, “Laser line shape and spectral density of frequency noise,” *Phys. Rev. A* **71**, 043809 (2005).
- [40] N. Bucalovic, V. Dolgovskiy, C. Schori, P. Thomann, G. D. Domenico, and S. Schilt, “Experimental validation of a simple approximation to determine the linewidth of a laser from its frequency noise spectrum,” *Appl. Opt.* **51**, 4582–4588 (2012).
- [41] D. Xu, F. Yang, D. Chen, F. Wei, H. Cai, Z. Fang, and R. Qu, “Laser phase and frequency noise measurement by Michelson interferometer composed of a 3×3 optical fiber coupler,” *Opt. Express* **23**, 22386–22393 (2015).
- [42] M. Osinski and J. Buus, “Linewidth broadening factor in semiconductor lasers—an overview,” *IEEE J. Quantum Electron.* **23**, 9–29 (1987).

- [43] E. H. Bernhardt, H. A. van Wolferen, L. Agazzi, M. R. Khan, C. G. Roeloffzen, K. Wörhoff, M. Pollnau, and R. M. de Ridder, “Ultra-narrow-linewidth, single-frequency distributed feedback waveguide laser in $\text{Al}_2\text{O}_3\text{:Er}^3$ on silicon,” *Opt. Lett.* **35**, 2394–2396 (2010).
- [44] K. Zhang and J. U. Kang, “C-band wavelength-swept single-longitudinal-mode erbium-doped fiber ring laser,” *Opt. Express* **16**, 14173–14179 (2008).
- [45] S. H. Xu, Z. M. Yang, T. Liu, W. N. Zhang, Z. M. Feng, Q. Y. Zhang, and Z. H. Jiang, “An efficient compact 300 mw narrow-linewidth single frequency fiber laser at $1.5\ \mu\text{m}$,” *Opt. Express* **18**, 1249–1254 (2010).
- [46] T. Feng, D. Ding, F. Yan, Z. Zhao, H. Su, and X. S. Yao, “Widely tunable single-/dual-wavelength fiber lasers with ultra-narrow linewidth and high OSNR using high quality passive subring cavity and novel tuning method,” *Opt. Express* **24**, 19760–19768 (2016).
- [47] M. Wahbeh and R. Kashyap, “Purity of the single frequency mode of a hybrid semiconductor-fiber laser,” *Opt. Express* **23**, 16084–16095 (2015).
- [48] D. de Felipe, Z. Zhang, W. Brinker, M. Kleinert, A. M. Novo, C. Zawadzki, M. Moehrl, and N. Keil, “Polymer-based external cavity lasers: Tuning efficiency, reliability, and polarization diversity,” *IEEE Photon. Technol. Lett.* **26**, 1391–1394 (2014).
- [49] P. Dong, T.-C. Hu, T.-Y. Liow, Y.-K. Chen, C. Xie, X. Luo, G.-Q. Lo, R. Kopf, and A. Tate, “Novel integration technique for silicon/III-V hybrid laser,” *Opt. Express* **22**, 26854–26861 (2014).
- [50] S. Srinivasan, M. Davenport, T. Komljenovic, J. Hulme, D. T. Spencer, and J. E. Bowers, “Coupled-ring-resonator-mirror-based heterogeneous III-V silicon tunable laser,” *IEEE Photon. J.* **7**, 1–8 (2015).
- [51] T. Creazzo, E. Marchena, S. B. Krasulick, P. K. L. Yu, D. V. Orden, J. Y. Spann, C. C. Blivin, L. He, H. Cai, J. M. Dallesasse, R. J. Stone, and A. Mizrahi, “Integrated tunable CMOS laser,” *Opt. Express* **21**, 28048–28053 (2013).
- [52] G. H. Duan, C. Jany, A. L. Liepvre, A. Accard, M. Lamponi, D. Make, P. Kaspar, G. Levaufre, N. Girard, F. Lelarge, J. M. Fedeli, A. Descos, B. B. Bakir, S. Messaoudene, D. Bordel, S. Menez, G. de Valicourt, S. Keyvaninia, G. Roelkens, D. V. Thourhout, D. J. Thomson, F. Y. Gardes, and G. T. Reed, “Hybrid III–V on silicon lasers for photonic integrated circuits on silicon,” *IEEE J. Sel. Top. Quantum Electron.* **20**, 158–170 (2014).
- [53] K. Nemoto, T. Kita, and H. Yamada, “Narrow-spectral-linewidth wavelength-tunable laser diode with Si wire waveguide ring resonators,” *Appl. Phys. Express* **5**, 082701 (2012).

