Multiwave-mode-locked solid-state lasers with up to 100 GHz, applied in a novel broadband telecom source

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MULTIWAVE – MODE-LOCKED SOLID-STATE LASERS WITH UP TO 100 GHZ, APPLIED IN A NOVEL BROADBAND TELECOM SOURCE

A dissertation submitted to

ETH ZURICH

for the degree of

DOCTOR OF SCIENCES

presented by

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December 2009
# Table of Contents

*Symbols and Abbreviations* ................................................................. VII  
*List of Figures* ................................................................................ XI  
*List of Tables* .................................................................................. XIII  
*Publications* ................................................................................... XV  
*Abstract* .......................................................................................... XVIII  
*Kurzfassung* ................................................................................... XX  

Chapter 1  
Introduction and motivation ......................................................... 1  

Chapter 2  
Passive mode-locking at high repetition rates ............................. 7  
  2.1 Principle modes of laser operation ........................................... 7  
  2.2 Mechanisms of passive mode-locking ....................................... 10  
    2.2.1 Fast saturable absorber .................................................... 11  
    2.2.2 Slow saturable absorber with dynamic gain saturation ....... 12  
    2.2.3 Slow saturable absorber with weak gain saturation .......... 12  
  2.3 Stability criterion for passive mode-locking ......................... 13  
  2.4 Semiconductor Saturable Absorber Mirror ......................... 15  
    2.4.1 Macroscopic properties .................................................. 16  
    2.4.2 SESAM structure .......................................................... 21  

Chapter 3  
SESAM characterization ................................................................. 27  
  3.1 Measurement setup ................................................................. 27  
  3.2 Alignment and calibration ....................................................... 30  
  3.3 Results .................................................................................... 32  

Chapter 4  
High repetition rate Er,Yb:glass lasers at 1.5 µm ......................... 35  
  4.1 Multi-GHz pulse sources at 1.5 µm ....................................... 35  
  4.2 Properties of Er,Yb:glass ......................................................... 38  
  4.3 Laser design considerations ............................................... 40
TABLE OF CONTENTS

4.3.1 Laser cavity design ........................................................................................ 40
4.3.2 Pumping considerations ............................................................................... 42
4.3.3 Pulse shaping ................................................................................................. 43

4.4 Er,Yb:glass lasers with 10-50 GHz ............................................................................. 44
4.4.1 Experimental setup ........................................................................................ 44
4.4.2 Results ............................................................................................................. 46

4.5 100-GHz Er,Yb:glass laser ........................................................................................... 47
4.5.1 Experimental setup ........................................................................................ 47
4.5.2 Results ............................................................................................................. 49
4.5.3 Post growth SESAM optimization .............................................................. 51
4.5.4 Laser result after SESAM optimization ...................................................... 54
4.5.5 Conclusion ...................................................................................................... 56

4.6 Overview of achieved results..................................................................................... 57
4.7 Design guidelines for high repetition rate lasers .................................................... 58

Chapter 5 Transverse mode degeneration effects 61
5.1 Transverse mode degeneracies in a 100-GHz laser ................................................ 61
5.1.1 Experimental identification of mode degeneracies .................................. 61
5.1.2 Theoretical determination of degenerate cavities ..................................... 64
5.1.3 Conclusion ...................................................................................................... 66

Chapter 6 Towards monolithic integration 69
6.1 10-GHz Er,Yb:YAB laser ............................................................................................. 71
6.1.1 Material properties of Er,Yb:YAB ................................................................. 72
6.1.2 Experimental setup ........................................................................................ 73
6.1.3 Results ............................................................................................................. 73
6.1.4 Conclusion ...................................................................................................... 74

6.2 QD-SESAM with lower $F_{sat}$ ............................................................................ 76
6.2.1 QD-SESAM design ........................................................................................ 77
6.2.2 Post-growth processing by chemical etching ............................................ 78
6.2.3 Preliminary results ........................................................................................ 80
6.2.4 Conclusion ...................................................................................................... 81
### Chapter 7  Multi-wavelength source

7.1 Concept of a multi-wavelength source ................................................................. 84
7.2 12.5-GHz and 25-GHz packaged ERGO lasers ..................................................... 88
   7.2.1 Spectral properties .......................................................................................... 90
   7.2.2 Wavelength tuning ....................................................................................... 95
   7.2.3 Wavelength locking ..................................................................................... 96
   7.2.4 Lifetime and temperature cycling .............................................................. 99
7.3 Integrated EDFA ...................................................................................................... 101
   7.3.1 Single-mode fiber amplifier ........................................................................ 101
   7.3.2 Polarization-maintaining fiber amplifier .................................................... 105
   7.3.3 Performance of integrated design .............................................................. 108
7.4 Spectral broadening ............................................................................................... 109
   7.4.1 Properties of highly nonlinear photonic crystal fiber ............................... 109
   7.4.2 Broadening-results for a 12.5 GHz comb .................................................. 110
   7.4.3 Broadening-results for a 25 GHz comb ..................................................... 111
   7.4.4 Conclusion .................................................................................................. 112
7.5 Mode selection ...................................................................................................... 112
   7.5.1 Fabry-Pérot filters ....................................................................................... 113
   7.5.2 Results of filtered frequency combs .......................................................... 115
7.6 System performance ............................................................................................. 116
   7.6.1 Comb control and wavelength locking of MWS ..................................... 116
   7.6.2 Spectral properties of MWS ................................................................. 122
   7.6.3 Results of transmission experiments ....................................................... 126
   7.6.4 Failure modes of the MultiWave source ................................................ 128

### Chapter 8  Conclusion and outlook

Total references: 141
Symbols and Abbreviations

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>absorption coefficient [m$^{-1}$]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>gain inversion parameter</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength [m]</td>
</tr>
<tr>
<td>$\xi_{\text{abs}}$</td>
<td>relative field enhancement in absorber region</td>
</tr>
<tr>
<td>$\tau$</td>
<td>recovery time [s]</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>pulse duration [s]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>optical frequency [rad·s$^{-1}$]</td>
</tr>
<tr>
<td>$A$</td>
<td>mode area [m$^2$]</td>
</tr>
<tr>
<td>$c_0$</td>
<td>vacuum speed of light [m·s$^{-1}$]</td>
</tr>
<tr>
<td>$d$</td>
<td>layer thickness, distance [m]</td>
</tr>
<tr>
<td>$E$</td>
<td>energy [J], time varying electrical field [V·m$^{-1}$]</td>
</tr>
<tr>
<td>$E_p$</td>
<td>pulse energy [J]</td>
</tr>
<tr>
<td>$E_{\text{sat}}$</td>
<td>saturation energy [J]</td>
</tr>
<tr>
<td>$f_{\text{CEO}}$</td>
<td>carrier-envelope offset frequency [Hz]</td>
</tr>
<tr>
<td>$\phi_{\text{CEO}}$</td>
<td>carrier-envelope offset phase [rad]</td>
</tr>
<tr>
<td>$f_{\text{rep}}$</td>
<td>repetition rate [Hz]</td>
</tr>
<tr>
<td>$F$</td>
<td>fluence [J·m$^{-2}$], finesse</td>
</tr>
<tr>
<td>$F_2$</td>
<td>induced absorption coefficient [J·m$^{-2}$]</td>
</tr>
<tr>
<td>$F_p$</td>
<td>pulse fluence [J·m$^{-2}$], defined as $E_p/\left(\pi\omega^2\right)$</td>
</tr>
<tr>
<td>$F_{\text{sat}}$</td>
<td>saturation fluence [J·m$^{-2}$]</td>
</tr>
<tr>
<td>$g$</td>
<td>gain</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck’s constant [J·s]</td>
</tr>
<tr>
<td>$I$</td>
<td>intensity [W·m$^{-2}$]</td>
</tr>
<tr>
<td>$L$</td>
<td>cavity length [m]</td>
</tr>
<tr>
<td>$m_{L}$</td>
<td>number of passes through gain medium</td>
</tr>
<tr>
<td>$n$</td>
<td>refractive index</td>
</tr>
</tbody>
</table>
VIII    SYMBOLS AND ABBREVIATIONS

ν          frequency
N          carrier density [m$^3$]
P          power [W]
r          radius [m]
R          intensity reflectivity
$R_{\text{lin}}$          linear reflectivity
$R_{\text{ns}}$          non-saturable reflectivity
$\Delta R$          modulation depth
$\Delta R_{\text{ns}}$          non-saturable losses
σ          cross section [m$^2$]
S          saturation parameter
T          intensity transmission
$T_R$          cavity roundtrip time [s]
z          position coordinate (in direction of beam) [m]
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>analog-to-digital</td>
</tr>
<tr>
<td>ASE</td>
<td>amplified spontaneous emission</td>
</tr>
<tr>
<td>BER</td>
<td>bit-error-rate</td>
</tr>
<tr>
<td>CEO</td>
<td>carrier-envelope offset</td>
</tr>
<tr>
<td>CEP</td>
<td>carrier-envelope phase</td>
</tr>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>DBR</td>
<td>distributed Bragg reflector</td>
</tr>
<tr>
<td>DEMUX</td>
<td>de-multiplex(ER)</td>
</tr>
<tr>
<td>DFB</td>
<td>distributed feedback</td>
</tr>
<tr>
<td>DI</td>
<td>de-ionized</td>
</tr>
<tr>
<td>DWDM</td>
<td>dense wavelength division multiplexing</td>
</tr>
<tr>
<td>EDFA</td>
<td>erbium doped fiber amplifier</td>
</tr>
<tr>
<td>ERGO</td>
<td>Er,Yb:glass oscillator</td>
</tr>
<tr>
<td>FSR</td>
<td>free spectral range</td>
</tr>
<tr>
<td>FWHM</td>
<td>full-width half-maximum</td>
</tr>
<tr>
<td>GDD</td>
<td>group delay dispersion</td>
</tr>
<tr>
<td>GTP</td>
<td>Glan-Thompson polarizer</td>
</tr>
<tr>
<td>HNLF</td>
<td>highly non-linear fiber</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>KLM</td>
<td>Kerr-lens mode-locking</td>
</tr>
<tr>
<td>MBE</td>
<td>molecular-beam epitaxy</td>
</tr>
<tr>
<td>ML</td>
<td>mode-locked</td>
</tr>
<tr>
<td>MOVPE</td>
<td>metal-organic vapor phase epitaxy</td>
</tr>
<tr>
<td>MSA</td>
<td>microwave spectrum analyzer</td>
</tr>
<tr>
<td>MUX</td>
<td>multiplex(ER)</td>
</tr>
<tr>
<td>MWS</td>
<td>multi wavelength source</td>
</tr>
<tr>
<td>OP</td>
<td>optically pumped</td>
</tr>
<tr>
<td>OPO</td>
<td>optical parametric oscillator</td>
</tr>
<tr>
<td>OSA</td>
<td>optical spectrum analyzer</td>
</tr>
<tr>
<td>OSNR</td>
<td>optical signal-to-noise ratio</td>
</tr>
<tr>
<td>Symbol</td>
<td>Abbreviation</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>OTDM</td>
<td>optical time division multiplexing</td>
</tr>
<tr>
<td>PBS</td>
<td>polarizing beam splitter</td>
</tr>
<tr>
<td>PCF</td>
<td>photonic crystal fiber</td>
</tr>
<tr>
<td>PD</td>
<td>photodiode</td>
</tr>
<tr>
<td>PGL</td>
<td>pulse generating laser</td>
</tr>
<tr>
<td>PI</td>
<td>proportional-integral (controller)</td>
</tr>
<tr>
<td>PM</td>
<td>polarization maintaining</td>
</tr>
<tr>
<td>PRBS</td>
<td>pseudo-random binary sequence</td>
</tr>
<tr>
<td>QD</td>
<td>quantum dot</td>
</tr>
<tr>
<td>QML</td>
<td>Q-switched mode-locking</td>
</tr>
<tr>
<td>QW</td>
<td>quantum well</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RIN</td>
<td>relative intensity noise</td>
</tr>
<tr>
<td>RZ</td>
<td>return-to-zero</td>
</tr>
<tr>
<td>SC</td>
<td>supercontinuum</td>
</tr>
<tr>
<td>SESAM</td>
<td>semiconductor saturable absorber mirror</td>
</tr>
<tr>
<td>SSL</td>
<td>solid-state laser</td>
</tr>
<tr>
<td>SMF</td>
<td>single-mode fiber</td>
</tr>
<tr>
<td>TBP</td>
<td>time-bandwidth product</td>
</tr>
<tr>
<td>TEC</td>
<td>thermo-electric cooler</td>
</tr>
<tr>
<td>VECSEL</td>
<td>vertical external-cavity surface emitting laser</td>
</tr>
<tr>
<td>WDM</td>
<td>wavelength division multiplexing</td>
</tr>
<tr>
<td>YAB</td>
<td>yttrium-aluminum triborate</td>
</tr>
</tbody>
</table>
List of Figures

Figure 2.1: Different temporal regimes of laser operation. 8
Figure 2.2: Three typical mode-locking mechanisms using a saturable absorber. 11
Figure 2.3: Typical nonlinear reflectivity and temporal behavior of a SESAM. 17
Figure 2.4: Nonlinear reflectivity curve including inverse saturable absorption. 19
Figure 2.5: Schematic of a SESAM structure. 22
Figure 2.6: Properties of an antiresonant SESAM. 24
Figure 2.7: Properties of a resonant SESAM. 25
Figure 2.8: Properties of an anti-reflection coated SESAM. 26
Figure 3.1: Experimental setup used to characterize the macroscopic SESAM properties. 28
Figure 3.2: Measured photodiode signal showing four different states. 30
Figure 3.3: Nonlinear reflectivity measurement of a calibration SESAM. 31
Figure 3.4: Calibration curve and measurement of a SESAM with low modulation depth. 33
Figure 4.1: Performance of competing GHz-sources emitting in the 1.5 µm spectral region. 36
Figure 4.2: Interaction cross sections and calculated gain spectra of Er,Yb:glass. 40
Figure 4.3: Photograph of several strongly curved mirrors used in different laser designs. 41
Figure 4.4: Calculated pulse duration versus modulation depth ΔR. 43
Figure 4.5: Schematic layout and photograph of a 50-GHz Er,Yb:glass laser cavity. 45
Figure 4.6: Optical properties of a 50-GHz Er,Yb:glass laser. 46
Figure 4.7: Schematic layout and photograph of a 101-GHz Er,Yb:glass laser cavity. 48
Figure 4.8: Calculated beam divergence in dependence of the cavity folding angle. 48
Figure 4.9: Properties of a 101-GHz Er,Yb:glass laser. 50
Figure 4.10: Mode-locked optical output power and efficiency of a 101-GHz Er:Yb:glass laser. 50
Figure 4.11: Nonlinear reflectivity measurements for resonant and antireflection coated SESAM. 52
Figure 4.12: Dispersion curves for different SESAM structures. 52
Figure 4.13: Nonlinear reflectivity measurements of antireflection coated SESAMs. 53
Figure 4.14: Properties of a 101-GHz Er:Yb:glass laser with optimized SESAM. 55
Figure 5.1: Stability range of a 100-GHz laser cavity with power oscillations and large drops. 62
Figure 5.2: Beam quality degradation associated with reduced output power. 63
Figure 5.3: Comparison of calculated and measured degeneration points of a 100-GHz cavity. 66
Figure 6.1: Monolithic cavity designs for high repetition rate lasers. 69
Figure 6.2: Polarized absorption and emission cross-section spectra of Er,Yb:YAB. 72
Figure 6.3: Optical properties of the first 10-GHz Er,Yb:YAB laser. 73
Figure 6.4: Calculated σ-polarized gain coefficient curves for different inversion parameters β. 75
Figure 6.5: QML output from Er,Yb:YAB laser operating at 1602 nm. 76
Figure 6.6: Design of QD-SESAMs with one and two QD layers. 78
Figure 6.7: Linear reflectivity of resonant QD-SESAMs. 79
Figure 6.8: Post-growth SESAM tuning by chemical etching. 80
Figure 6.9: Nonlinear reflectivity measurements of QD-SESAMs with tuned resonance. 81
Figure 7.1: Simplified schematic of a standard WDM transmission system. 84
Figure 7.2: Simplified schematic of a WDM system deploying a multi-wavelength source. 85
Figure 7.3: Output of a 25-GHz modelocked laser in the time- and frequency domain. 86
Figure 7.4: Fundamental building blocks of a MWS. 87
Figure 7.5: Breadboard setup and packaged version of a 12.5-GHz ERGO cavity. 88
Figure 7.6: Spectral intensity of a 12.5-GHz ERGO with OSNR >40 dB. 90
Figure 7.7: Beating measurement principle for two mode-locked lasers. 91
Figure 7.8: Beating measurement of a 25-GHz and a 12.5-GHz laser. 93
Figure 7.9: Beating measurement of a 25-GHz and a cw DFB laser. 94
Figure 7.10: Relative intensity noise of a 25-GHz ERGO laser. 95
Figure 7.11: Wavelength tuning performance of a 12.5-GHz ERGO laser. 96
Figure 7.12: Block diagram of an active feedback loop for wavelength locking an ERGO laser. 97
Figure 7.13: Wavelength deviation measurement of a wavelength locked 12.5-GHz ERGO laser. 98
Figure 7.14: Output power of an ERGO laser recorded over 1560 hours. 99
Figure 7.15: Temperature cycling results for a 12.5-GHz ERGO laser. 100
Figure 7.16: Block-diagram of a typical layout used in the EDFA simulations. 102
Figure 7.17: Simulation results for an EDFA implementing doped SM-fiber. 103
Figure 7.18: Spectral properties of an EDFA using SM active fiber. 104
Figure 7.19: Simulation results for an EDFA implementing doped PM-fiber. 105
Figure 7.20: EDFA output power for both design approaches in comparison. 106
Figure 7.21: Spectral properties of an EDFA using PM active fiber. 107
Figure 7.22: Spectral properties of an integrated EDFA using PM-active fiber. 108
Figure 7.23: Microstructure and dispersion profile of a photonic crystal fiber. 110
Figure 7.24: Broadened optical spectrum form a 12.5-GHz laser. 111
Figure 7.25: Broadened optical spectrum from a 25-GHz laser. 112
Figure 7.26: Transmission function of an ideal etalon. 114
Figure 7.27: Spectrally filtered optical spectrum with 100-GHz and 50-GHz channel spacing. 116
Figure 7.28: Carrier-envelope offset of individual laser pulses. 117
Figure 7.29: Frequency comb shifted by the carrier-envelope offset frequency. 118
Figure 7.30: Block diagram of a multi-wavelength source with integrated wavelength locking. 121
Figure 7.31: Wavelength deviation measurement of a wavelength-locked MultiWave system. 121
Figure 7.32: Spectral power density of a 100-GHz frequency comb. 123
Figure 7.33: Beating measurement setup for a 25-GHz ERGO and a 50-GHz MultiWave source. 124
Figure 7.34: Linewidth measurement of a 50-GHz MultiWave source. 124
Figure 7.35: Relative intensity noise of an isolated channel of a 100-GHz MultiWave source. 126
Figure 7.36: Eye-diagrams and bit-error-rate measurements of the final multi-wavelength source. 127
List of Tables

Table 2.1: Losses of antiresonant and resonant DBRs with different number of layer pairs. 23
Table 4.1: Properties of Er,Yb-doped phosphate glass (Kigre QX). 39
Table 4.2: Nonlinear reflectivity measurement results of antireflection coated SESAMs. 53
Table 4.3: Laser results obtained at very high repetition rates with SiN-coated SESAMs. 55
Table 4.4: Overview of results achieved with high repetition rate Er,Yb:glass lasers. 57
Table 6.1: Etchant recipe for slow GaAs-etching. 79
Publications

Parts of this thesis are published in the following journal papers and conference proceedings.