- [54] R. Tang, T. Kita, and H. Yamada, “Narrow-spectral-linewidth silicon photonic wavelength-tunable laser with highly asymmetric Mach-Zehnder interferometer,” *Opt. Lett.* **40**, 1504–1507 (2015).
- [55] S. Yang, Y. Zhang, D. W. Grund, G. A. Ejzak, Y. Liu, A. Novack, D. Prather, A. E.-J. Lim, G.-Q. Lo, T. Baehr-Jones, and M. Hochberg, “A single adiabatic microring-based laser in 220 nm silicon-on-insulator,” *Opt. Express* **22**, 1172–1180 (2014).
- [56] S. Keyvaninia, G. Roelkens, D. V. Thourhout, C. Jany, M. Lamponi, A. L. Liepvre, F. Lelarge, D. Make, G.-H. Duan, D. Bordel, and J.-M. Fedeli, “Demonstration of a heterogeneously integrated III-V/SOI single wavelength tunable laser,” *Opt. Express* **21**, 3784–3792 (2013).
- [57] T. Kita, K. Nemoto, and H. Yamada, “Silicon photonic wavelength-tunable laser diode with asymmetric Mach-Zehnder interferometer,” *IEEE J. Sel. Top. Quantum Electron.* **20**, 344–349 (2014).

8

Summary

In this thesis we describe investigations of a novel class of semiconductor-glass waveguide hybrid lasers. We show that such lasers provide an unprecedented spectral purity as well as tunability among all chip-based diode lasers. The concept of the investigated hybrid lasers is based on spectral control of light generated with a laser diode using highly frequency selective, tunable optical feedback provided by an integrated photonic circuit. In this work, we have employed InP laser diodes that generate light at around $1.5\ \mu\text{m}$ wavelength, as an important as well as representative example. The integrated waveguide feedback circuits are based on microring resonators (MRRs). The waveguide platform selected for the feedback circuits utilizes Si_3N_4 as the waveguide core material and SiO_2 as cladding material (*TriPleXTM*), because this provides exceptionally low propagation loss in combination with high index contrast, to enable large optical path lengths (for linewidth narrowing) and sophisticated circuit geometries in a compact, chip-sized format. The main advantages of feedback using low-loss microring resonators, when compared to conventional optical feedback using integrated Bragg gratings, are i) ease in fabrication without requiring complex re-growth nor fine lithography; ii) a significant enhancement of the effective length associated to multiple passes at resonance. Thereby MRRs extend the overall optical length of the laser cavity which narrows the laser emission linewidth; iii) a spectrally sharp filtering characteristic.