Journal papers

Conference publications


Posters


Abstract

In this thesis we investigate passively mode-locked solid-state lasers emitting in the 1.5-μm spectral region with multi-GHz repetition rates and describe their application in a novel broadband telecom source.

There are numerous applications for multi-GHz laser sources in science and technology such as optical clocks, frequency comb metrology or advanced high-speed return-to-zero data transmission systems. All of these applications have in common that they require a pulse source which is efficient, compact, affordable and reliable in operation. The complexity and costs of current sources have prevented a significant market penetration for commercial employment. Passively mode-locked, high repetition rate solid-state lasers are a promising technology, as they are simple and they satisfy the demands on a commercial laser source. They can be efficiently pumped by reliable telecom-grade laser diodes and their resonator is very compact. Because their pulse generation is entirely passive, no high frequency electronics is needed. However, achieving stable operation at tens of GHz is challenging because at these high repetition rates it is difficult to suppress Q-switched mode-locking such that sophisticated cavity designs are required.

In this thesis, we present results from a fundamentally mode-locked Er,Yb:glass laser with a record high repetition rate of 100 GHz. The laser cavity with an overall length of only 1.26 mm is folded, using a folding mirror with a radius of curvature of only 0.5 mm, to obtain a mode-size small enough to exceed the saturation fluence of the semiconductor saturable absorber mirror (SESAM). In an iterative process we improved the laser resonator, such that we achieved an average output power of 35 mW and a pulse duration of 1.6 ps. By optimizing the dispersion of the SESAM, we could reduce the pulse duration by 30% to obtain 1.1-ps pulses. We also describe and discuss the influence of transverse cavity-mode degeneracies, which can lead to instabilities and which are presented for the first time for high repetition rate lasers.

Because the optimization of SESAMs for self-starting, passive mode-locking at record high repetition rates requires precise optical characterization, we built a setup for high precision, wide dynamic range nonlinear reflectivity measurements in the
1.5-µm spectral region. It achieves an accuracy for the measured reflectivity of 0.05% for an incident fluence varied over 3.5 orders of magnitude.

A monolithically integrated laser design could ease the assembly of commercial high repetition rate lasers and therefore facilitate cheap mass production. The small emission cross section of Er,Yb:glass and the saturation fluence values of quantum well SESAMs prohibit stable mode-locking with equal modesizes in the gain and on the SESAM which is a prerequisite for monolithic integration. We examine a new gain material with an enhanced gain cross section and demonstrate in a proof-of-principle experiment a fundamentally modelocked 10-GHz Er,Yb:YAB laser with 10 mW output power, which is the highest reported repetition rate obtained from a 1.5-µm crystalline gain medium. For monolithic integration the modesize on the SESAM has to be significantly increased such that absorbers with significantly reduced saturation fluences but still moderate modulation depths are required. We started to work on 1.5-µm quantum dot (QD) SESAMs which have this potential. However, the growth of QDs in this spectral regime is still challenging and further optimization is required to achieve suitable absorber parameters.

Based on a fundamentally mode-locked Er,Yb:glass laser, we demonstrate a novel, cost-effective multi-wavelength source for wavelength division multiplexing (WDM) telecom systems. The laser, operating at 12.5 GHz or 25 GHz, generates a stable, equally spaced wavelength grid, which is spectrally broadened in a highly nonlinear photonic crystal fiber to increase the number of wavelength channels. High-finesse Fabry-Pérot filters adapt the output to industry-standard wavelength grids. The demonstrated 50-GHz and 100-GHz multi-wavelength sources are capable of generating wavelength channels filling up the entire telecom C- and L-bands. Bit-error-rate (BER) measurements and eye diagrams show that the generated channels exhibit a performance comparable to commercial distributed feedback (DFB) lasers. The concept offers a simple upgrade path to increase its channel count: by changing the output filter, different ITU grid spacings down to 12.5 GHz can be generated, thereby increasing the overall system bandwidth. We optimized the core component, the Er,Yb:glass laser, for high reliability and did not observe any degradation over a time period of more than 1500 hours or a failure in an extended temperature range. We believe that the presented multi-wavelength source can become an interesting alternative to conventional DFB laser arrays, to be used in commercial transmission systems.
Kurzfassung

In dieser Doktorarbeit untersuchen wir passiv-modengekoppelte Multi-GHz Festkörperlaser im 1.5-µm Spektralbereich, und beschreiben deren Anwendung in einer neuartigen, breitbandigen Lichtquelle für Telekommunikationsanwendungen.


In dieser Arbeit demonstrieren wir einen fundamental modengekoppelten Er,Yb:Glas Laser, mit einer bisher unerreichten Pulsfrequenz von 100 GHz. In der gefalteten Laserkavität, mit einer Gesamtlänge von 1.26 mm, wird ein Faltspiegel mit einem Krümmungsradius von lediglich 0.5 mm verwendet, um die Modengrössen auf dem SESAM so weit zu reduzieren, dass die Sättigungsfluenz überschritten werden kann. In einem iterativen Prozess haben wir den Laserresonator soweit verbessert, dass wir eine mittlere Ausgangsleistung von 35 mW bei einer Pulsdauer von 1.6 ps erreichen. Durch Optimierung der dispersiven Eigenschaften des SESAMs können wir die Pulsdauer um 30% auf 1.1 ps reduzieren. Wir diskutieren erstmalig für hoch repetierende Laser, den Einfluss von Frequenz-Entartungen höherer Transversal-
moden, welche zu unerwünschten Instabilitäten in der Laserdynamik führen können.

Da die Optimierung von SESAMs zum Modenkoppeln bei bisher unerreichten Repetitionsraten eine genaue Kenntnis ihrer optischen Eigenschaften voraussetzt, haben wir eine Apparatur für hochpräzise nichtlineare Reflexionsmessungen gebaut. Diese ermöglicht Reflektionsmessungen über einen Dynamikbereich von 3.5 Größenordnungen für die einfallende Fluenz, eine absolute Abweichung der gemessenen Reflektivität von 0.05%.


Als Anwendung für hoch repetierenden Laser beschreiben wir eine kostengünstige Breitband-Lichtquelle, welche die physikalischen Eigenschaften eines fundamental modengekoppelten 12.5-GHz Lasers, einer photonischen Kristall-Faser, sowie die Transmissionseigenschaften von Fabry-Pérot Filtern mit hoher Finesse ausnutzt. Der Laser produziert einen gleichförmigen Frequenzkamm, welcher durch die photonische Kristall-Faser spektral verbreitert wird, um zusätzliche Bandbreite
zu erzeugen. Das Fabry-Pérot Filter adaptiert schliesslich die erzeugte Kamm-Frequenz an standardisierte Industire-Frequenzraster. Die entwickelten Quellen, mit einem Frequenzabstand von \(50\,\text{GHz}\) beziehungsweise \(100\,\text{GHz}\), sind in der Lage, die Telekommunikationsbänder C und L komplett abzudecken. Messungen zur Signalqualität und der Bitfehler-Rate zeigen, dass die erzeugten Kommunikationskanäle eine vergleichbare Qualität zu kommerziell genutzte Diodenlaser-Systeme aufweisen. Zusätzlich besitzt die Quelle eine einfache Möglichkeit zur Erweiterung der Bandbreite: durch Auswechseln oder Entfernen des Ausgangsfilters können verschiedene Frequenzraster bis zur fundamentalen Frequenz von \(12.5\,\text{GHz}\) erzeugt werden, wodurch die System-Bandbreite erhöht wird. Die Kernkomponente des Systems, ein ausgereift konstruierter Er,Yb:Glas Laser, ist äusserst zuverlässig, wie wir in Lebensdauer- und Temperaturtests feststellen konnten. Der Laser hat über 1500 Stunden und in einem Temperaturintervall von \(8\text{-}42^\circ\text{C}\) keinerlei Degradationerscheinungen gezeigt. Die entwickelte Breitband-Quelle ist unserer Meinung nach eine interessante Alternative zu herkömmlichen Diodenlasern, welche bisher in kommerziellen Übertragungssystemen genutzt werden.
Chapter 1

Introduction and motivation

After the first experimental demonstration of a laser by Theodore Maiman in 1960, it was his assistant Irnee D’Haenens who called it “a solution that is looking for a problem” [1]. At the time, nobody could imagine the tremendous success the laser would experience in the coming years. Out of the countless applications in which lasers are used today, probably the most prominent ones, that are affecting our daily life, are optical data storage and retrieval, as it is used in CD-, DVD- or BluRay-devices, and broadband communication via optical fibers. While optical storage media might soon be outdated, optical communication is becoming more and more important. Today, audio and video data is distributed via the internet and stored in high-capacity solid-state memory, superseding complex and sensitive mechanical drives for optical storage media. The future trend is to totally suspend data storage at the user site and to stream media on demand via broadband connections. The key technology enabling this is the glass fiber and high capacity fiber-optical networks.

The advent of broadband optical communication was soon after the invention of the laser, which offered the potential of a carrier with extremely high bandwidth. But it was not before the development of low-loss optical fibers [2, 3], that long-haul data transmission became available. The importance of this invention was honoured in 2009 with the Nobel-Prize in physics awarded to Charles Kuen Kao “for groundbreaking achievements concerning the transmission of light in fibers for optical communication”.

Multi-GHz lasers emitting in the 1.5 µm spectral range are particularly interesting for fiber-optical telecommunication applications as they operate in the window of
minimal glass absorption, which enables long-haul data transfer. Pulsed lasers with high repetition rate are important tools for advanced high-speed return-to-zero (RZ) data transmission systems, typically operating at 40 Gbit/s or higher: data streams are encoded on the pulse train with a modulator, which then only has to change its state between two successive pulses. This approach reduces the highly stringent demands on the slopes of the modulator, as the pulse shaping is already done by the laser source. In current state-of-the-art high bit-rate data transmission systems, the pulsed laser source usually runs at a much lower repetition rate and needs to be time multiplexed to the desired frequency [4]. A pulse source directly operating at the system frequency with high average output power can greatly simplify the system design, as the multiplexing device as well as the additionally required amplifiers can be omitted.

Despite their characteristics in the time domain, which in telecom applications are especially important for optical-time-division-multiplexing (OTDM) systems, mode-locked high repetition rate lasers generate a stable comb-shaped spectrum in the frequency domain. The comb-lines of this spectrum, which are basically the longitudinal modes of the laser cavity, are equidistantly spaced in frequency with the spacing being determined by the repetition rate of the laser. Therefore mode-locked GHz-lasers are intrinsically wavelength-stable multi-channel sources that can be used for wavelength-division-multiplexing (WDM) systems.

Besides telecom, there are numerous other applications for multi-GHz laser sources in science and technology such as optical clocking [5], photonic switching [6] or high-speed electro-optic sampling [7], just to mention a few. Especially in frequency metrology GHz frequency-combs are anticipated for direct frequency comb spectroscopy [8], as they offer high spectral power per comb line leading to an increased signal-to-noise ratio. Also applications like optical clocks [9] or the frequency comb calibration of high-resolution astronomical spectrographs [10-12] benefit from GHz frequency combs. All of these applications have in common that they require a pulse source which is compact, affordable and reliable in operation. Furthermore it should exhibit low noise and timing jitter and emit close to transform limited pulses with a high extinction ratio and wavelength tunability or setifiability in the regime of interest.
The great interest in 1.5-µm GHz-laser sources with sufficient power levels provided a strong motivation for numerous different approaches to develop and improve lasers generating such pulse trains. Some examples are harmonically mode-locked fiber lasers [13], hybrid mode-locked edge-emitting semiconductor lasers [14], passively mode-locked VECSEL (Vertical External Cavity Surface Emitting Laser) [15] or synchronously pumped monolithic optical parametric oscillators (OPO) [16]. Diode-pumped passively mode-locked Er,Yb:glass lasers offer an excellent alternative to the technologies mentioned before. Due to their miniature cavities they are compact, can be pumped by standard telecom diodes and only need a low-cost gain medium and a semiconductor saturable absorber mirror (SESAM) [17-19]. Because the pulse generation is entirely passive, no high frequency electronics is required. Although their basic design is very simple, there are numerous challenges, like the design of very compact stable laser cavities or the development of suitable saturable absorbers. For a long time it was believed that passive mode-locking of a solid-state laser at GHz repetition rates is not possible [20] or at least impractically difficult. This was mainly due to the strong tendency of solid-state lasers to Q-switched mode-locking, which is mainly a result of the long upper state lifetimes and high gain saturation values of solid-state gain materials. A major breakthrough was the demonstration of the first passively, fundamentally mode-locked 10-GHz Er,Yb:glass laser in 2002 [21]. Since then, a profound understanding of the Q-switching dynamics [22-24] and the consequent exploitation of the flexibility of semiconductor saturable absorber mirrors have led to fundamentally mode-locked 1.5-µm lasers with record high repetition-rates.

In the first part of this thesis we investigate the properties of high repetition rate Er,Yb:glass lasers resulting in the demonstration of a laser operating at 100 GHz with 1.1-ps pulses and with up to 35 mW average output power [25, 26], which is the highest repetition rate of a 1.5-µm solid-state laser demonstrated so far. The described laser has a folded cavity layout and is build with discrete elements. To simplify the assembly of commercial versions but also to possibly further increase the repetition rate of the demonstrated lasers, we study the feasibility of monolithic integration, for which SESAMs with extremely low saturation fluences are required. SESAMs with absorbers based on quantum dots (QD) rather than quantum wells (QW) have this potential. We therefore study the feasibility of 1.5-µm QD-SESAMs. In addition, alternative gain media with larger emission cross sections would ease
monolithic integration. We investigate the properties of Er,Yb:YAB which offers a four times larger emission cross section than standard doped phosphate glasses. We demonstrate the first multi-GHz operation of this material, which at the same time is the highest repetition rate demonstrated with an Er-doped crystalline gain material operating at 1.5 µm.

Besides increasing the repetition rate of pulsed laser sources, to increase the bit-rate in existing transmission channels of fiber-optical telecom systems, an alternative way to broaden the transmission bandwidth is to increase the number of independent transmission channels. WDM is an attractive upgrading possibility to expand the bandwidth of already existing fiber networks to cope with today’s demands. In currently installed commercial WDM network architectures, each data channel requires its own wavelength-stabilized continuous-wave laser. Usually banks of distributed feedback (DFB) diode lasers are used in these systems, where each laser requires dedicated drive electronics. One possibility to reduce the complexity and the overall costs of a dense wavelength division multiplexing (DWDM) transmission system is an optical source capable of simultaneously generating a large number of different wavelengths with a defined spectral spacing through a single device. Fundamentally mode-locked high repetition rate lasers offer these properties. However, the number of channels directly generated from a laser within a certain power range is usually comparably low. With a highly nonlinear fiber, the output of the laser can be spectrally broadened, thereby increasing the number of available wavelength channels.