A fundamental and well-known property of single-frequency lasers based on resonators is that the spectral purity of the output increases, i.e., its spectral bandwidth decreases, with increasing the photon lifetime in the resonator. In diode lasers this can be achieved to a certain extent by lowering the optical roundtrip losses, while the most effective method is via increasing the resonator length. In Chapter 3, we present a first version of a hybrid laser that possesses reduced roundtrip losses as achieved with an improved optical coupling between

the diode and silicon nitride waveguide mode fields. The optical length of the cavity is increased appreciably from about 1.4 mm (of the solitary diode) to about 9.4 mm. In this particular hybrid laser, to achieve single-frequency oscillation over a wide tuning range via exploiting the Vernier effect, the spectral feedback filtering is based on two small, tunable MRRs of slightly different size (49.5 and 54 μm radius). Already with the MRRs having moderate quality factors ($Q \approx 2000$) the laser shows a strong linewidth reduction, to a 3-dB linewidth of about 24 kHz. With electric tuning of the optical lengths of the MRRs via the thermo-optic effect, the laser wavelength becomes tunable over a range of 45 nm, thereby covering a wide range of the laser's gain spectrum.

To explore the potential of using narrowband amplification as well as frequency and phase synchronization, such as for application in integrated microwave photonics, in Chapter 4 we report the first injection locking experiments with a hybrid laser. We have used these experiments to estimate the Q-factor of the laser cavity. A possible future use of injection locking is the measurement of losses in laser resonators also of complex design, such as the hybrid lasers described here are based upon.

Most of the investigations thus far reported are carried out with the two chips fixed on separate sub-mounts for alignment with regard to each other. However, the full future application potential of so-called hybrid lasers can only be gained with optical integration, i.e., firmly and permanently mounting the chips to each other with high precision and strong optical coupling. In Chapter 5 we report the first integration of an InP-Si₃N₄ hybrid laser. Based on mode overlap calculations and laser rate equations we demonstrate that optical integration of such lasers is feasible with current mounting technology. The integrated hybrid laser shows a clear single-frequency oscillation with wide tunability, and with narrow linewidth at the 100 kHz-level throughout the tuning range. This proves that the underlying facet-to-facet (longitudinal) mode coupling between chips is a viable integration concept.

Systematically and efficiently pursuing the concept of semiconductor-glass waveguide hybrid lasers also requires that the output properties of such lasers can be theoretically predicted. Only when the many parameters entering the functional design of the waveguide feedback circuits are properly chosen based on modeling, a proper performance, such as single-frequency operation and a narrow linewidth, can be expected after fabrication and integration. To aid this process, in Chapter 6 we presented the first theoretical analysis of such hybrid lasers that includes a spatially resolved modeling of the gain section. Using numerical solutions of a transmission line model, a hybrid laser based on a dual-MRR Vernier feedback circuit is investigated. We calculate the laser's frequency noise spectra and obtain the laser's intrinsic linewidth vs the output power. We compare the results with previous theory that takes a spatially inhomogeneous gain distribution in the semiconductor into account via a modification of the mean-field approximation. The comparison shows that higher losses in the optical coupling between the chips requires also spatially-resolving models for index related broadening effects, to enable a proper prediction of the laser

linewidth.

Finally, in Chapter 7 we describe how the expertise gained with modeling, laser-design and experimental investigation is used to realize a semiconductor-glass hybrid laser with a record-low spectral linewidth. Making use of a feedback circuit that involves three MRRs in series and double pass we demonstrate a laser linewidth as low as 290 Hz, which is clearly the narrowest intrinsic linewidth that has ever been achieved with a chip-based diode laser. The same laser also shows a record-wide wavelength tunability, more than 80 nm, i.e. fully covering the gain bandwidth of the laser diode with appreciable output power (up to 13 mW) coupled out of a single mode fiber attached to the laser.

Nederlandse Samenvatting

In dit proefschrift beschrijven we een nieuw type hybride laser gebaseerd op een diodelaser gekoppeld aan een in glas gntegreerd optisch terugkoppelcircuit. We tonen aan dat zulke lasers zowel een ongekend smalle spectrale lijnbreedte als unieke verstemming bieden in vergelijking met alle andere op chips gebaseerde diodelasers.