In the second part of this thesis we describe in detail the development of such a multi-wavelength source (MWS), exploiting the properties of fundamentally mode-locked high repetition rate lasers and highly nonlinear fibers, to produce a large number of wavelength channels, covering entire communication bands in the 1.5-µm spectral region. The source is designed to match the widely used 50 GHz and 100 GHz grid spacing for DWDM systems. Because the system is operating at a fundamental laser frequency of 12.5 GHz or 25 GHz respectively, a high-finesse Fabry-Pérot filter is used at the output, to suppress the dispensable channels. Although it would be more power-efficient to directly generate a frequency comb with the desired spacing, we found lasers operating at an integer fraction of the desired grid spacing to be more efficient particularly in the spectral broadening
section. Compared to 50- or 100 GHz lasers, they generally offer higher pulse peak powers (assuming similar average output power) leading to a more homogeneous energy distribution in the generated spectral components over a larger wavelength interval. In addition, these lasers offer a higher overall bandwidth because of the larger number of individual channels. With emerging ultra dense system grids of 25 GHz or even 12.5 GHz, a MWS based on these fundamental repetition rates can easily be upgraded to offer the full system bandwidth simply by replacing or removing the output filter.

This thesis is organized as follows: Chapter 2 gives an overview of passive modelocking. The SESAM is introduced as a versatile passive loss modulator, and fundamental SESAM designs are discussed. In Chapter 3, a method for wide dynamic range nonlinear reflectivity measurements is described. The presented measurement setup is used for the characterization of SESAMs. In Chapter 4, after discussing general design considerations for high repetition rate lasers, we present results of a 100-GHz Er,Yb:glass laser. In Chapter 5 we discuss the influence of frequency degenerate higher order spatial modes and present how they can affect the laser performance. Chapter 6 contains first steps towards monolithic integration: we present first experimental results with a new gain material and an attempt to develop a QD-SESAM with low saturation fluence. In Chapter 7 we describe in detail the development of a multi-wavelength source to be used in DWDM telecom systems, which is exploiting the physical properties of mode-locked high repetition rate lasers. Chapter 8 closes with a conclusion and an outlook.
Chapter 2

Passive mode-locking at high repetition rates

Today, lasers are used in a wide field of applications ranging from scientific over medical, telecommunication or entertainment to material processing in a manifold of different ways. Specific applications require lasers with specific properties and adapted parameters such as average output power, wavelength or, if used in pulsed operation, pulse duration, energy or peak power. Car bodies are welded with lasers offering continuous output powers of several kilowatts (kW) while next-generation telecommunication applications require lasers emitting only milliwatts (mW) but in pulses of only a few hundred femtoseconds (fs) duration. In this chapter we will briefly discuss fundamental modes of laser operation before we describe in more detail the technique of passive mode-locking used to obtain ultrashort laser pulses. We will discuss challenges for passively mode-locking high repetition rate lasers and we will introduce the semiconductor saturable absorber mirror (SESAM) as a versatile loss modulator to facilitate passive mode-locking.

2.1 Principle modes of laser operation

To differentiate between fundamental properties, lasers can be classified into four principle modes of operation, namely continuous-wave (cw), Q-switched, continuous-wave mode-locked and Q-switched mode-locked (QML). The temporal characteristics of these different modes are depicted in Figure 2.1.
Lasers with high average output power usually operate in cw mode, independent of their specific architecture. In cw operation, lasers can run with a single longitudinal mode of the optical resonator, providing a narrow linewidth emission with good coherence, which is interesting for spectroscopy and interferometry. For many applications, laser pulses instead of a continuous laser emission are required. Depending on the desired pulse duration different pulsing techniques are applied. The most simple approach to produce pulses is an amplitude modulation of the emission of a cw laser. Depending on the modulator used, pulses with a duration ranging from milliseconds (ms) down to some ten picoseconds (ps) can be generated, but with rather low pulse energy and peak power.

![Different temporal regimes of laser operation](image)

Figure 2.1 Different temporal regimes of laser operation. In pulsed operation modes the dashed lines at the bottom depict the average power level which for comparison is equal in all three graphs.

Another intuitive method is the modulation of the laser pump power such as current modulation for electrically pumped lasers, or flashlamps in optically pump lasers, which is refered to as “gain switching”. In semiconductor lasers pulses as short as 40 ps have been demonstrated using current modulation [27]. Flashlamp-pumped solid-state lasers are widely used in spot-welding applications as they provide large pulse energies with pulses in the millisecond regime and are cost efficient.

With the technique of Q-switching, continuously pumped lasers can generate pulses with pulse energies and pulse peak powers exceeding their average output
power by several orders of magnitude. In a Q-switched laser, pulses are generated by modulating the quality factor Q of the laser resonator. While pumping the laser medium, initially the losses in the cavity are kept above the lasing threshold. In this state the pump energy is accumulated in the gain medium. When the losses are reduced, the intracavity power builds up quickly, leading to a saturation of the gain which finally drops below the laser threshold again. Pulses of Q-switched lasers emitting only a few watt of average power can easily be used for material processing, to evaporate metal for example. Pulse durations of Q-switched lasers are usually in the nanosecond (ns) regime, but pulse durations below 100 ps have also be demonstrated [28].

Significantly shorter pulses, in the regime of picoseconds (ps) to femtoseconds (fs), can be obtained with mode-locked (ML) lasers. Multiple longitudinal modes of a laser resonator are phase-locked by an intracavity loss modulator, such that individual pulses are travelling inside the laser cavity. Mode-locked lasers cannot have a single frequency output, but will always exhibit a finite optical bandwidth. In mode-locked operation, the laser pulse duration is well below the cavity roundtrip time opposed to Q-switched operation, where the laser pulse duration exceeds the cavity roundtrip time.

In the special case of fundamental cw mode-locking, only one single pulse is travelling inside the cavity, emitting an attenuated copy of itself every time it hits the output coupler. The repetition rate of the formed periodic pulse train is determined only by the roundtrip time of the pulse inside the resonator. Therefore fundamental mode-locking leads to an excellent pulse-to-pulse stability and timing jitter performance [29]. In harmonically mode-locked lasers, multiple pulses are oscillating in a cavity such that the effective repetition rate of the laser usually will be an integer multiple of the fundamental resonance frequency. Harmonic mode-locking naturally exhibits lower pulse-to-pulse stability and timing jitter performance and even pulse drop-outs, requiring additional stabilization and control electronics [30, 31].

For high-repetition-rate lasers, fundamental mode-locking leads to relatively short cavities, as the pulse repetition rate of the laser is only determined by the roundtrip time of the intracavity pulse. For a standing wave cavity of a fundamentally mode-locked laser the pulse repetition rate \( f_{\text{rep}} \) is given by
\( f_{\text{rep}} = \frac{c_0}{2L}, \)  

with \( L \) being the cavity length and \( c_0 \) the speed of light, such that a 100-GHz laser for example has a cavity length in air of only 1.5 mm.

While the pulse energy in cw mode-locked lasers is typically below that of Q-switched lasers, mode-locked pulses can achieve much higher peak powers due to their ultrashort duration. For many applications, cw mode-locking is the preferred mode of operation as it is the most stable and predictable one in terms of pulse-power, peak intensity and pulse repetition rate. For applications in frequency metrology, phase stabilization of the laser output is only possible with cw mode-locking.

In Q-switched mode-locking (QML) operation the mode-locked laser pulses are additionally modulated by a Q-switched envelope. This operation regime is often avoided as each burst of pulses has to build up from noise, leading to poor coherence and noise performance. For cw mode-locked solid-state lasers QML is usually regarded as an instability. Especially for solid-state lasers with very high repetition rates, like the ones described in this thesis, avoiding QML is a major challenge [22, 32].

2.2 Mechanisms of passive mode-locking

Passive mode-locking is a very successful technique for the generation of ultrashort pulses at GHz repetition rates. Compared to active mode-locking, passive techniques do not require GHz driving electronics, such that passively mode-locked laser sources can be more compact, reliable and cost efficient. In addition, the dynamics of passive modulators is much faster than the switching speed of typical active modulators, which enables the generation of shorter pulses. All lasers described in this thesis rely on passive mode-locking, such that we want to describe this technique in more detail.

To understand the mechanisms of passive mode-locking, it is convenient to describe the dominating effects in the time domain: to enable mode-locking, a loss-modulator has to be placed inside the laser cavity that forces the intracavity power into short light pulses around the temporal minimum of the loss modulation. For passive mode-locking one has to rely on an effect that reduces the losses inside a
laser cavity for higher light intensities. An incident laser pulse, which can initially be a small noise fluctuation, then produces its own loss modulation, which is referred to as passive mode-locking. Different physical effects can be used to achieve such a modulation. In the following we want to concentrate on saturable absorbers to be used as the loss modulator.

Three typical mode-locking mechanisms using a saturable absorber: (i) fast saturable absorber, the recovery time of the absorber is faster than the pulse duration. For absorbers with slow recovery we distinguish between strong dynamic gain saturation (ii) and weak gain saturation (iii).

Three fundamental models for passive mode-locking with saturable absorbers are depicted in Figure 2.2: (i) a fast saturable absorber in combination with weak gain saturation [33], (ii) a slow saturable absorber with strong dynamic gain saturation [34] and (iii) a slow saturable absorber with weak gain saturation. In all three cases a short net-gain window has to be created to form and to sustain the pulse inside the laser cavity.

2.2.1 **Fast saturable absorber**

For a fast saturable absorber, the absorber recovery time is shorter than the pulse duration \( \tau_A < \tau_p \) thereby determining the pulse shaping. The loss modulation follows the pulse shape and the net gain window is closed after the pulse has passed. This was initially believed to be the only stable solution to passively mode-lock solid-state lasers. The mechanism used in Kerr-lens mode-locked (KLM) lasers also can be
described by this model, although in KLM lasers, strictly speaking, there is no real absorber involved. Instead a lens with an intensity dependent focal length (Kerr-lens) in combination with either a hard or a soft aperture is used to induce higher losses for lower intensities inside the laser cavity, thereby favouring pulsed over cw operation. KLM lasers have produced the shortest pulses directly generated by a laser oscillator with pulse durations <6 fs [35, 36]. However, KLM lasers usually have to be operated close to a stability limit of the laser cavity, making the laser sensitive against mechanical stability or environmental influences like temperature changes. The mode-locking of lasers using fast saturable absorbers is usually not self-starting, such that an initial perturbation has to be induced for example by a mechanical vibration of a cavity element.

2.2.2 Slow saturable absorber with dynamic gain saturation

For pulse durations in the picosecond regime one usually relies on slow saturable absorbers, where the recovery time of the absorber is long compared to the pulse duration ($\tau_\text{A} > \tau_\text{p}$). Depending on the gain medium used in a laser, the pulse shaping mechanisms can differ. For gain media with a large gain cross section and therefore a short upper state lifetime, the intracavity laser pulse can saturate the gain. Therefore, when using a slow saturable absorber together with strong dynamic gain saturation, both gain and loss inside the cavity saturate. It is important that the saturation energy of the absorber is substantially lower than the gain saturation energy, such that a net-gain window is formed,

$$\frac{E_{\text{sat,abs}}}{E_{\text{sat,gain}}} \ll 1.$$  \hspace{1cm} (2.2)

The resulting net gain window is shaping the pulse as it is shown in Figure 2.2 (ii). Examples for this mechanism are semiconductor- or dye-lasers. Lasers relying on this scheme have the advantage that they virtually show no tendency for Q-switched mode-locking. Mode-locking processes using slow saturable absorbers are usually self-starting and very stable, which is a major advantage.

2.2.3 Slow saturable absorber with weak gain saturation

Gain media with small gain cross sections and thus long upper state lifetimes, such as solid-state gain materials, usually have saturation energies much larger than typical intracavity pulse energies. Therefore dynamic gain saturation is usually not
achieved. For a slow saturable absorber in conjunction with weak gain saturation, as it is depicted in Figure 2.2 (iii), one would believe that stable mode-locking is not possible, as the long net gain behind the pulse would amplify noise, leading to an increasing pulse width or to instabilities. However, the saturable absorber is mainly acting on the leading edge of the laser pulse thereby constantly shifting the pulse slightly backwards in time, such that the pulse itself is swallowing any amplified noise behind it. Numerical simulations have shown that the recovery time of the absorber can be at least twenty times longer than the pulse duration to still form a pulse [37]. Depending on the recovery time of the saturable absorber, pulse durations in the picoseconds regime can be achieved with this mode-locking scheme. The lasers described in this thesis all rely on this mode-locking mechanism.

To obtain pulses in the sub-ps regime with slow saturable absorbers and weak gain saturation, additional stabilizing effects are required. By properly balancing self-phase modulation (SPM) and group delay dispersion (GDD) inside the laser cavity, soliton pulses can be formed. In this case the pulse duration is only determined by the SPM coefficient, the total intracavity GDD and the pulse energy. The saturable absorber in this case is only used for self-starting and stabilizing the mode-locking process.

2.3 Stability criterion for passive mode-locking

For a long time it was believed that passively mode-locking a solid-state laser at GHz repetition rates is not possible or at least impractically difficult [20]. This was mainly due to the strong tendency of solid-state lasers to Q-switched mode-locking, which is mainly a result of the long upper state lifetimes and high gain saturation values of solid-state gain materials. A profound understanding of the Q-switching dynamics [22] and improvements of the passive modulators have led to fundamentally mode-locked lasers with repetition-rates up to 160 GHz [38] or pulse durations as short as 5.8 fs [35, 36].

In passively cw-mode-locked lasers Q-switching can occur due to the following scenario: if the pulse energy of a mode-locked pulse rises slightly due to small fluctuations, it will bleach the intracavity saturable absorber slightly stronger, thereby decreasing its losses. The particular power fluctuation will first grow exponentially until the pulse starts to saturate the gain, which causes the pulse
energy to drop below the steady-state value of cw-mode-locking. In this phase the gain recovers to restart the process. If the mode-locked pulses are completely suppressed at the minimum of this Q-switching envelope, laser emission has to restart from noise again. This QML behaviour can be avoided if the gain saturation is sufficiently strong to stop the exponential rise. For solid-state lasers this is challenging because their gain media often exhibit only small emission cross sections, leading to large saturation energies

$$E_{\text{sat},L} = \frac{\hbar \nu_L}{m_L \sigma_{\text{em},L}} A_{\text{eff},L}.$$  \hspace{1cm} (2.3)

Here $h$ is Planck’s constant, $\nu_L$ is the laser frequency, $m_L$ is the number of passes through the gain, $\sigma_{\text{em},L}$ is the emission cross section of the gain material and $A_{\text{eff},L}$ is the effective mode size in the gain medium.

Starting from rate equations for the intracavity power, gain and saturable absorption, Hönniger et al. have derived the following general stability criterion against Q-switching [22]:

$$E_p^2 > E_{\text{sat},L} E_{\text{sat},A} \Delta R$$  \hspace{1cm} (2.4)

where $E_p$ is the intracavity pulse energy, $E_{\text{sat},L}$ is the saturation energy of the gain medium, $E_{\text{sat},A}$ is the saturation energy of the saturable absorber and $\Delta R$ is the loss modulation (given in percent), mostly referred to as modulation depth, of the saturable absorber. For their considerations they assumed fundamental mode-locking and a slow saturable absorber that is strongly saturated and which fully recovers within the cavity roundtrip time. They further assumed that the laser is operated far above threshold.

For the practical design of a laser cavity, it is more convenient to rewrite inequality (2.4). Using $E_p^2 = (P_{\text{intra}} / f_{\text{rep}})^2$, $E_{\text{sat},L} = F_{\text{sat},L} A_{\text{eff},L}$ and $E_{\text{sat},A} = F_{\text{sat},A} A_{\text{eff},A}$ we get

$$\left( \frac{P_{\text{intra}}}{f_{\text{rep}}} \right)^2 > F_{\text{sat},L} A_{\text{eff},L} F_{\text{sat},A} A_{\text{eff},A} \Delta R$$  \hspace{1cm} (2.5)

with $P_{\text{intra}}$ being the intracavity power, $f_{\text{rep}}$ the laser repetition rate, $F_{\text{sat}}$ the saturation fluence and $A_{\text{eff}}$ the effective mode area in the laser gain medium (L) and on the
absorber (A) respectively. It is immediately obvious, that inequality (2.5) is getting more stringent for higher values of $f_{\text{rep}}$. Equation (2.5) reveals the engineering parameters that we can use to fulfil the inequality. They can be grouped into two categories: (1) the effective mode areas $A_{\text{eff,L}}$ in the gain medium and $A_{\text{eff,A}}$ on the absorber, and (2) the parameters of the saturable absorber, namely the modulation depth $\Delta R$ and the saturation fluence $F_{\text{sat,A}}$. The mode areas can be influenced by the cavity design of the laser and should be as small as possible to ease inequality (2.5). The saturable absorber should exhibit low saturation fluence together with a reasonably low modulation depth.

The stability criterion given above is quite general and works well for a broad range of lasers. However, for high repetition rate lasers, some of the assumptions that are made to derive equations (2.4) and (2.5) are not always well satisfied such that these inequalities are often not fulfilled, sometimes even by several orders of magnitude. In section 2.4.1 we will discuss that we have to consider additional effects, which have an influence on the given stability criterion and we will modify equation (2.4) to become less stringent for high repetition rates.

2.4 Semiconductor Saturable Absorber Mirror

Semiconductor alloys are ideally suited to be used as saturable absorbers, as their optical properties can be engineered over a broad wavelength range by changing their alloy composition and their physical dimensions. Furthermore, their recovery dynamics can be controlled, for example with the density of structural defects [39], to obtain recovery times ranging from the picosecond- to the femtosecond regime. Light with a photon-energy larger than the semiconductor bandgap can be absorbed, thereby exciting electrons from the valence- to the conduction band. For intense light fields, the absorption is saturated and transparency can be obtained, if the absorption equals the stimulated emission. On a timescale of tens to hundreds of femtoseconds the carriers thermalize to form a thermal equilibrium among themself. On a longer timescale, typically ranging from pico- to nanoseconds, depending on the mobility of the carriers and the defect density, the carriers recombine, such that the absorption recovers. The two different processes are helpful as the longer time constant enables self-starting mode-locking, while the fast time constant can reduce the pulse duration.
By incorporating low dimensional semiconductor structures like quantum wells (QW) or quantum dots (QD) into a distributed Bragg-reflector (DBR), one can form a semiconductor saturable absorber mirror (SESAM) [17, 18, 40], that can be used inside a laser resonator as a high-reflecting end mirror. The reflectivity of a SESAM increases with increasing incident light intensities, such that weak power fluctuations of a cw operated laser can lead to the formation of mode-locked laser pulses. A crucial advantage of SESAM mode-locking as opposed to KLM, is the fact, that the absorber parameters are intrinsic properties of the SESAM and do not directly depend on the laser cavity design. This offers more degrees of freedom for the design of a laser cavity. Furthermore, compared to bulk saturable absorbers, the SESAM has only a very small penetration depth contributing to the laser cavity length, which is advantageous for high repetition rate lasers.

2.4.1 Macroscopic properties

In contrast to saturable absorbers based on dyes or doped crystals, the SESAM offers unique design flexibility to custom-tailor its linear and nonlinear optical properties. Its key parameters are the modulation depth $\Delta R$, which is the maximal possible change of reflectivity, the saturation fluence $F_{\text{sat},A}$, which is the pulse fluence required to saturate $1/e$ of the modulation depth $\Delta R$, the nonsaturable losses $\Delta R_{\text{ns}}$, the linear reflectivity $R_{\text{lin}}$, which is the minimal reflectivity at low intensities, the maximal obtainable reflectivity $R_{\text{ns}}$ as well as the recovery time $\tau_A$. They determine the dynamics of passively ML lasers. For convenience we define the saturation parameter $p_{\text{sat},A} = \frac{p_{\text{sat},A}}{p_{\text{sat},A}^{\text{sat},A}}$, where $p_{\text{sat},A}$ is the pulse fluence, $p_{\text{sat},A}^{\text{sat},A}$ the pulse energy and $E_{\text{sat},A} = F_{\text{sat},A} \cdot A_{\text{eff},A}$ the saturation energy of the absorber. The saturation parameter determines how many times above the saturation fluence a saturable absorber is operated in a laser.

Figure 2.3 (left) shows a typical reflectivity curve of a SESAM as a function of the incident pulse fluence, together with the key parameters. This curve can be completely described by only three parameters, namely $R_{\text{lin}}, R_{\text{ns}}$ and $F_{\text{sat},A}$, which are not directly experimentally accessible, but have to be retrieved from a model function used to fit measured reflectivity data.
PASSIVE MODE-LOCKING

Figure 2.3 Typical nonlinear reflectivity behaviour in dependence of the incident pulse fluence (left) and temporal impulse response (right) of a semiconductor saturable absorber mirror (SESAM).

The nonsaturable losses $\Delta R_{ns}$ and the modulation depth $\Delta R$ can then be calculated by using

$$\Delta R_{ns} = 1 - R_{ns}$$  \hspace{1cm} (2.6)

$$\Delta R = R_{ns} - R_{lin}$$  \hspace{1cm} (2.7)

To retrieve the model function, we describe the saturation behaviour of a slow saturable absorber by a simple two-level model, neglecting intraband relaxations as well as trapping, recombination, carrier diffusion or temperature effects. With a lateral flat-top approximation for the test-laser beam profile one obtains [41, 42]

$$R(F) = R_{ns} \frac{\ln \left( \frac{1 + R_{lin}}{R_{ns}} \cdot e^{S} - 1 \right)}{S}$$

as a model function. To consider pulses from a laser with a Gaussian beam profile, one has to integrate over the entire beam profile to obtain [43]

$$R^{Gauss}(F_p) = \frac{1}{2F_p} \int_0^{2F_p} R(F) \, dF$$

with the fluence defined as $F_p = E_p / (\pi \omega^2)$. This integral has to be solved numerically within the fit-procedure. For a good accuracy it is important to fit the measured nonlinear reflectivity data with $R^{Gauss}$ given in equation (2.9).
Figure 2.3, right shows the temporal response of a SESAM, which is determined by the carrier dynamics in the absorber. The recovery behavior can be measured by means of pump-probe techniques: the absorber is first fully saturated by a strong pump pulse, after a varying time delay the reflectivity is measured by weak probe pulse. In general a SESAM exhibits two different temporal components within its recovery: a fast component ($\tau=50$ fs–200 fs) arises from intraband thermalization while a slower component, which is in the order of tens to hundreds of picoseconds, originates from interband recombination. For high repetition rate lasers, we usually rely on the slow recovery component. With the growth temperature, one can influence the recovery time of a particular SESAM. Low growth temperature enhances the interband trap density leading to faster recovery times, but usually with increased nonsaturable losses as a trade off. It has been shown, however, that annealing procedures [44] or dopants [45] can help to obtain fast recovery times together with low nonsaturable losses. This is advantageous, as a faster recovery in general allows for shorter pulses [37].

As we have seen in Figure 2.3 (left), the reflectivity of a SESAM is expected to increase with increasing pulse energy. However, for higher pulse energies the reflectivity can decrease again [24]. This roll-over of the nonlinear reflectivity curve, caused by inverse saturable absorption, has important consequences for the Q-switching dynamics of passively mode-locked lasers. Particularly for high repetition rate lasers it leads to significantly lower QML thresholds than expected from equation (2.4). While for short pulses in the few hundred femtosecond regime, this inverse absorption can be well explained by two-photon absorption (TPA), for picosecond pulses the physical origin is yet not clear. The inverse absorption in this case is larger than expected and cannot be explained by TPA alone (although TPA also contributes). It could be verified experimentally, that the inverse absorption of picosecond pulses is enhanced at very high repetition rates [46]. In this operation regime, slow saturable absorbers cannot fully recover to their initial state, which leads to an accumulation of carriers in the excited state. These carriers enhance second order effects and therefore play an important role for the inverse absorption [46]. Figure 2.4 shows the modified nonlinear reflectivity behaviour versus the saturation parameter $S$ together with the macroscopic key parameters. Due to the roll-over of the saturation curve, we obtain a reduced effective modulation depth $\Delta R_{\text{eff}}$. As the linear reflectivity is not affected, this leads to an increased effective
nonsaturable loss $\Delta R_{\text{ns,eff}}$. We define a fluence $F_0$ at the maximum of the obtainable reflectivity with a corresponding saturation parameter $S_0 = F_0 / F_{\text{sat}}$.

![Graph showing calculated nonlinear reflectivity versus saturation parameter $S$ for strong (dashed) weak (dotted) and no (solid) inverse saturable absorption (in this case caused by two-photon absorption (TPA) only) [24].](image)

For a modified model function of the resulting reflectivity curve, equation (2.8) has to be multiplied with a correction factor $\exp\left(-\frac{F}{F_2}\right)$, where $F_2$ is the inverse absorption coefficient, to obtain

$$R(F) = R_{\text{ns}} \left(\frac{1 + R_{\text{lin}} / R_{\text{ns}} \left(\exp^S - 1\right)}{S} \cdot \exp\left(-\frac{F}{F_2}\right)\right).$$

(2.10)

Again, to correct for a Gaussian beam profile equation (2.10) has to be inserted into (2.9).

As we have already mentioned, there is no model yet to calculate $F_2$ in the case of picosecond pulses at very high repetition rates, such that $F_2$ has to be retrieved from nonlinear reflectivity measurement data. Preferably such a characterization should be done at the target pulse duration and the closest possible repetition rate. From the experimentally retrieved data one can calculate $S_0$ with

$$S_0 = \sqrt{\frac{F_2 \Delta R}{F_{\text{sat}}}}.$$ 

(2.11)
Inverse saturable absorption reduces the tendency for Q-switched mode-locking [47], not only due to the reduced effective modulation depth but, more important, due to the reduced slope of the nonlinear reflectivity curve. One can show that this influence leads to the following modified stability condition (well above threshold) [47]

\[
E_p^2 > \frac{E_{\text{sat},A} \Delta R}{\frac{1}{E_{\text{sat},1}} + \frac{1}{A_{\text{eff},A} F_2}}
\]

(2.12)

with \( A_{\text{eff},A} \) being the effective mode area on the absorber. For \( F_2 \to \infty \), that is without any inverse saturable absorption, equation (2.12) reduces to (2.4) again. When designing a SESAM for a high repetition rate laser, \( F_2 \) has to be chosen carefully: one would assume, that the lowest possible value for \( F_2 \) (which is equivalent to strong inverse saturable absorption) is favourable. However, the resulting reduced effective modulation depth reduces the strength of the pulse shaping and therefore can lead to the generation of longer pulses or increased susceptibility to perturbations. For a sufficient pulse shaping it is necessary that

\[
F_2 > \frac{2F_{\text{sat}}}{\Delta R}
\]

(2.13)

otherwise the induced absorption is stronger than the saturable absorption, leading to zero modulation depth. In addition, the increased nonsaturable losses affect the available output power and the efficiency of the laser. Finally, a strong roll-over can induce multiple pulsing, as the losses can become lower if the pulse energy is split among multiple pulses. For stable operation typical values of \( S \) vary between 2 and 10; values around 4 lead to the shortest pulses for lasers without soliton pulse shaping [37]. Inverse saturable absorption caused by TPA mainly occurs in the cap layer, the spacer layer and the DBR layers of the SESAM and only to a negligible amount in the absorber layer, because of its very small thickness. By substitution of layer materials or by moving the absorber layer within the SESAM structure it is possible to custom tailor \( F_2 \) to a desired value [24, 48].
Additional remarks on QML stability criteria

Inverse saturable absorption and the introduction of the $F_2$ parameter have a big impact on the stability criterion for mode-locked lasers: $F_2$ values of several 100 mJ/cm² (which means a very weak roll-over) already relax the condition drastically. For practical SESAM devices, condition (2.12) usually still does not hold strictly at high repetition rates. In the derivation of the initial QML stability criterion given by equation (2.4), a fully saturated SESAM ($S \geq 5$) is assumed. At multi-GHz repetition rates, the intracavity pulse energy is rather low, leading to a saturation parameter $S$ well below five. This leads to an overestimated QML threshold from equation (2.4).

Further, for high repetition rates the saturable absorption might not fully recover between subsequent pulses, depending on the repetition rate of the laser and the recovery time of the SESAM. This not only leads to the above mentioned accumulation of carriers in the excited state but also directly to a reduced effective modulation depth and therefore again to an overestimated QML threshold. One should note that the reduced effective modulation depth will never approach zero because of a residual contribution resulting from the fast recovery component, which is usually not exploited in our case.

Another contribution affecting the QML threshold originates from the gain medium: Er,Yb-doped phosphate glass is an inhomogenously broadened gain material, as laser atoms at different sites in the matrix see different local surroundings. This leads to a certain distribution of emission- and absorption cross sections. Calculations are usually performed with averaged cross sections but the gain saturation fluence is dominated by the ions with the highest cross section. Therefore the gain saturation fluence will be overestimated leading again to an overestimation of the QML threshold.

2.4.2 SESAM structure

Generally speaking, a SESAM is a semiconductor absorber embedded in a Fabry-Pérot-structure. In our case, the Fabry-Pérot consists of a high reflecting distributed Bragg reflector (DBR) and the semiconductor-air interface, serving as the second mirror. The properties of the second mirror can be modified by an optical coating or be replaced by a second DBR to modify the electric field inside the structure or the group delay dispersion of the device. SESAMs are usually grown either by
molecular beam epitaxy (MBE) or metal-organic chemical vapour deposition (MOCVD). Figure 2.5 shows a schematic of a typical SESAM structure.

![Structure of a SESAM with DBR, spacer layer, absorber and cap layer (left to right).](image)

On top of the DBR, embedded between transparent spacer- and cap-layers, is sitting the absorber section consisting of one or multiple quantum wells (QW) or quantum dot (QD) layers respectively. The material composition of the absorbers is chosen such that the bandgap energy of the material matches the photon energy of the laser wavelength. The spacer layer is usually chosen such that the absorber layers sit in an anti-node of the standing wave pattern of the electric field inside the multilayer structure. With the thickness of the cap-layer the magnitude of the electric field at the absorber position can be controlled. With an accumulated roundtrip phase in the cap layer of \((2m - 1)\pi\), we speak of an antiresonant structure while for a roundtrip phase of \(2m\pi\) the structure is resonant.

**DBR**

The DBR inside the SESAM structure consists of alternating \(\lambda/4\) layers of high refractive index material (in our case GaAs with \(n_{GaAs} = 3.377\) at 1.55 µm) and low refractive index material (in our case AlAs with \(n_{AlAs} = 2.8938\) at 1.55 µm). With increasing number of layer pairs the reflectivity of a DBR increases while the reflectivity bandwidth remains constant. Depending on the thickness of the topmost DBR layer, the mirror will be either antiresonant or resonant. For DBRs with the same number of layer pairs, the transmission through a resonant device can be more than ten times higher compared to the antiresonant structure as it is shown in Table 2.1. One has to take these losses into account when designing a SESAM. As we will see in section 4.3.1, for high repetition rate lasers it is especially important to keep intracavity losses low, such that in the resonant case we need 30 DBR layer pairs to...
reduce the transmission losses to 0.03% which is low compared to the typical output coupling in the order of 1%.

<table>
<thead>
<tr>
<th>mirror pairs</th>
<th>antiresonant T [%]</th>
<th>resonant T [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.09</td>
<td>1.11</td>
</tr>
<tr>
<td>25</td>
<td>0.01</td>
<td>0.19</td>
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<tr>
<td>30</td>
<td>0.00</td>
<td>0.03</td>
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</tbody>
</table>

Table 2.1 Transmission losses of antiresonant and resonant DBRs with different number of layer pairs.

**Antiresonant SESAM**

Figure 2.6 (left) shows the index profile and the electric field distribution of an antiresonant SESAM. An InGaAs QW-absorber is embedded between \( \frac{\lambda}{2} \) GaAs spacer- and \( \frac{\lambda}{4} \) cap layers, resulting in a rather low electric field at the absorber position. The local field intensity \( I(z) \) inside the SESAM is calculated from the normalized electric field \( E_n(z) \), the incident intensity \( I_{inc} \) and the local refractive index \( n(z) \):

\[
I(z) = n(z) |E_n(z)|^2 \cdot I_{inc}
\] (2.14)

For a 100% reflective DBR the resulting maximum intensity \( |E_n(z)|^2 \) outside the structure would be four. We define a field enhancement factor \( \xi_{abs} \) for the absorber as

\[
\xi_{abs} = |E_n(z_{abs})|^2
\] (2.15)

with \( z_{abs} \) being the z-position of the absorber. The field enhancement is an important design parameter as it directly influences the macroscopic properties of a SESAM: the modulation depth is proportional to the field enhancement \( \Delta R \propto \xi_{abs} \) while the saturation fluence is inverse proportional \( F_{sat} \propto 1 / \xi_{abs} \). The product \( \Delta R \cdot F_{sat} \) remains constant. As we have seen in section 2.3, for high repetition rate lasers, one of the main goals is to get this product as small as possible. In the antiresonant structure the field enhancement is rather low, \( \xi_{abs} = 4 / n^2 \approx 0.34 \) (for the GaAs/AlAs material system), leading to typical saturation fluences in the order of tens to hundreds of micro-Joule per square centimetre and to modulation depths below 1%. In high
repetition rate lasers, antiresonant SESAM are generally used only in systems with high average output power, where the pulse energy is sufficiently large to saturate the absorber [49]. The advantages of antiresonant devices are their flat GDD profiles and their wavelength independent field enhancement factor (Figure 2.6, right). Further they are relatively insensitive to growth errors.

![Figure 2.6](image)

**Figure 2.6** Properties of an antiresonant SESAM. Left: refractive index profile (solid) and electric field (dashed). Right: the calculated GDD (solid) and field enhancement at the absorber position (dashed) are rather flat in dependence of the incident wavelength.

**Resonant SESAM**

Figure 2.7 shows the properties of a resonant SESAM [19]. The absorber is placed on top of a $\lambda/2$ GaAs spacer layer while the thickness of the GaAs cap layer is reduced to only a few nanometers, protecting the absorber from oxidization. This results in a field enhancement at the absorber of $\xi_{\text{abs}} = 3.9$ (for GaAs/AlAs), which is about a factor of 12 larger compared to an antiresonant device. A resonant SESAM therefore has a low saturation fluence, often below 10 µJ/cm². This would be favourable for high repetition rate lasers, as pulse energies are in general very low. In turn the modulation depth of the resonant structure is rather high, which can lead to Q-switching instabilities, such that resonant devices are mostly not suitable for the use in high repetition rate lasers. In addition, a resonant structure exhibits enhanced non-saturable losses, which are not desired, and a strong wavelength dependent phase change, leading to a strongly varying GDD (Figure 2.7, right, solid), which ultimately limits the operation bandwidth. Because of the strong wavelength dependence, resonant devices are fairly sensitive to growth errors.
Antireflection coated SESAM

With an antireflection coating applied to a resonant SESAM, one can get an intermediate solution between the resonant and the antiresonant case (Figure 2.8) [19]. The coating is a dielectric $\lambda/4$-layer with a refractive index lower than that of the low-index DBR material, reducing the resonance inside the SESAM and the field enhancement at the absorber position. Due to the lower resonance, the GDD of an antireflection coated SESAM is rather flat and close to zero around the SESAMs design wavelength (Figure 2.8, right, solid), enabling the generation of short pulses at high repetition rates [19].
The field enhancement is about half the value of a resonant device but rather wavelength independent (Figure 2.8, right, dashed). For high repetition rate lasers the antireflection coated SESAM is an ideal choice as it offers moderately low saturation fluence together with low modulation depth and a broad operating bandwidth. In addition it is comparably insensitive against growth errors.
Chapter 3

SESAM characterization

Precise knowledge of the nonlinear reflectivity change is crucial to optimize SESAMs for self-starting, passive mode-locking at record high repetition rates. In the framework of this thesis we built a high-precision, wide dynamic range nonlinear reflectivity measurement setup operating in the 1.5-µm spectral region, which is a slightly modified version of the one described by Maas et al. [50].