Het concept van de hybride laser is gebaseerd op de spectrale controle van het licht afkomstig van een laserdiode door middel van zeer frequentie-selectieve, instelbare optische terugkoppeling welke gerealiseerd wordt met behulp van een gntegreerd fotonisch circuit. In dit onderzoek hebben we InP laserdiodes, die licht genereren met een golflengte van ongeveer $1.5\text{ }\mu\text{m}$, gebruikt als belangrijk en representatief voorbeeld. De gntegreerde golfgeleidercircuits voor de feedback zijn gebaseerd op microring resonatoren (MRR). Het gekozen platform (TriPleX) voor de feedbackcircuits bestaat uit golfgeleiders van silicium nitride met een mantel van silicium oxide. Dit platform wordt gekenmerkt door uitzonderlijk lage propagatieverliezen in combinatie met een hoog index-contrast, waardoor zeer lange optische padlengtes (voor het verkleinen van de lijnbreedte) en geavanceerde geometrien realiseerbaar zijn in een compact formaat. De belangrijkste voordelen van terugkoppeling met behulp van MRR-en met lage verliezen in vergelijking met conventionele optische terugkoppeling via gntegreerde Bragg tralies zijn i) eenvoudige fabricage waarbij hergroei en precisie-lithografie niet vereist zijn; ii) een significante verhoging van de effectieve lengte omdat er bij resonantie sprake is van meerdere rondgangen van het licht in de ring. Hierdoor verhogen een of meerdere MRR-en de totale optische lengte van de laser-trilholte, zodat de lijnbreedte van de laserstraling smaller wordt; iii) nauwbandige spectrale filtering.

Een fundamentele en zeer bekende eigenschap van monochrome lasers gebaseerd op resonatoren is dat een langere levensduur van een foton in de resonator leidt tot een hogere spectrale zuiverheid, dat wil zeggen, een kleinere spectrale bandbreedte. In een diodelaser kan dit tot op zekere hoogte bereikt worden door het verlagen van het rondloopverlies, echter het vergroten van de resonatorlengte is de effectiefste methode. In Hoofdstuk 3 beschrijven we een eerste versie van een hybride laser met verlaagde rondloopverliezen, wat bereikt werd door de transversale lichtverdeling (transversale mode) in de diode en de silicium nitride golfgeleider beter op elkaar af te stemmen. De optische lengte van de trilholte van deze laser is aanzienlijk toegenomen, van ongeveer 1.4 mm

(voor de diode zelf) naar ongeveer 9.4 mm. Om via het Vernier effect oscillatie op een enkele, breed instelbare frequentie te bereiken is de spectrale filtering in deze laser gebaseerd op twee kleine, instelbare MRR-en met net verschillende straal (radii van 49.5 en 54 μm). Zelfs met MRR-en met een beperkte kwaliteitsfactor ($Q \approx 2000$) vertoont de laser een sterk verlaagde lijnbreedte van ongeveer 24 kHz. Via verwarmingselementen boven de MRR-en en het thermo-optisch effect kan de optische padlengte elektronisch geregeld worden, en kan de golflengte van de laser ingesteld worden over een bereik van 45 nm. Dit bereik komt bijna overeen met het bereik waarover de laserdiode licht kan versterken.

Om het potentieel van smalbandige versterking en frequentie- en fasesynchronisatie te verkennen, bijvoorbeeld voor toepassingen in de gegtegreerde microgolf-fotonica, presenteren we in Hoofdstuk 4 de eerste injection locking experimenten met een hybride laser. We hebben deze experimenten gebruikt om de Q-factor van de laser-trilholte te schatten. Een mogelijke toepassing van injection locking is dat hiermee de verliezen bepaald kunnen worden van zowel eenvoudige als complexe resonatoren, bijvoorbeeld van resonatoren zoals gebruikt in de hybride lasers die in dit proefschrift beschreven worden.