3.1 Measurement setup

Compared to previous approaches developed by Haiml et al. [43], this setup reduces the overall complexity and the amount of expensive equipment, while increasing the accuracy. For the measured reflectivity, we achieve an accuracy of 0.05% for an incident pulse fluence varied over 3.5 orders of magnitude.

The measurement system, which is shown in Figure 3.1, consists of three main building blocks: A mode-locked laser source (not shown), a variable attenuation stage and the main detection section. As we want to characterize samples under conditions similar to those the SESAM will experience in a laser cavity, the used laser source should offer comparable pulse duration and the same center wavelength. Further, the pulse energy must be sufficient to saturate the SESAM under test. The pulse fluence incident on the sample should be at least 10 times the saturation fluence of the sample, for a precise parameter extraction [43]. Because at high repetition rates, the absorption of some SESAMs does not fully recover between subsequent pulses, ideally the test laser source should operate at the same pulse repetition rate as the laser the SESAM-sample will be used in, to obtain most accurate...
results. In our case this is not possible, as suitable lasers with sufficient output power do not exist to date.

Our laser source is a 62-MHz Er,Yb:glass laser with an average output power of 55 mW and a center wavelength of 1535 nm. Because the laser is SESAM mode-locked without any dispersion compensation, we obtain a pulse duration of 2.5 ps, which is comparable to typical pulse durations of high repetition rate lasers. The time-bandwidth product of 0.54 is 1.7 times the transform limit for sech² pulses. To obtain the pulse fluence required to saturate the sample at least ten times above its saturation fluence, we strongly focus the laser beam onto the sample under test, thereby achieving a maximal fluence of 330 µJ/cm². With the attenuation stage we obtain a lower limit of 0.08 µJ/cm². As we want to develop SESAMs with a saturation fluence of 1-5 µJ/cm², this dynamic range of about 3.5 orders of magnitude is sufficient to accurately extract the SESAM parameters from the measured data.

Figure 3.1 Characterization setup to determine the nonlinear reflectivity behaviour of a SESAM. The output of the pulsed laser source propagates through an isolator, eliminating back reflections, then through a variable attenuation stage into a detection section. The reflectivity of the SESAM is determined by measuring the response from a reference and a signal arm and computing the ratio.
In the detection section, the SESAM is measured under normal incidence. Because of the high reflectivity of the SESAM, this leads to strong back-reflections into the laser source. We therefore use a 30-dB isolator to prevent perturbations in the mode-locked laser.

Because the variable attenuation section has to cover a wide dynamic range, we used two crossed Glan-Thompson polarizers (GTP), with an extinction ratio of 100'000:1, in conjunction with a rotatable λ/2-wave. In principle the attenuation stage could be build with the two polarizers only, using the second one to select the desired polarization, while the first, rotating one, adjusts the attenuation. Because the used Glan-Thompson polarizers have an asymmetric acceptance angle, with only 0.5° to one side, it is difficult to use them in a rotation stage, while maintaining proper beam alignment over the full rotation angle. We therefore used a λ/2-wave plate to rotate the linear polarization between the crossed polarizers, thereby adjusting the attenuation. Because we use picoseconds pulses for our characterization, the limited bandwidth of a λ/2-wave plate is not an issue.

The detection section looks somewhat similar to a Michelson interferometer: a non-polarizing 50:50 beam splitter (BS) divides the incident beam into a reference beam, which is sent to a high reflector, and a sample beam, which is focussed on the SESAM under test. Both reflected beams are recombined by the beam splitter and detected by a photodiode. Close to the beam splitter, we use a 4-segment chopper wheel to separate the reference- and the sample beam in time, such that they can be detected independent of each other with one single detection system. With this configuration, one either detects the reference signal or the sample signal exclusively such that the reflectivity of the sample can be retrieved in dependence of the incident pulse fluence (we assume that the high reflector in the reference arm does not change its reflectivity with varying incident fluence). By lifting the rotation axis of the chopper wheel above the optical axis, one obtains not only two but four different states: 1. detection of the reference, 2. detection of both superimposed beams, 3. detection of the sample beam only and 4. both beams are blocked. This has the advantage that in state 4 the background signal from environmental light and also from the photodiode’s dark current can be detected and later discriminated from the signals measured in state 1 and 3.
Figure 3.2  Measured photodiode signal showing four different states. The
SESAM reflectivity can be calculated from levels A and B.

The detected signal over time leads to a step-function as it is shown in Figure 3.2. This signal is sampled with a 24-bit analog-to-digital (AD) converter and evaluated with a computer. Before digitizing, a computer-controlled transimpedance-amplifier is amplifying the photodiode signal. By adapting the amplification, we can always use the full dynamic range of the AD converter.

From the digitized signal, levels A and B can be calculated by subtracting the absolute voltage measured in state 4 from the signals obtained in states 1 and 3 respectively. The nonlinear reflectivity \( R \) of the sample under test is then obtained by dividing \( B \) and \( A \) as \( R = B/A \). This evaluation is averaged over 500 periods, thereby minimizing noise influences, such that the averaged reflectivity has a standard deviation of 0.01%. The incident fluence can be calculated from level A and the gain of the transimpedance amplifier. An accuracy of 5% of the determined fluence will result in the same inaccuracy for the fitted saturation fluence, which is usually good enough.

### 3.2 Alignment and calibration

Because of the required high precision of the measured reflectivity-change and the large dynamic range of the incident fluence, the measurement is very sensitive against stray light or parasitic reflections. Particularly at low fluences, we have
observed up to 2% absolute errors in the measured reflectivity caused by parasitic perturbations. A good shielding of the detector and proper alignment of the setup therefore is essential. Most optics which are used in transmission are slightly tilted, to prevent reflections from the surfaces hitting the photodiode. To achieve identical photoelectric conversion from the detector for the reference- and the sample beam, the optical layout of the setup is designed such that we obtain the same spot size and lateral position on the photodiode for both beams. The laser beam that enters the setup is collimated after the isolator, with a beam-waist on the reference mirror. If the sample is also placed in the waist of the focussing lens, both returning beams have the same beam parameter again. To verify the final diameter and position of both beams, a beam profiler can be used at the detector position.

![Figure 3.3 Nonlinear reflectivity measurement of a SESAM used to determine the beam waist of the focused sample beam. The fit-curve matches the measured data very well. Because of the large modulation depth, the saturation fluence (vertical dashed line) can be determined very accurately.](image)

For a measurement, the sample under test has to be placed exactly at the waist of the focussing lens under normal incidence. To calibrate the sample orientation, we first remove the focussing lens and align the back-reflex of the SESAM on a far aperture in the incident beam path. After this, the lens is inserted and aligned such that the back-reflex from the SESAM again hits the aperture. To obtain the exact focus position, several measurements are performed while moving the SESAM along the optical axis through the caustic of the focussing lens. The focus is the position in which we obtain the lowest saturation fluence. The saturation fluence is retrieved
from the measured data by using the fit function (2.10) with finite spot size correction (2.9). For this calibration procedure we use a SESAM with a particularly high modulation depth of about 6% (Figure 3.3), because the saturation fluence can be determined most accurately for such a sample.

When replacing the calibration SESAM by a new sample, special care has to be taken, as minor misalignments can lead to large measurement errors. To ease the alignment of the sample orientation, we implemented a flip-mirror into the detection arm, sending the reflected beams onto a CCD-camera. Once the setup is calibrated, the position of the sample beam can be marked on the CCD observation screen such that other samples can be aligned to the same spot. To retain the focal position, we use a green alignment laser reflecting off the sample under a flat angle of incidence with respect to the sample surface, to hit an alignment-aperture. In this configuration the reflected beam is highly sensitive to the z-position of the sample with a reproducibility of approximately 10 µm, which is well below the Rayleigh length of approximately 60 µm.

After calibrating the position of the sample, the reflectivity has to be calibrated by measuring the reflectivity of a high reflecting mirror, instead of a SESAM. This should result in a flat response with respect to the incident fluence, at the nominal reflectivity of the used high reflector. The flatness of this calibration curve is a good measure for the alignment accuracy of the setup. Figure 3.4 (left) shows a measurement of a high reflector with a flatness of 0.05%. Because of the additional lens, the signal from the sample arm is typically somewhat lower than the reference signal (as it is shown in Figure 3.4, left). We compensate for this offset by a calibration factor. In case of systematic errors, the calibration can be a function of the incident fluence. To determine the maximal incident fluence, the maximum average power (corrected with the duty-cycle of the chopper wheel) as well as the beam diameter are measured at the sample position. Furthermore we have to determine the exact repetition rate of the laser source.

3.3 Results

With this new setup we were able to measure SESAMs with a modulation depth of only about 0.16%, as it is shown in Figure 3.4 (right). This was not possible with the previous existing setup build by Haiml et al. where the achievable resolution for
the measured reflectivity was limited to about 0.3%. More results will be given in section 4.5.3 where we used the setup for the optimization of a SESAM employed in a 100-GHz laser and in section 6.2, where we report an approach to develop a 1.5-μm quantum-dot SESAM.

Figure 3.4 Measurement of a high reflecting mirror without calibration (left). The flatness of the measured response is 0.05%. With the setup, SESAMs with a modulation depth below 0.2% can be characterized (right). The vertical dashed line displays the determined saturation fluence $F_{\text{sat}}$. 

![Graph](image-url)
Chapter 4

High repetition rate Er, Yb:glass lasers at 1.5 µm

In this chapter we will discuss fundamental properties of high repetition rate Er, Yb:glass lasers and address important design considerations. We will present results obtained from fundamentally mode-locked Er, Yb:glass lasers with repetition rates up to 100 GHz. To the best of our knowledge, this is the highest repetition rate obtained directly from a passively mode-locked solid-state laser oscillator operating in the 1.5-µm telecom window. For comparison, we start with a brief overview of competing technologies used to produce multi-GHz pulse trains in the 1.5-µm spectral range and discuss their particular properties and performance.

4.1 Multi-GHz pulse sources at 1.5 µm

As described in Chapter 1, there is great interest in GHz-laser sources operating in the 1.5 µm spectral regime, which provided a strong motivation for numerous different approaches to develop and improve lasers generating such pulse trains (Figure 4.1). For comparison it is instructive to briefly consider the performance and particular properties of different technologies, used to generate multi-GHz pulse trains in the 1.5-µm spectral regime.

First, we address edge-emitting semiconductor lasers which are often used for applications in the 1.5 µm region, because they are compact, reliable and cheap. They can be passively mode-locked or hybrid mode-locked (which is a combination
of active and passive techniques) at very high repetition rates but at limited average output power and pulse peak power. Because it is essential for mode-locking to operate the laser in a single transverse mode, the total mode area is limited in these devices, leading to a low average output power. Because of the comparably long beam path in a medium with large refractive index, edge emitting semiconductor lasers in general show strong dispersive effects and high nonlinearities at high peak powers. Also the noise performance of edge emitting lasers is intrinsically comparably poor [51]. Up to 1.5 THz pulse-trains could be generated with passive harmonically mode-locked edge emitters but with compromised pulse quality [52].

![Figure 4.1 Performance of competing GHz-sources emitting in the 1.5 µm spectral region [16, 21, 25, 52-71].](image)

Another type of semiconductor laser are vertical external cavity surface emitting lasers (VECSEL), also often referred to as semiconductor disk lasers. In a VECSEL light is emitted perpendicular to the epitaxial interface, leading to an extremely short gain length, which reduces dispersive effects. Large mode areas and a nearly one dimensional heat flow generally facilitate high output powers and good beam quality with short pulses at high repetition rates. In addition, their exceptionally low gain saturation fluence eliminates the tendency for Q-switching instabilities. However, in the 1.5 µm spectral region the full potential has not yet been exploited. So far a maximal repetition rate of 3 GHz with 3.2-ps pulses and 120 mW of average output power could be achieved [61]. This is mainly due to shortcomings of the different material systems used in this spectral regime: either the index-contrast
within the material system is comparably low (leading to either complex heterostructures or enhanced losses) while the gain sections are of good quality or the other way round. A promising way to overcome this issue could be the wafer fusion technique, combining different material systems, and therefore improving the overall device performance [72].

Fiber lasers have drawn much interest in the recent years, due to some of their very attractive properties: they are compact, efficient, mechanically stable, virtually maintenance free, often pumped by reliable and long lasting telecom diodes and they can produce a diffraction limited output even at very high output levels. To reach multi-GHz pulse repetition rates, fiber lasers usually have to be harmonically mode-locked due to their comparably long resonators. This is mostly done by active mode-locking techniques as passive approaches often lack of equidistant pulse spacing due to multi-pulse bunching [73], or show enhanced supermode noise background [74]. Active mode-locking always requires GHz driving electronics. Because of the long gain-interaction length, fiber lasers are rather susceptible to environmental influences. Therefore additional stabilization- or noise-suppression techniques often have to be applied, making GHz fiber lasers somewhat complex and expensive. With harmonically mode-locked fiber lasers up to 200 GHz in 1-ps pulses with an average output power of 6 mW [66] and 430 mW at 100 GHz and picoseCONDS pulses have been reported [65]. Just lately, with the availability of highly doped Er,Yb-fibers, a fundamentally mode-locked 10-GHz fiber laser was demonstrated, not suffering from the above mentioned issues. This laser is passively mode-locked by a carbon-nanotube saturable absorber, and generates rather long pulses of 4.1 ps and an average output power of 30 mW [71].

At 1.5 µm, solid-state gain media suitable for multi-GHz operation are rather limited. Lasers based on Cr:YAG offer several interesting features: due to their broad absorption band around 1 µm they can be pumped with laser diodes operating around 970 nm but also with high-power high-brightness lasers such as Nd-doped solid-state lasers or Yb-doped fiber lasers. Their emission bandwidth fully covers the telecom bands and even supports the generation of ultrashort pulses below 20 fs [75]. Although Cr:YAG offers comparably high emission cross sections the material suffers from poor laser efficiency at high repetition rates, mainly due to compromised crystal quality at high doping levels [76]. Therefore the doping-concentration for Cr:YAG is limited such that rather long gain crystals are required,
ultimately limiting the achievable repetition rate to a few GHz. Furthermore, to achieve useful output-powers high-power solid-state lasers or fiber lasers with excellent beam quality are required for pumping, making the overall system bulky and expensive. Nevertheless, pulses as short as 81 fs with an average power of 85 mW at 4 GHz could be demonstrated so far [57], but at pump-powers exceeding 2.5 W.

While synchronously pumped monolithic optical parametric oscillators (OPO) [77] offer a very broad tuning range [62] and high output power [63], the principal concept is fairly complex and therefore not cost effective. To pump the oscillator, a high repetition-rate laser pump source is needed, which again has to be pumped by another high power pump laser. In addition synchronization electronics for the pump laser is required and for very high output powers one needs intermediate fiber amplifiers. With synchronously pumped OPOs repetition rates up to 81 GHz, a tuning range of up to 153 nm and output-powers of up to 2.1 W could be achieved. All of these results showed reasonable pulse durations in the low ps-regime.

Passively mode-locked Er,Yb:glass lasers represent a simple and efficient way to directly generate a high repetition rate ps-pulse train with excellent pulse quality in the telecom C-band (1530 nm-1565 nm). Due to their miniature cavities they are compact, they can be pumped by standard telecom diodes and only need a low-cost gain medium, which is available in good optical quality, and a SESAM. Because their pulse generation is entirely passive, no high frequency electronics is required. Fundamentally mode-locked, they exhibit excellent timing jitter performance and their high-Q cavities lead to a very low quantum noise limit [29, 78, 79]. These advantages motivated us, to focus our interest on the development of these lasers. In the following we describe in more detail the properties of Er,Yb:glass lasers and report about record high pulse repetition rates obtained with this type of laser.

4.2 Properties of Er,Yb:glass

For lasers operating in the 1.5 µm spectral region, the choice of gain media is rather limited. We found Er:Yb-doped phosphate glass to be a good choice, as it offers a broad gain bandwidth, which covers almost the entire telecom C-band and also supports reasonably short pulses. In addition it has its absorption peak at 976 nm and can therefore be pumped by rugged, high brightness, standard telecom laser
diodes. Er,Yb:glass is robust and low-cost as it can be produced in large quantities with excellent optical quality. Less favourable is the low emission cross-section as well as the low thermal conductivity of the glass matrix. While the emission cross-section leads to a strong tendency for QML, the low thermal conductivity limits the maximum output power, either by enhanced thermal lensing effects or ultimately by thermally induced fracture. Typically, optical damage occurs for absorbed pump powers above 1-2 W [80]. Er,Yb-doped crystal hosts, which offer better thermal properties, typically show poor laser efficiency [81, 82] and are therefore not suitable for high repetition rate passively mode-locked lasers. Only lately, a promising new Er,Yb-doped crystal has been reported together with corresponding laser results. We will get back to this material in section 6.1. There have also been different successful approaches to improve the thermal properties of Er,Yb-doped glasses [83]. However, we worked with standard QX-phosphate glasses from Kigre as they show sufficient thermal fracture resistance for power levels typically used in telecom applications and thermal lensing is not a limiting factor in our cavities. Table 4.1 lists the most important properties of Er,Yb-doped phosphate glass.