Het tot dusver gerapporteerde onderzoek is grotendeels uitgevoerd met de laserdiode en terugkoppelchip gemonteerd op aparte uitlijntafels. Echter, het volledige potentieel van hybride lasers voor toekomstige toepassingen komt alleen tot wasdom door gebruik te maken van optische integratie, dat wil zeggen, waarbij de chips, met hoge nauwkeurigheid en goede optische koppeling, stevig en permanent aan elkaar bevestigd worden.

In Hoofdstuk 5 presenteren we de eerste integratie van een hybride InP-Si₃N₄ laser. Door het berekenen van de koppeling tussen de lichtvelden in de InP diodelaser en de Si₃N₄ golfgeleider te combineren met het berekenen van het laservermogen via de zogenaamde rate equations, tonen we aan dat hybride optische integratie van dit soort lasers haalbaar is met huidige montagetechnieken. De gegtegreerde hybride laser oscilleert op een enkele frequentie met een lijnbreedte van ongeveer 100 kHz, welke ingesteld kan worden over een breed bereik. Dit bewijst dat het onderliggende concept, het koppelen van (longitudinale) modes tussen twee chipfacetten, een bruikbare integratiemethode is.

Om het concept van hybride gegtegreerde lasers van halfgeleiders en glas op een systematische en efficiënte manier te verkennen, is het nodig dat de eigenschappen van dit soort lasers theoretisch voorspeld kunnen worden. De theoretische modellen kunnen gebruikt worden om de juiste waarde van de vele ontwerpparameters van het terugkoppelcircuit vast te stellen, zodat verwacht mag worden dat de laser, na de fabricage en integratie, oscilleert op de juiste enkele golflengte met de correcte smalle lijnbreedte. Om dit proces te bevorderen, beschrijven we in Hoofdstuk 6 de eerste theoretische analyse van een hybride laser, waarbij een transmissielijn model gebruikt wordt voor het modelleren van de ruimtelijke verdeling van de versterking. De numerieke oplossing van dit

transmissielijn model wordt gebruikt om een hybride laser met een terugkoppelcircuit bestaande uit twee MRR-en te onderzoeken. We berekenen het spectrum van de ruisfrequenties en daarmee de intrinsieke lijnbreedte van de laser. We vergelijken de resultaten met een bestaand model gebaseerd op de gemiddelde-veld benadering, welke is aangepast om rekening te houden met een ruimtelijk inhomogene verdeling van de versterking in de halfgeleider. De vergelijking toont aan dat, als er sprake is van een hoog optisch koppelingsverlies tussen de chips, modellering van de ruimtelijke verdeling van brekingsindex gerelateerde effecten noodzakelijk is om de lijnbreedte correct te voorspellen.

Ten slotte beschrijven we in Hoofdstuk 7 hoe de opgebouwde expertise in modellering, laserontwerp en experimenteel onderzoek is toegepast om een hybride halfgeleider-glas-laser te realiseren met een ultrasnelle lijnbreedte. Met een terugkoppelcircuit bestaande uit drie MRR-en in serie, die tweemaal worden doorlopen, demonstreren we oscillatie op een enkele golflengte met een extreem smalle lijnbreedte van 290 Hz, onmiskenbaar de smalste intrinsieke lijnbreedte ooit behaald met een op chips gebaseerde diodelaser. De golflengte kan ingesteld worden over een recordbereik van 80 nm, wat correspondeert met de volledige versterkingsbandbreedte van de diodelaser. De hybride laser heeft een aanzienlijk uitgangsvermogen van maximaal 13 mW, gemeten aan het uiteinde van een single-mode glasvezel die aan de laser is vastgehecht.

9

Conclusions

Conclusions

Based on the achievements that are described in this thesis, we conclude that semiconductor-silicon nitride (glass) hybrid waveguide lasers show a great potential for use in a large number of applications. Providing an extensive list and according discussion is difficult and also beyond the scope of this thesis. A coarse division may be based upon the laser wavelength.

Regarding the wide spectral coverage and wide wavelength tunability, we see a high potential for spectroscopic, metrological and sensing applications. The generality of the concept of longitudinal integration using facet-to-facet coupling principally makes the entire transparency range of the used $\text{Si}_3\text{N}_4/\text{SiO}_2$ waveguides accessible, which ranges from the visible (about 400 nm) to the mid-infrared (at least 2.5 μm , Si_3N_4 itself even to about 7 μm). For this purpose a next step is to apply the concept also with semiconductor amplifier chips based on materials other than InP, such as GaN, GaAs, InGaAsSb/AlGaAsSb, with an according modification of the waveguide and coupler parameters.

Regarding the relative narrow telecom wavelength around 1.5 μm we discuss briefly the options for three examples related to communication systems, where we expect a significant impact of the chip-size hybrid lasers. In these applications, the size, weight, electrical-to-optical efficiency, robustness and intrinsically low susceptibility to perturbing vibrations are of high importance.

As the first example, the extremely narrow linewidth from a chip-sized diode laser might be exploited for future fiber-optic communication systems as local oscillator for advanced modulation formats. For these systems, the Lorentzian component of the laser lineshape is the relevant component because it is usually directly related to the performance (e.g., bit error rate). The influence of the excess frequency noise at low noise frequencies can be neglected, particularly at high bit rate systems [1, 2]. Therefore, the narrowing of the Lorentzian component, i.e., the Schawlow-Townes limit, is highly desired. When aiming at such linewidth-narrowing, the approach investigated in this thesis appears quite promising, as it enables the realization of chip-based laser sources with narrow Lorentzian linewidths.

For application in space telecommunication [3], it becomes necessary to equip the laser with long-term stability, which reduces frequency noise at low-noise frequency (e.g., thermal drifts and vibrations). However, reducing such noise, first of all, requires a proper identification and characterization of the contributing noise sources. A first step in this direction is the recording of frequency noise spectra as described in Chapter 7. Reducing the noise at low frequencies will, e.g., require an improved temperature stabilization and using low-noise pump current sources. For further noise reduction, one has to consider to frequency stabilize these hybrid lasers. Such frequency stabilization can be achieved using different techniques, such as locking the laser frequency to a reference cavity [4] or to an absolute frequency reference, e.g., an acetylene (C_2H_2) Doppler-free absorption line [5]. Given that it is easier to realize servo

loops that suppress slow noise such as below 1 MHz [6], the feasibility of stabilizing the hybrid laser appears promising, because the noise density lies above the Shawlow-Townes limit only at low frequencies, below 500 kHz (Chapter 7).

A third field of application, where the integrated hybrid laser would become centrally relevant, is microwave photonics. This field is actually the wider project framework within which the work of this thesis was carried out [7]. In this project the goal is to demonstrate the technological feasibility of a fully integrated optical beamforming network (OBFN). Such modules aim on controlling, with optical means on photonic chips, the output direction and the direction of reception in microwave antenna arrays, to be used in satellite communications or in local wireless mobile phone networks [8].

Previous efforts have focused on optimizing only the passive functionalities of OBFNs. The other essential components, specifically, the lasers used to generate optical carriers and local oscillators had remained external devices [9], which has two strong disadvantages. The use of external lasers inevitably induces extra coupling losses which reduces the usable laser power and thus the signal throughput. Furthermore, using external lasers dramatically increases the size of the whole system.

An on-chip realization of the entire system that can remove these disadvantage is shown in Fig. 9.1 [8]. The system is based on optically integrating an active platform (that amplifies light and modulates it using InP) and a passive platform (that provides adjustable optical delay, splitting and combining). The hybrid laser in this fully integrated OBFN device forms a central part of the system, where the subsequent functionalities, i.e., modulation and detection (on the InP chip) as well as filtering and delay (on the Si_3N_4 chip), hinge on the laser performance.