<table>
<thead>
<tr>
<th>Properties of Er,Yb:glass (Kigre QX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>emission wavelength peak [nm]</td>
</tr>
<tr>
<td>fluorescence linewidth, FWHM [nm]</td>
</tr>
<tr>
<td>upper-state lifetime [µs]</td>
</tr>
<tr>
<td>Emission cross section [10^{-20} cm^2]</td>
</tr>
<tr>
<td>Absorption cross section (@ 977 nm) [10^{-20} cm^2]</td>
</tr>
<tr>
<td>Saturation fluence [mJ/cm^2]</td>
</tr>
<tr>
<td>Thermal conductivity (@ 300 K) [W/m K]</td>
</tr>
<tr>
<td>dn/dT (@ 300 K) [10^6 K^{-1}]</td>
</tr>
<tr>
<td>Refractive index (laser line)</td>
</tr>
</tbody>
</table>

Table 4.1 Properties of Er,Yb-doped phosphate glass (Kigre QX).

Because the lower lasing level of erbium is populated at room temperature, Er,Yb:glass is a quasi–three level laser medium, such that re-absorption losses lead to an inversion dependent effective gain curve. To use a maximum of the rather broad fluorescence bandwidth of Er,Yb:glass, an accurate adjustment of the inversion level is needed. Figure 4.2 (left) shows the emission- and absorption cross sections of a 2-
mm thick Brewster plate of QX/Er phosphate glass, doped with $4.5 \times 10^{19}$ Er ions/cm$^3$ and $1.4 \times 10^{21}$ Yb ions/cm$^3$. Figure 4.2 (right) shows the calculated gain spectra obtained from these cross sections, for different inversion levels [84] (note that the measured cross sections differ from the values given in Table 4.1, which were taken from the official data sheet). It is clearly visible that a flat gain profile with a broad gain bandwidth of about 40 nm (FWHM) is obtained at an inversion level of 70%. Such a gain profile, which is supporting shorter pulses and a larger tuning range, can be achieved with an appropriate output coupling rate.

Because erbium has a low absorption cross section around 1 µm, most of the pump radiation is absorbed by the Yb-ions, which are used as a sensitizer and have an efficient absorption band between 970 nm and 980 nm. The concentration of Yb-ions is usually quite high (>20 % in our case), which leads to short absorption lengths and also to a resonant, non-radiative energy transfer to the Er-ions, which provide the laser transition in the 1.5 µm range.

4.3 Laser design considerations

4.3.1 Laser cavity design

Starting from well-known MHz SSL-cavities, to achieve GHz repetition rates with fundamental mode-locking, the length of the optical resonator has to be reduced by a fair amount. As an example, the resonator length of a 10-GHz standing-wave cavity in air is about 15 mm and consequently only about 1.5 mm for a 100-GHz laser. In general, standing wave cavities are preferred over ring cavities, as the double-pass
through the gain reduced the QML threshold. As equation (2.5) implies, one requirement to suppress QML at high repetition rates, are small mode-areas in the gain medium as well as on the saturable absorber. In such short laser resonators, this can only be realized with strongly curved mirrors and a folded cavity configuration. For the lasers presented in this chapter we used mirrors with radii of curvature reaching from 5 mm down to 0.4 mm, which is quite demanding from a manufacturing point of view. To maintain high intracavity power and therefore reduce the QML threshold, it is important to build cavities with a very high Q-factor. Therefore low output coupling and mirrors with extremely low losses and good scattering properties are essential. In an iterative process we optimized the surface-accuracy as well as the micro-roughness of these mirrors to reach the required quality. Low scattering properties in general are crucial for stable operation as the laser becomes sensitive to weak spurious reflections due to the small modulation depth of the used saturable absorbers. Scattered reflections can lead to satellite pulses in the cavity, resulting in undesired frequency sidebands in the output of the laser. To further reduce scattering it is important to achieve and maintain a good surface cleanliness in the manufacturing process, to avoid inclusions of dust particles and cleaning traces into the coatings. The used dielectric coatings should exhibit low intrinsic scattering properties. Figure 4.3 shows some of the rather small cavity mirrors used in the lasers presented in this thesis.

Figure 4.3 Photograph of several strongly curved mirrors used in different laser designs. To improve the mirror handling, the substrate diameter is chosen to be somewhat larger than the clear aperture.
4.3.2 Pumping considerations

The pumping technique has to be considered, as it sets a lower limit for laser mode size in the gain medium. We generally use a longitudinal pumping-scheme, matching the laser cavity mode to the pump mode in the gain element. For stable single transverse mode operation we choose the pump mode to be slightly smaller than the laser mode. The lower limit of the laser mode size in the gain element is then set by the minimal achievable pump spot size, and therefore by the beam quality of the used pump source. In addition, the absorption length of the gain medium has to be especially considered as it sets additional constraints: when the collimated pump beam is focused into the gain glass, the Rayleigh length of the pump focus has to be adapted to the thickness of the gain element. For a given beam quality of the pump beam, the beam waist diameter scales with the Rayleigh length. A short absorption length of the gain medium allows a thinner gain element and therefore a smaller pump beam waist. An ultimately limiting factor for the minimal reasonable pump mode size might be thermally induced fracture of the gain material which prohibits too strong focusing.

Of course it is possible to use a high power, high brightness solid-state laser pump source, such as a cw Ti:Sapphire laser operating in TEM$_{00}$ mode. For simplicity and efficiency (with respect to the laser performance as well as the overall system costs) we prefer direct diode-pumping. We use standard telecom fiber-coupled laser diodes which are wavelength stabilized at 976 nm by a fiber Bragg-grating (FBG), delivering up to 750 mW out of a polarization maintaining (PM) single-mode fiber. Due to the fiber Bragg-grating the output of the pump diode is insensitive against thermal variations.

Depending on its thermal properties, a gain material will always show thermal lensing effects under strong pumping. In our case the focal length of the induced thermal lens in the gain element can easily reach values comparable to the radii of the curved cavity mirrors. For the above mentioned reasons, we usually place the gain element in a waist of the intracavity field. Because of the relatively small pump mode radius of typically 20-30 µm, the stability of the cavity versus a varying thermal lens is large [85], such that the induced thermal lens usually has only a negligible effect on our cavity design.
4.3.3 Pulse shaping

In passively mode-locked high repetition rate lasers the pulse shaping is usually done by a slow saturable absorber only. Therefore the modulation depth of the absorber has an important influence on the minimal achievable pulse duration of the laser. As an estimate we can use

\[ \tau_p \approx \frac{1.07 \Delta \nu_g}{\Delta R} \sqrt{\frac{g}{\Delta R}} \]  

(4.1)

to calculate the pulse duration (FWHM)[37], where \( \Delta \nu_g \) is the gain bandwidth, \( g \) is the saturated roundtrip gain and \( \Delta R \) is the modulation depth of the saturable absorber. It becomes apparent that a larger modulation depth \( \Delta R \) has a stronger pulse shaping effect, leading to shorter pulses.

![Figure 4.4 Calculated pulse duration versus modulation depth \( \Delta R \) for an estimated constant gain bandwidth of 1.91 THz (± 15 nm at 1535 nm center-wavelength) and different values of the saturated roundtrip gain \( g \). A larger modulation depth \( \Delta R \) has a stronger pulse shaping effect leading to shorter pulses but also to Q-switching instabilities. Effects of the inversion-dependent gain bandwidth are neglected.](image)

However, the stability criterion for QML, given in equation (2.4), prohibits a large modulation depth. If we want to increase the repetition rate of a laser, in general we have to decrease the modulation depth of the saturable absorber to maintain stable cw mode-locking (assuming that we can keep the saturation parameter \( S \) constant by decreasing the mode area on the SESAM respectively). By doing so, we
automatically increase the pulse duration. Together with a decreasing cavity roundtrip time, this leads to a potential pulse overlap that finally limits the achievable repetition rate. By rewriting the stability criterion given in (2.4) to become

\[ \frac{E_p}{E_{sat,L}} > \frac{\Delta R}{S} \]  

(4.2)

with the saturation parameter \( S = \frac{E_p}{E_{sat,A}} \), we can see that the brightness of the pump together with the absorption length of the gain material ultimately limits the achievable minimal pulse duration, as they determine the maximal achievable value for \( E_p/E_{sat,L} \) and therefore the upper bound for \( \Delta R \) (\( E_{sat,L} \) depends on the effective laser mode area in the gain medium, as written in equation (2.3)).

Typical pulse durations for high repetition rate solid-state lasers lie well within the single-digit picosecond regime. For significantly shorter pulses soliton mode-locking [86-88] appears to be an attractive technique, combining anomalous second order dispersion with self-phase modulation, to shape the pulse. However, for Er,Yb:glass lasers operating in the multi-GHz regime the laser’s pulse peak-power drops and the gain length becomes very short, such that the obtained non-linear phase change in the gain medium becomes too small for soliton pulse formation. To obtain pulses well within the femtosecond regime, a saturable absorber with a substantially faster recovery time is needed, such as SESAMs relying on the Stark-effect [89]. However, for the 1.5 \( \mu \)m spectral range, such devices have not been reported so far.

4.4  Er,Yb:glass lasers with 10-50 GHz

4.4.1  Experimental setup

Figure 4.5 shows the setup of a diode pumped multi-GHz solid-state laser. The laser is based on a V-shaped resonator, consisting of three mirrors: two curved dielectric mirrors, one being the output coupler with a transmission between 0.5% and 1.3%, and the SESAM used as the end mirror of the resonator (Figure 4.5, left). The SESAM is mounted on a piezo-element enabling us to fine-tune the repetition rate of the laser over several MHz (depending on the fundamental repetition rate) with a precision of about 1 kHz.
Figure 4.5  Experimental setup for a V-shaped 10-50 GHz Er,Yb:glass laser cavity. Schematic (left) and photograph of a 50 GHz laser (right). As shown in the schematic, different pumping options are possible, depending on the clear aperture of the used mirrors.

The gain glass, which is placed between the two curved mirrors, is pumped either through the cavity folding mirror or alternatively through the output coupler. In the latter case an additional dichroic mirror is used to separate the laser output from the pump beam. To reduce losses and parasitic reflections and therefore maintain a high-Q cavity, the gain glass is inserted in a flat-flat configuration under Brewster’s angle rather than under normal incidence with anti-reflection coatings applied to the optical surfaces. This also ensures linearly polarized laser operation. In all lasers we use Kigre-QX Er,Yb co-doped phosphate glass. With increasing repetition rate, the thickness of the gain element has to be reduced for geometrical reasons. To compensate for the shorter gain length, the doping concentrations are increased accordingly (actual doping levels are proprietary information of Time-Bandwidth Products Inc.). The laser cavities up to a repetition rate of 25 GHz allow the additional insertion of a solid 20-μm low-finesse etalon (not shown in the picture), which enables wavelength-tuning of the laser emission over almost the entire telecom C-band.

The used SESAMs are MBE-grown and consist of a 30 GaAs/AlAs layer-pair DBR, with a single InGaAs QW-absorber on top, embedded between transparent GaAs spacer- and cap layers. The thicknesses of the GaAs layers are adapted to achieve a saturation fluence of 15 μJ/cm² and a modulation depth of 0.4%, with the absorber sitting in an antinode of the standing-wave pattern of the electric field.

Our optical design is optimized to achieve small mode diameters in the gain medium as well as on the SESAM. Because of the limited degrees of freedom the mode-sizes cannot be optimized independent of each other such that a global optimum has to be found.
4.4.2 Results

With this cavity design we could achieve repetition rates ranging from 10 GHz up to 50 GHz. In particular the 12.5-GHz and the 25-GHz lasers that we developed for the multi-wavelength source described at length in Chapter 7 are based on this design. Figure 4.6 shows the output parameters of a 50-GHz laser. More detailed results of the different lasers built with this principle optical layout are listed in Table 4.4 in section 4.6.

In an additional experiment, we have broaden the output of the 50-GHz laser with a highly nonlinear photonic crystal fiber (PCF) to obtain a multi-wavelength source directly matching the 50-GHz ITU telecommunication grid [90]. Because the concept of a multi-wavelength source for telecom applications will be described in detail in Chapter 7, we do not want to go into further details at this point.

Higher repetition rates than 50 GHz are not feasible with this approach mainly due to the extent of the gain element which is used under Brewster’s angle, thereby filling up most of the free space inside the cavity (Figure 4.5, right). This prevents the cavity mirrors to be moved closer together.

With a new cavity design, Zeller et al. could overcome this limitation to achieve a repetition rate of 77 GHz in 3-ps pulses and an average output power of 10.7 mW [70]. In the new design, the shape of the Er,Yb:glass was changed to a triangular geometry such that it could be used in a flat-brewster configuration. Together with a
flat output coupler on a wedged substrate, the overall cavity length could be reduced by 35%. In addition the size of the curved folding mirror was reduced to a diameter of 0.8 mm with a clear aperture of about 0.7 mm. But again, a further increase of the repetition rate was limited by geometrical restrictions.

4.5 100-GHz Er,Yb:glass laser

In this section we demonstrate a SESAM mode-locked diode-pumped Er:Yb:glass laser, which operates at a record high repetition rate of 101 GHz, generating 35 mW average power in 1.6 ps pulses. Previously, such repetition rates directly generated by a fundamentally mode-locked laser were only achieved around 1-µm wavelength. There, gain media with larger emission cross section are available [38], which strongly reduces the tendency for Q-switching instabilities [22]. Compared to previous results [70, 91] we have significantly increased the pulse repetition rate, reduced the pulse duration by a factor of two and increased the average output power by a factor of three.

4.5.1 Experimental setup

To achieve a repetition rate of 100 GHz, fundamental mode locking leads to an extremely small cavity length of about 1.26 mm (taking into account that the beam-path inside the gain medium, with a refractive index of 1.53 at 1550 nm, represents a substantial fraction of the overall cavity length). The used cavity is a modified version of the design suggested by Zeller et al. [70]. We redesigned the geometrical shape of the folding mirror and the gain element and used a partially monolithic approach: the output-coupler coating is now directly applied to the flat side of the gain medium (Figure 4.7, left). Gain length, folding angle and mode-sizes have been adapted for stable cw mode-locking, while the overall pump geometry remained unchanged. Furthermore and most important, we improved the surface quality of the highly curved folding mirror (radius of curvature: 0.5 mm) as well as the scattering properties of the dielectric coating. By these measures, we increased the average output power and reduced the pulse duration substantially compared to previous results. Figure 4.7 shows a schematic of the setup (left), and a photograph of the actual laser cavity (right). The folding angle of the curved folding mirror is calculated such that it compensates the astigmatism introduced by the gain element as it is shown in Figure 4.8. The cavity has a round and stigmatic output beam, which can be efficiently coupled into a standard single-mode fiber.
Figure 4.7 Experimental setup for the 101 GHz laser cavity: schematic (left) and photograph (right). The Er,Yb:glass is flat on one side, coated with a 1.2% output coupler and under Brewster's angle inside the cavity. The collimated pump beam is focused into the gain glass such that it is mode-matched to the laser mode. The output beam is collimated by the same lens. Both beams are separated afterwards by a dichroic mirror. OC: output coupler.

Figure 4.8 Calculated beam divergence in dependence of the cavity folding angle. The laser cavity was designed such that the folding mirror compensates for the astigmatism introduced by the gain element. At a folding angle of 43 degrees the output beam is round and stigmatic.
At such high repetition rates, the intracavity pulse energies become very low (around 0.35 pJ in the described laser). To suppress Q-switched mode-locking, a small mode radius of about 15 µm is used in the gain medium. In addition, a tight focus of about 4 µm radius on the SESAM is needed for a sufficient saturation of the absorber [92]. The SESAM consists of an InGaAs quantum well embedded in a low finesse design, resulting in low saturation fluence of about 10 µJ/cm² and a modulation depth below 1% [19].

4.5.2 Results

We have generated a pulse train at 101.5 GHz with pulses of 1.6 ps pulse duration and 20 dB extinction ratio (Figure 4.9, left). Normally we would use a fast photodiode together with a microwave spectrum analyzer to determine the repetition rate, however, such devices operating to beyond 50 GHz were not available for this work. Therefore the repetition rate was determined with an autocorrelator from Femtochrome Research Inc. (model FR-103MN), by measuring the distance between the peaks of the autocorrelation and the first cross-correlations (Figure 4.9, right). The autocorrelator uses a rotating prism-pair as its varying delay arm, which is not internally compensated to provide a linear time scale at its analog output. If a large time-window is measured, some deviations from linearity have to be corrected. To calibrate the autocorrelator, we used a laser with 200-fs pulses at 1.5 µm wavelength to measure the temporal shift of the pulse peak position with respect to the length of the fixed delay arm. We could fit this dependence with a 2nd order polynomial to avoid an error of 10% over a scan length of 40 ps compared to a linear fit. As an additional verification, we also measured the distance between the autocorrelation- and the cross-correlation peaks by varying the fixed delay arm. We measured a path-length of 1.48 mm which corresponds to a pulse repetition rate of 101.28 GHz. This is in good agreement with the above result. The high average output power of 35 mW allowed us to directly measure the autocorrelation from the laser output without any further amplification, thus avoiding noise- and dispersion-issues which could be introduced by using a fiber-amplifier to amplify the pulse train. The optical spectrum shown in Figure 4.9 (left) is centered at 1534.8 nm with a full width at half maximum of 2.6 nm. This results in a time bandwidth product (TBP) of 0.53, which is 1.7 times the transform limit for sech² pulses. We measured the mode spacing in the optical spectrum to be 0.8 nm, which corresponds to a
repetition rate of 101.81 GHz, also confirming the repetition rate as measured with the autocorrelator.