Both types of involved chips have been designed and fabricated, with the InP chips fabricated via so-called multi-project wafer runs provided by *Oclaro* whereas the Si_3N_4 chips were fabricated by *LioniX* using their TriPleXTM technology. Currently, samples of the fabricated InP and Si_3N_4 chips are being tested in preparation for a fully integrated system, which forms an essential aspect of near-future work. For the far future, such OBFN systems also appear to be rather important components that can provide unprecedented bandwidth with low power consumption for the next generation 5G mobile phone networks [10, 11].

Figure 9.1: Fully integrated hybrid InP and Si_3N_4 optical beamforming module, as an example for a complex microwave photonic system. The shown module is designed to control the direction of transmission of a phase array antenna [8] Highlighted with the red dashed line is the on-chip hybrid laser controlled via two microring resonators (MRRs) in Vernier configuration. The other components are a modulator for signal input (green rectangle), a tree-shaped delay circuit based on tunable MRRs (green dashed line) and an array of photodetectors that feed the elements of the transmission antenna array.

Bibliography

- [1] K. Kikuchi, “Characterization of semiconductor-laser phase noise and estimation of bit-error rate performance with low-speed offline digital coherent receivers,” *Opt. Express* **20**, 5291–5302 (2012).
- [2] D. Zhang, J. Zhao, Q. Yang, W. Liu, Y. Fu, C. Li, M. Luo, S. Hu, Q. Hu, and L. Wang, “Compact MEMS external cavity tunable laser with ultra-narrow linewidth for coherent detection,” *Opt. Express* **20**, 19670–19682 (2012).
- [3] L. Bartelt-Berger, F. Heine, U. Hildebrand, D. Lange, S. Seel, T. Schwinder, and B. Smutny, “Space qualified ultra stable laser source,” in “Technical Digest. Summaries of papers presented at the Conference on Lasers and Electro-Optics. Postconference Technical Digest (IEEE Cat. No.01CH37170),” (2001), pp. 580–581.
- [4] J. Alnis, A. Matveev, N. Kolachevsky, T. Udem, and T. W. Hänsch, “Sub-hertz linewidth diode lasers by stabilization to vibrationally and thermally compensated ultralow-expansion glass fabry-pérot cavities,” *Phys. Rev. A* **77**, 053809 (2008).
- [5] K. Numata, J. Camp, M. A. Krainak, and L. Stolpner, “Performance of planar-waveguide external cavity laser for precision measurements,” *Opt. Express* **18**, 22781–22788 (2010).
- [6] P. Samutpraphoot, S. Weber, Q. Lin, D. Gangloff, A. Bylinskii, B. Braverman, A. Kawasaki, C. Raab, W. Kaenders, and V. Vuletić, “Passive intrinsic-linewidth narrowing of ultraviolet extended-cavity diode laser by weak optical feedback,” *Optics express* **22**, 11592–11599 (2014).
- [7] Rijksdienst voor Ondernemend Nederland, ‘IOP Photonic Devices’, <http://www.rvo.nl/subsidies-regelingen/iop-photonic-devices>
- [8] C. G. H. Roeloffzen, L. Zhuang, C. Taddei, A. Leinse, R. G. Heideman, P. W. L. van Dijk, R. M. Oldenbeuving, D. A. I. Marpaung, M. Burla, and K.-J. Boller, “Silicon nitride microwave photonic circuits,” *Opt. Express* **21**, 22937–22961 (2013).
- [9] L. Zhuang, C. G. H. Roeloffzen, A. Meijerink, M. Burla, D. A. I. Marpaung, A. Leinse, M. Hoekman, R. G. Heideman, and W. van Etten,

- “Novel ring resonator-based integrated photonic beamformer for broadband phased array receive antennas—part II: Experimental prototype,” *J. Lightwave Technol.* **28**, 19–31 (2010).
- [10] J. S. Fandiño, P. Muñoz, D. Doménech, and J. Capmany, “A monolithic integrated photonic microwave filter,” *Nature Photonics* (2016).
- [11] 5Gppp, “5G innovations for new business opportunities,” 5G-PPP White paper (2017).