Figure 4.9  Properties of a 101-GHz laser: optical spectrum (left, solid line), together with an ideal sech$^2$ fit (grey dashed line), giving an optical bandwidth of 2.6 nm centered at 1534.8 nm. The mode separation is 0.8 nm. The inset shows the spectrum on a logarithmic scale. Right: autocorrelation trace including cross-correlations (solid line) with fit-curve using ideal sech$^2$ pulses (grey dashed line). Cavity roundtrip time $T_R = 9.85$ ps. The pulses have a duration of 1.6 ps.

Figure 4.10  Mode-locked optical output power of a 101-GHz Er:Yb:glass laser. An average output power of 35 mW could be obtained at a pump power of 370 mW. The QML-threshold was at 2.8 mW, above this power-level the mode-locking was stable. The optical-to-optical efficiency is close to 10%.
The Q-switching threshold is below 2.8 mW output power. Above this power level, the pulse train is stable, which we could verify with the autocorrelator. Figure 4.10 shows the laser slope above the QML threshold together with the optical-to-optical efficiency. At 35 mW the power characteristic was not yet rolling over, such that higher output powers seem to be feasible. We did not further increase the pump power to avoid thermally induced damage of the gain element.

What is worth noting, besides the high repetition rate and the average output power, is the overall short pulse duration. Compared to the laser design described in section 4.4, in this setup the gain element is placed at the end of the laser cavity. This can lead to enhanced spatial hole burning effects which flatten the saturated gain and allow for larger lasing bandwidth thereby supporting shorter pulses [93, 94]. To reduce the pulse duration even further, we will optimize the dispersion of the SESAM, as it is described in the next section.

4.5.3 Post growth SESAM optimization

To achieve mode-locking with the 100-GHz laser described in section 4.5 we used a resonant SESAM with a quarterwave topcoating of fused silica (SiO$_2$), serving as an antireflection coating (in the following we will refer to this coating as “O1-coating”). Compared to the uncoated SESAM the antireflection coating leads to a reduced modulation depth $\Delta R$, reduced nonsaturable losses $\Delta R_{\text{ns}}$ but an increased saturation fluence $F_{\text{sat, A}}$, due to the reduced field enhancement at the absorber position (Figure 4.11). In addition, the O1-coated SESAM has a flat and slightly negative dispersion at the laser wavelength (Figure 4.12, right, black) compared to the uncoated device, which shows a strong variation (Figure 4.12, left). Note that the dispersion of the uncoated device is slightly shifted compared to the calculated curve (Figure 4.12, left), indicating a minor growth error of the SESAM structure.

Numerical simulations have shown, that slightly positive dispersion in the laser cavity can lead to close to transform limited pulses [95]. To optimize the dispersion, we applied four different SiN coatings with increasing thicknesses (later referred to as coatings N1 to N4), starting from an optical layer thickness similar to the O1-coated device up to a layer thickness yielding the same field enhancement as the SESAM with the O1-coating (SiN has a refractive index of 1.89 at 1550 nm wavelength compared to 1.446 for SiO$_2$ such that the field enhancement with the SiN coating becomes smaller for the same optical layer thickness, as the index contrast is
With these SiN coatings we can obtain positive GDD values at the laser wavelength, as it is shown in Figure 4.12 (right). The dispersion was measured by white-light interferometry, with a resolution of about 50 fs\(^2\).

Figure 4.11 Nonlinear reflectivity measurement of the uncoated (hollow dots) and a coated (solid dots) SESAM, done at 1535 nm with 2.4-ps pulses. Solid lines: respective fitting curves. The vertical lines indicated the determined saturation fluence. The coated sample shows reduced modulation depth \(\Delta R\) and nonsaturable losses \(\Delta R_{ns}\) but increased \(F_{sat}\) as expected. Due to the large field enhancement, the uncoated (resonant) SESAM shows a rollover behavior in the measured fluence range.

Figure 4.12 Calculated (solid) and measured (dots) dispersion curves of uncoated SESAM (left) and antireflection coated SESAMs (right). The GDD of the coated samples is shifted and reduced compared to the uncoated (resonant) sample.
With increasing thickness of the SiN layer (from N1 to N4) the zero-dispersion wavelength is red-shifted leading to increasing GDD values in the observed wavelength band.

In Figure 4.11 and Figure 4.13 we show nonlinear reflectivity measurements of the different SESAMs at a laser wavelength of 1535 nm. The measurement data (dots) is fitted with the model function (2.10) taking into account the finite spot size (solid lines).

![Figure 4.13 Nonlinear reflectivity measurements of antireflection coated SESAMs (dots) together with fitting curves (solid) and determined saturation fluences (vertical lines).](image)

<table>
<thead>
<tr>
<th>sample</th>
<th>$F_{\text{sat}}$ [µJ/cm²]</th>
<th>$\Delta R$ [%]</th>
<th>$\Delta R_{\text{ns}}$ [%]</th>
<th>$F_2$ [mJ/cm²]</th>
<th>$F_{\text{sat}}\Delta R$</th>
<th>$\xi_{\text{abs}}$</th>
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<td>9.0</td>
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<td>0.13</td>
<td>∞</td>
<td>5.3</td>
<td>1.88</td>
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</table>

Table 4.2 Nonlinear reflectivity measurement results of antireflection coated SESAMs. As a comparison, the uncoated device is listed in line one.
The coatings lead to the expected changes in the macroscopic properties, reducing \( \Delta R \) and increasing \( F_{\text{sat}} \), but the values do not scale with the field enhancement factor \( \xi_{\text{abs}} \) as we would have expected from section 2.4.2. Therefore the product \( F_{\text{sat}} \Delta R \) also does not remain constant. One has to note, that the modulation depth of the coated samples is \(<0.6\%\), therefore a high precision setup is needed to measure the nonlinear reflectivity. For this purpose we used the setup described in Chapter 3, which has an accuracy of 0.05\%. Although the modulation depth can be measured with high accuracy, at these low reflectivity changes, we have experienced an uncertainty for the absolute saturation fluence of more than 20\% (we have to keep in mind, that the fluence is varied over 3.5 orders of magnitude and the data is fitted over this range). In addition, MBE-grown structures usually show a gradient in layer thicknesses with respect to the radial position on the substrate. As the used samples stem from different parts of a wafer, their initial intrinsic properties vary. The used samples were not individually characterized before the coating process such that we cannot correct the measured data to compensate for the intrinsic properties.

From the measurements, samples N3 and N4 look promising: compared to the O1-coated SESAM, sample N4 shows a reduced saturation fluence and an increased modulation depth, facilitating shorter pulses. The GDD of sample N4 at the laser wavelength is the highest of all produced devices. Sample N3 shows slightly enhanced modulation depth (compared to the O1-coated sample), 30\% lower saturation fluence, a moderate positive GDD and the lowest nonsaturable losses of all devices. All samples were employed in the 100-GHz laser cavity, to determine their performance.

### 4.5.4 Laser result after SESAM optimization

With all SiN-coated SESAMs we could achieve stable mode-locking in the 100-GHz cavity. The N1-coated SESAM was extremely sensitive against QML and offered only a very limited stability range and a low damage threshold. The N2-coated sample showed the best power efficiency although it exhibits the highest saturation fluence and modulation depth, leading to increased absorption losses. With both mentioned SESAMs the pulse duration could not be reduced compared to the E-coated device.

Coatings N3 and N4 showed a significant improvement compared to the result shown in section 4.5.2.: with both coatings the pulse duration could be reduced by
about 30%, at the expense of a 14% output power reduction. The N4-coated SESAM achieved the overall highest repetition rate together with short pulses: we could generate a pulse train at 101.6 GHz with 1.1-ps pulses (Figure 4.14, right) and an average output power of 30 mW. The optical spectrum shown in Figure 4.14 (left) is centered at 1534.2 nm with a full width at half maximum of 2.8 nm. This results in a TBP of 0.39, which is 1.25 times the transform limit for sech² pulses. All obtained results are listed in Table 4.3.

![Figure 4.14 Properties of a 101-GHz laser, operated with an optimized SESAM: optical spectrum (left, solid line), together with an ideal sech² fit (grey dashed line). The inset shows the spectrum on a logarithmic scale. Right: autocorrelation trace (solid line) with fit-curve using ideal sech² pulses (grey dashed line). Cavity roundtrip time $T_R = 9.84$ ps. The pulses have a duration of 1.1 ps.](image)

<table>
<thead>
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<th>sample</th>
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<th>$\tau_p$ [ps]</th>
<th>$P_{av}$ [mW]</th>
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<td>1.87</td>
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<td>N3-coating</td>
<td>98.3</td>
<td>1.06</td>
<td>29.6</td>
</tr>
<tr>
<td>N4-coating</td>
<td>101.6</td>
<td>1.1</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4.3 Summary of laser results obtained at very high repetition rates with SiN-coated SESAMs.
With additional improvements in the dispersion management we expect that the pulse duration can be further decreased into the sub-picosecond regime. We have observed pulse durations of about 900 fs, but laser operation was not stable over time at this point.

4.5.5 Conclusion

We have demonstrated a fundamentally SESAM mode-locked Er:Yb:glass laser with a repetition rate of 101 GHz at 1534.2 nm and an average output power of 35 mW in 1.6-ps pulses. By systematically varying the SESAM design, thereby changing the dispersion of the respective device, we could reduce the pulse duration by about 30% to get 1.1-ps pulses with an average output power of 30 mW. The mode locking of all demonstrated lasers is self-starting and stable. To the best of our knowledge, this is the highest repetition rate generated directly from a passively mode-locked solid-state laser oscillator operating in the 1.5-μm telecom window. Compared to previous results, we have increased the repetition rate exceeding 100 GHz, while increasing the average output power by a factor of three and reducing the pulse duration by a factor of three. The high average output power at high repetition rate, the good pulse quality and pulse-to-pulse phase stability, and the compact and simple setup make this laser a competitive alternative to harmonically mode-locked fiber lasers [65], semiconductor lasers [59] and distributed feedback (DFB) lasers [96] for high-speed data-transmission applications.

We believe that with the current design approach the repetition rate of an Er,Yb:glass-based laser cannot be increased significantly further. A fundamentally mode-locked laser with a substantially higher pulse repetition rate would require a different mechanical setup: in the present design the cavity-length cannot be reduced much further as the individual components again start to interfere. In addition the dimensions of the individual components cannot be reduced much further. In the present setup the clear aperture of the folding mirror is only about 400 μm. A further reduction of the diameter would lead to increasing diffraction losses and aberrations, reducing the Q-factor of the cavity. Also the used gain length has a lower bound which is limited by the doping concentration of the active ions in the glass matrix and ultimately by the thermal fracture resistance of the glass. At Yb-doping levels above 25 wt-% ion clustering often appears [97]. Furthermore a too high doping concentration in the thermally poor conducting glass can lead to undesired thermal
effects (like thermally induced birefringence) or even catastrophic failure due to fractures. A typical absorption length \((1/e)\) of 0.5 mm requiring optical path lengths in the gain medium of 0.5-1 mm sets the lower limit to the cavity length and therefore limits the maximum achievable repetition rate to about 200 GHz. Still the main limiting factors are the small emission cross section of the gain glass and the saturation fluence of the SESAM. In Chapter 6 we will discuss, how to possibly overcome these limiting issues.

### 4.6 Overview of achieved results

Table 4.4 gives an overview of the results achieved with high repetition rate Er,Yb:glass lasers. The listed results were either obtained within the framework of this thesis, but also, for completeness and for comparison, in work performed earlier in our group.

<table>
<thead>
<tr>
<th>(f_{\text{rep}}) [GHz]</th>
<th>wavelength [nm]</th>
<th>(P_{\text{av}}) [mW]</th>
<th>(\tau_p) [ps]</th>
<th>TBP</th>
<th>OSNR [dB]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (10.67)</td>
<td>1529-1569</td>
<td>15</td>
<td>3.8</td>
<td>0.47 (sech(^2))</td>
<td>[21]</td>
<td></td>
</tr>
<tr>
<td>9.95328</td>
<td>1528-1563</td>
<td>30</td>
<td>1.2-1.9</td>
<td>&gt;20</td>
<td></td>
<td>[98]</td>
</tr>
<tr>
<td>12.5</td>
<td>1528-1563</td>
<td>30</td>
<td>1.2-2.7</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.8-13.3</td>
<td>1533-1555</td>
<td>24</td>
<td>1.8</td>
<td>0.85 (Gauss)</td>
<td>[99]</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1528-1561</td>
<td>25</td>
<td>1.9</td>
<td>0.75 (sech(^2))</td>
<td>[67]</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1534</td>
<td>18</td>
<td>4.3</td>
<td>0.44 (Gauss)</td>
<td>50</td>
<td>[68]</td>
</tr>
<tr>
<td>50 (49.87)</td>
<td>1533 (?)</td>
<td>7.5</td>
<td>2.1</td>
<td>0.57 (sech(^2))</td>
<td>65</td>
<td>[69]</td>
</tr>
<tr>
<td>77</td>
<td>1535.8</td>
<td>10.7</td>
<td>3.0</td>
<td>0.37 (sech(^2))</td>
<td>56</td>
<td>[70]</td>
</tr>
<tr>
<td>90</td>
<td>1535.3</td>
<td>10</td>
<td>4.1</td>
<td>0.42 (sech(^2))</td>
<td>(58)</td>
<td>[91]</td>
</tr>
<tr>
<td>101</td>
<td>1534.8</td>
<td>35</td>
<td>1.6</td>
<td>0.53 (sech(^2))</td>
<td>55</td>
<td>[25]</td>
</tr>
<tr>
<td>101</td>
<td>1534.2</td>
<td>30</td>
<td>1.1</td>
<td>0.39 (sech(^2))</td>
<td>55</td>
<td>[100]</td>
</tr>
</tbody>
</table>

Table 4.4 Overview of results achieved with high repetition rate Er,Yb:glass lasers. \(P_{\text{av}}\): average output power, \(\tau_p\): pulse duration, TBP: time-bandwidth product, OSNR: optical signal-to-noise figure.
4.7 Design guidelines for high repetition rate lasers

To summarize the design considerations and the experience gained with the experimental setups described before, we want to give some focussed, practical guidelines for the design of passively mode-locked high repetition rate lasers, most of which are based on the stability criteria given in equations (2.4) and (2.12).

Choice of gain medium

An ideal gain medium for high repetition rate lasers should have low intrinsic losses, a large emission cross section, a short pump absorption length and of course an emission at the desired wavelength. The large emission cross section allows for a low gain saturation fluence while a short absorption length facilitates a small pump spot size in the gain medium, as the spot size is ultimately limited by the Rayleigh range of the pump beam. Both properties enable a lower QML threshold. Typical absorption lengths are in the order of 0.5 mm, which finally sets a lower limit for the minimal achievable cavity length and therefore the maximal achievable repetition rate. With a chosen gain medium and given saturation fluence \( F_{\text{sat,A}} \) from a saturable absorber, the required mode-sizes can be calculated with the stability criterion and an appropriate laser cavity can be designed.

Cavity design

The design of standing wave cavity is preferred as the double pass through the gain lowers the effective saturation fluence and therefore the QML threshold by a factor of two compared to a ring resonator. The mode-sizes in the gain material and on the SESAM should be small, such that the components are strongly saturated. One should be aware that a too small spot on a SESAM can lead to carrier diffusion effects, which would increase the effective saturation fluence [101]. For stable single transverse mode operation the pump spot should be chosen to be slightly smaller than the laser mode. To maintain a high intracavity pulse energy an output coupling in the order of 1%-3% is adequate. Parasitic losses should be minimized by using high quality, low scattering mirrors.

Pump

A diffraction limited pump source is ideal as the beam quality of the pump sets the lower limit to spot-size in the gain. Also a single transverse mode pump will result
in the best laser noise performance as mode fluctuations from multimode pumps can translate into enhanced relative intensity noise of the laser. When designing a pump focusing optics one should be aware of thermally induced fracture or thermal lensing effects as well as upper state lifetime quenching for too high pump intensities.

**Saturable absorber**

The most important and most flexible component is the saturable absorber which in our case is a SESAM exclusively. The modulation depth $\Delta R$ of the SESAM should be high enough to shape short pulses and to enable self starting mode-locking, but low enough to suppress QML. Reasonable values are 0.5%-2%, depending on the gain bandwidth. The saturation fluence $F_{sat,A}$ should be low, possibly <10 µJ/cm², as this reduces the QML threshold and relaxes the demands on the absorber mode size and therefore simplifies the cavity design. Low saturation fluence can always be achieved with a resonant SESAM design but at the cost of increased wavelength dependence which reduces the wavelength tuning range, increased group delay dispersion (GDD) leading to longer pulses and increased modulation depth, raising the QML threshold again. With dielectric top-coatings, good intermediate solutions can be found. A good crystalline quality reduces the nonsaturable losses $\Delta R_{ns}$ and therefore the parasitic losses, but usually increases the recovery time of the absorber. For a recovery time exceeding the cavity roundtrip time $T_r$ the SESAM will not fully recover, which will reduce the effective modulation depth $\Delta R$. At the same time carriers will be accumulated in the excited state leading to enhanced higher order effects like induced free carrier absorption or Auger recombination, which enhance the rollover of the nonlinean reflectivity. The inverse saturable absorption must be well adapted: to prevent multiple pulsing the SESAM should always be operated with a saturation parameter $S < S_0$. Furthermore, for sufficient pulse shaping, one should keep $S^2 > 2$ (this condition can be derived by combining equations (2.11) and (2.13)).
Chapter 5

Transverse mode degeneration effects

It is well known from the literature that laser cavities in general exhibit frequency degeneracies of transverse cavity modes at certain resonator lengths within their stability range [102, 103]. For lasers designed to operate in the fundamental mode (TEM₀₀) this is especially distracting, because at such degeneracy-points, higher order spatial modes can resonantly couple to the fundamental mode [104] and become predominant in the cavity. For a passively mode-locked laser this can lead to instabilities, as the SESAM is not sufficiently saturated by these modes anymore, and Q-switching can occur. In this chapter we report about the experimental identification of such degenerate cavity modes in high repetition rate lasers and their influence on the laser performance.