List of publications

Journal articles

- **Y. Fan**, R. E.M. Lammerink, R. M. Oldenbeuving, P. J.M. van der Slot, and K.-J. Boller, "*Spectral linewidth analysis of semiconductor hybrid lasers with feedback from an external waveguide resonator circuit*," in preparation (2017).
- **Y. Fan**, A. Dräbenstedt, V. Seyfried, R. M. Oldenbeuving, M. Hoekman, D. Geskus, R. Dekker, R. G. Heideman, C. G.H. Roeloffzen and K.-J. Boller, "*290 Hz intrinsic linewidth of a chip-based widely tunable InP-Si₃N₄ hybrid laser*," in preparation (2017).
- **Y. Fan**, J. P. Epping, R. M. Oldenbeuving, C. G.H. Roeloffzen, M. Hoekman, R. Dekker, R. G. Heideman, P. J.M. van der Slot and K.-J. Boller, "*Optically integrated InP-Si₃N₄ hybrid laser*," IEEE Photonics Journal, **8**(6) (2016).
- **Y. Fan**, R. M. Oldenbeuving, M. R.H. Khan, C. G.H. Roeloffzen, E. J. Klein, C. J. Lee, H. L. Offerhaus, and K.-J. Boller, "*Q-factor measurements through injection locking of a semiconductor-glass hybrid laser with unknown intracavity losses*," Optics Letters **39**(7), 1748 (2014).

Refereed international conference proceedings

- **Y. Fan**, J. P. Epping, R. M. Oldenbeuving, C. G.H. Roeloffzen, M. Hoekman, R. Dekker, R. G. Heideman, P. J.M. van der Slot and K.-J. Boller, "*Optically integrated InP-Si₃N₄ hybrid laser*," IEEE Summer Topicals Meeting Series, Newport Beach, California (USA) (2016).
- J. Zhao, R. M. Oldenbeuving, J. P. Epping, M. Hoekman, R. G. Heideman, R. Dekker, **Y. Fan**, K.-J. Boller, R. Ji, S. Fu, L. Zeng, "*Narrow-linewidth widely tunable hybrid external cavity laser using Si₃N₄/SiO₂ microring resonators*," 13th International Conference on Group IV Photonics, Shanghai, China (2016) (2016).
- **Y. Fan**, Y. Klaver, V. Moskalenko, E. A.J.M. Bente, J. Javaloyes, P. J.M. van der Slot, K.-J. Boller, "*Modelling of a passively modelocked*

- semiconductor-glass waveguide hybrid laser*," Proceedings of the 20th Annual Symposium of the IEEE Photonics Benelux Chapter , 129-132, Brussels, Belgium (2015).
- **Y. Fan**, R. M. Oldenbeuving, P. J.M. van der Slot, and K.-J. Boller, " *A semiconductor-glass waveguide hybrid laser with ultra-long cavity length*," Proceedings of the 20th Annual Symposium of the IEEE Photonics Benelux Chapter , 121-124, Brussels, Belgium (2015).
 - **Y. Fan**, R. M. Oldenbeuving, D. H. Geuzebroek, A. Leinse, P. J.M. van der Slot, K.-J. Boller, " *Glass waveguide-semiconductor hybrid lasers*," European Conference on Lasers and Electro-Optics and the International Quantum Electronics Conference, paper CJ-12.2, Munich, Germany (2015).
 - **Y. Fan**, R. M. Oldenbeuving, E. J. Klein, C. J. Lee, H. Song, M. R.H. Khan, H. L. Offerhaus, P. J.M. van der Slot and K.-J. Boller, " *A hybrid semiconductor-glass waveguide laser*," SPIE Proceedings 9135, 91351B, Brussels, Belgium (2014) **Best student paper**.

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