5.1 Transverse mode degeneracies in a 100-GHz laser

5.1.1 Experimental identification of mode degeneracies

Cavity elements inside a laser resonator usually have a certain range with respect to their position along the optical axis, for which the resonator will be stable. For multi-GHz lasers, the stability range of the SESAM, being used as an end-mirror, is in the order of few 100 µm. To obtain stable mode-locking, the SESAM usually has to be moved once through this range in order to find the smallest beam diameter on the device, leading to the best saturation of the absorber. The stability range is usually limited on one end by the growing mode-size in the gain, continuously raising the laser threshold. On the other end it is limited by the mode-size on the SESAM getting infinitely small which results in an unstable resonator. Within this range a rather smooth varying laser output power is expected. When measuring this
dependence by scanning the end mirror through the stability range with a spatial resolution of about 40 nm, the observed behaviour is somewhat different: at certain distinct points the output power drops significantly, as shown in Figure 5.1. In addition, a comparably strong power oscillation is measured.

Both observations are well reproducible over multiple scans and can be explained as follows: the amplitude oscillations on the measurement curve are not due to noise but originate from the limited number of Fabry-Pérot modes of the laser cavity. An evaluation of 15 consecutive oscillations gives a period of 0.78 µm, which is approximately half the wavelength of the laser output. While varying the cavity length, the longitudinal cavity modes are moved accordingly through the gain-profile, leading to power oscillations in the output. This shifting of the longitudinal modes can be observed with an optical spectrum analyzer.

The larger power drops originate from frequency degenerate higher order spatial modes, which resonantly couple to the fundamental mode. When higher order modes occur, they introduce an efficient power-loss channel, as some modes are quenched through effects of spatial hole burning in the inversion of the gain medium, leading to output power drops or even a complete laser shut-off. This is
particularly distracting in a cavity with a very limited longitudinal stability range (with respect to the SESAM position) like in our case. For stable operation of high repetition rate mode-locked lasers, it is important to accurately examine the cavity’s stability range, as certain cavity lengths and their vicinity have to be avoided.

Because power drops and degraded beam quality lead to instabilities in the mode-locking, we investigated the mode degeneracies in our cavities in cw-operation, for which the SESAM was replaced by a highly reflective end mirror. To detect the beam quality deteriorations of a 100 GHz laser cavity, we scanned the stability range with a reduced spatial resolution of about 200 nm (to reduce the overall measurement time) and recorded the output-power as well as the beam profile of the laser. Figure 5.2 again shows multiple large power drops within the stability range together with the associated beam profiles.

Figure 5.2 Stability range (with respect of the end mirror position) of a 100-GHz laser cavity in cw operation, scanned with a spatial resolution of 200 nm. The observed power drops can clearly be associated with strong beam quality degradations of the laser output. At normal power levels the output beam is close to diffraction limited.
In every power dip, the beam quality is clearly degraded, while at normal power levels, the output beam is nearly diffraction limited. The positions of the individual degeneracies are reproducible over multiple scans for a fixed particular pump power. However, with varying pump power they slightly shift in position, as the changing thermal lens in the gain medium changes the resonator conditions. One should be aware of this effect if a laser is operated close to a degenerate point and the pump power is altered. In the measurement shown in Figure 5.2 the above mentioned power oscillations are not visible anymore, due to the reduced spatial resolution. Note that the absolute position of the individual power dips is different compared to those depicted in Figure 5.1. The reason for these deviations are slight modifications of the laser cavity.

5.1.2 Theoretical determination of degenerate cavities

By modelling the laser cavity with \( \text{ABCD} \) matrix formalism one can calculate the position of the degeneracy points within the stability range. For a laser cavity which is radial-symmetric with respect to the intracavity laser mode, it is straightforward to calculate the resonance frequencies of Hermite-Gaussian laser modes with

\[
V_{m,n,q} = \frac{c}{2L_{\text{eff}}} \left[ q + (m+n+1) \cos^{-1} \left( \pm \sqrt{A_i D_i} \right) \right]
\]  

(5.1)

\[ A_i \quad B_i \]
\[ C_1 \quad D_1 \]: single-pass cavity matrix

as described in \[105\]. Degeneracies arise where different cavity modes have the same frequency, such that

\[
V_{m+n, q+\Delta q} = V_{m,n,q} \quad (5.2)
\]

The relative positions of the intracavity optical elements are included in the cavity single-pass matrix. By inserting equation (5.1) into (5.2) we can solve for the position
of the component we are interested in, which is included in $A_iD_1$, resulting in the degeneracy points of the cavity:

$$A_iD_1 = \cos^2\left(\frac{-\Delta q}{\Delta m + \Delta n} \pi\right) = \cos^2\left(\frac{M}{N} \pi\right)$$

(5.3)

with $M = -\Delta q$ and $N = \Delta m + \Delta n$. For practical purposes, usually only small values of $M$ and $N$ have to be considered, as the mode coupling strength decreases with increasing mode numbers [104]. We can see, that all cavity-related data in equation (5.1) are included in

$$\cos^{-1}\left(\sqrt{\frac{A_iD_1}{\Delta m + \Delta n}}\right)$$

(5.4)

which is the Gouy Phase shift of the electric field. By introducing any asymmetry into a laser resonator, as it is done by inserting Brewster elements or tilted curved mirrors, one has to separately evaluate the tangential and the sagittal plane of the cavity. For the resulting optical resonance frequencies, the Gouy phase shift of both planes contributes equally [42] (p. 647, “Astigmatic Mode Functions”), such that we obtain

$$V_{m,n,q} = \frac{c}{2L_{\text{eff}}} \left[ q + (m + n + 1) \frac{\cos^{-1}\left(\pm\sqrt{A_{i,\text{tan}}D_{i,\text{tan}}/\Delta m}\right) + \cos^{-1}\left(\pm\sqrt{A_{i,\text{sag}}D_{i,\text{sag}}/\Delta n}\right)}{2\pi}\right] .$$

(5.5)

Because of this simple modification it is not always trivial to solve equation (5.5) analytically. In this case numerical techniques should be used to calculate the degeneracy points. One should note that any misalignment or broken cavity symmetry (as in our cavities) will enhance the effective mode coupling such that higher order modes can couple to the fundamental mode and therefore reduce the beam quality [104].
Comparing measurement data with theoretically calculated degeneracy positions is rather difficult for a 100 GHz laser as many cavity parameters are not precisely known. Because we use a prism shaped gain glass, the used effective gain length has a quite large uncertainty, effecting the position of all other cavity elements. Figure 5.3 shows such a comparison. The solid grey lines represent the calculated positions. Some positions are in a very good agreement with the measured power drops while others can not clearly be related to some distinct measurement feature. Of course not every mode degeneracy has to result in a power drop, such that the beam quality could still be somewhat deteriorated in these points. Further experiments would be necessary to proof this.

5.1.3 Conclusion

To conclude, we have shown that beam quality deteriorations due to degenerate higher order spatial modes have to be considered when building a high repetition rate laser, as they can lead to instabilities during laser operation and even to a complete laser shut off. In general, it is not possible to fully suppress degeneration effects in a laser cavity. To reduce the effective number of contributing modes, it is good practice to pump with a smooth and symmetric beam profile and to avoid misalignments and any kind of asymmetries inside the laser cavity, as for an ideal circular symmetry the coupling between the fundamental Gaussian mode and
Hermite-Gaussian modes with an odd index will vanish and no energy will be transferred [104].

With the cavity single-pass matrix, it is possible to calculate the cavity configurations at which degeneracies occur. For high repetition rate cavities, this is rather difficult. Usually the stability range of the cavity is already in the order of a few 100 µm and even more limited by the operating parameters to achieve cw-modelocking. Because the geometric cavity parameters are usually not precisely known for these lasers, it is also difficult to precisely determine the degeneration points in advance. In this case, they have to be determined experimentally, preferably in cw-operation. However, for lasers operating at Megahertz repetition rates, it is highly interesting to calculate degenerate points in advance, as these lasers often offer a large stability range with respect to the position of their individual components, and the spacing of the individual degenerate points is rather large as well. Therefore there is enough freedom for optimizing the laser cavity to operate in a stable regime.
A lot of outstanding results have been demonstrated with passively mode-locked high repetition rate Er,Yb:glass lasers, but despite their interesting features they are not widespread in commercial applications. With the current optical designs the assembly of stable commercial systems is still demanding and not suitable for mass production. For many commercial applications competing products with compromised properties but significantly lower acquisition costs are preferred. In telecom transmission systems for example, semiconductor lasers are used, whose prices have dropped significantly in recent years. To compete with these alternative sources, the manufacturing process of Er,Yb:glass lasers has to be simplified.

One possible simplification could be a straight two-mirror cavity based on a partially monolithic design, bonding together the gain element and the saturable
absorber (Figure 6.1, left), or even a fully monolithic approach, which would also include the output coupling mirror (Figure 6.1, right). In the spectral regime around 1 µm, where gain media with larger gain cross sections are available, such designs have been demonstrated with repetition rates up to 160 GHz [38, 49, 106, 107]. However, these approaches require equal mode sizes in the gain medium and on the absorber (also often referred to as 1:1 mode-locking). In the high repetition rate lasers reported in Chapter 4 the mode size ratio of gain element versus saturable absorber is typically in the order of 5. If we rewrite equation (2.4) to become

\[ E_p^2 > E_{\text{sat},l} E_{\text{sat},A} \Delta R = \frac{A_{\text{eff},l} h \nu}{\sigma_{\text{em}} + \sigma_{\text{abs}}} A_{\text{eff},A} F_{\text{sat},A} \Delta R \]  \hspace{1cm} (6.1)

we can see that gain media with substantially higher interaction cross sections \( \sigma_{\text{em}} \) and \( \sigma_{\text{abs}} \) and saturable absorbers with very low saturation fluence \( F_{\text{sat},A} \) are needed to maintain stable mode-locking while increasing the mode-size on the absorber to obtain a mode size ratio of 1.

Recently, new Er,Yb-doped crystalline gain materials with good optical quality have been reported together with corresponding laser results [108-110]. They offer a higher gain cross section and also better thermal properties compared to doped phosphate glass.

In different spectral regions, SESAMs have been reported for which the saturation fluence could be significantly reduced by using absorption layers based on quantum dots (QD) rather than quantum wells (QW) [111]. By varying the dot density, QD-SESAMs offer an additional degree of freedom, such that modulation depth and saturation fluence of the SESAM can be adjusted independent of each other. In the 1.5-µm spectral region QD-SESAMs have also been reported [112, 113] but with properties that are not suitable for mode-locking high repetition rate lasers.

If stable mode-locking can be achieved with a mode size ratio of 1, high repetition rate solid-state lasers with straight cavities could be assembled with techniques, similar to those used for microchip lasers emitting at 532 nm (like the ones used in green laser pointers), reducing the complexity and the overall costs of the devices. In principle these microchip devices are fully featured diode-pumped solid-state lasers with integrated nonlinear frequency conversion. Early models also included a
Towards monolithic integration

A saturable absorber section to facilitate passive Q-switching, which was necessary to achieve the peak intensities needed for efficient frequency conversion. The optical components of such lasers are bonded together to form an optical resonator possibly with a separate, external output coupling mirror. They are stable, reliable and can be mass-produced at very low cost: in recent years the prices of such microchip lasers have dropped by 99%, today they cost only a few US$. With this technology, passively mode-locked GHz-sources could become a cheap mass-product like green laser pointers are today. For many applications they would be an interesting and cost effective alternative to semiconductor lasers.

In this chapter we will present preliminary results of our efforts towards 1:1 mode-locking of 1.5-µm high repetition rate lasers. In section 6.1 we report the first 10-GHz operation of Er,Yb:YAB, the highest repetition rate obtained from a crystalline gain material in the 1.5-µm spectral region. In section 6.2 we report about initial results on 1.5-µm QD-SESAMs. The results described in this chapter are all of preliminary nature as this is still ongoing work.

6.1 10-GHz Er,Yb:YAB laser

In 2007 Lagatsky et al. presented the first mode-locked laser results from a new crystalline gain material Er,Yb:YAl₅(BO₃)₄, or short Er,Yb:YAB. The reported laser operated in the 1.5-µm spectral region at a pulse repetition rate of 166 MHz [110, 114]. The gain material has the notable property that it offers a four times higher emission cross section compared to the widespread Er,Yb-doped phosphate glasses [115], which makes it highly attractive to be used in 1.5-µm multi-GHz lasers. Due to its reduced saturation energy, the material offers a lower QML-threshold. This is not only one of the prerequisites that we need for a monolithic integration but it also relaxes the demands on the cavity design of high repetition rate lasers in general, as it also allows larger beam diameters in the gain medium of a folded resonator. In this section we present the first multi-GHz laser results that could be achieved with Er,Yb:YAB, which is also the highest repetition rate so far obtained from a crystalline material in the 1.5-µm spectral region. The experiments were conducted in collaboration with N. Kuleshov et al. from Belarus State Polytechnical Academy, Minsk who kindly provided the YAB material and A. Lagatsky from the University of St. Andrews.
6.1.1 Material properties of Er,Yb:YAB

In this section we want to briefly introduce some properties of Er,Yb:YAB that are relevant for our experiments. More detailed information about the crystal structure, growth details and the full spectroscopic properties can be found in [108, 115-117].

Er,Yb:YAB has a strong absorption band at 976 nm with an absorption cross section in the $\sigma$-polarization of about $2.75 \times 10^{-20}$ cm$^2$ and a bandwidth of 17 nm, such that it can be pumped with standard InGaAs laser diodes. Figure 6.2 shows the absorption and the calculated stimulated emission cross-sections in the spectral range around 1.5 $\mu$m. In general the $\sigma$-polarized bands are stronger than the $\pi$-polarized ones. The strongest emission maximum with a cross-section of about $3.8 \times 10^{-20}$ cm$^2$ is located at 1532 nm in $\sigma$-polarization (as a comparison, Er,Yb:glass has an emission cross-section of $0.8 \times 10^{-20}$ cm$^2$).

Er,Yb:YAB is a negative uniaxial crystal with a refractive index of $n_o=1.75$ for the ordinary axis and of $n_e=1.68$ for the extraordinary axis. With $4.7$ Wm$^{-1}$K$^{-1}$ its thermal conductivity is about 5.5 times higher compared to doped phosphate glass.
6.1.2 Experimental setup

For our experiments we used an optical setup as described in section 4.4., optimized for a repetition rate of 10 GHz and with an output coupling of 1.3%. The doping levels for the used YAB-crystal were 1.5% (at.) of Erbium- and 12% (at.) of Ytterbium-ions which corresponds to ion concentrations of $8.25 \times 10^{20}$ cm$^{-3}$ (Er) and $6.6 \times 10^{21}$ cm$^{-3}$ (Yb) respectively. With these doping levels the crystal has a low-signal absorption coefficient of 12 cm$^{-1}$ in $\sigma$-polarization at 976 nm. As for the Er,Yb:glass lasers, the gain medium was uncoated and inserted under Brewster’s angle. Because of the birefringence of YAB, special attention has to be paid on the cutting scheme of the crystal, as partial coupling into the wrong optical axis can lead to excessive losses. When used under normal incidence, uniaxial crystals are often c-cut, meaning that the c-axis of the crystal is perpendicular to the optical surfaces. However, we used an a-cut crystal (optical surfaces parallel to crystal’s c-axis) with a thickness of 1.2 mm and $2 \times 2.5$ mm$^2$ lateral dimensions. With this cutting scheme we could ensure that the electric field vector in the cavity is always perpendicular to the crystal’s c-axis and therefore in the most efficient $\sigma$-polarization, independent of the precision of the adjusted Brewster angle. Because of the deviant refractive index of YAB (compared to glass) and the resulting different Brewster angle, the folding angle of the cavity was adjusted to obtain a round output beam again.

6.1.3 Results

![Optical spectrum and autocorrelation trace of the laser output](image)

Figure 6.3 Properties of the first 10-GHz Er,Yb:YAB laser: optical spectrum of the laser output (left) and autocorrelation trace (right, solid) together with the fit-curve for an ideal 6.9-ps sech$^2$ pulse train (grey, dashed). The repetition rate of the laser is determined with a microwave spectrum analyzer to be 9.63 GHz (not shown).
We first examined the laser in cw-operation: with a pump-power of 400 mW we got an output power of 34.8 mW. Several competing longitudinal modes could be observed around 1603 nm and also a beat node at 9.57 GHz. By inserting a 20-µm fused-silica solid etalon we could force the output wavelength to 1532 nm, but smooth wavelength tuning was not possible at this point. With the etalon inserted, the cw-output power dropped to 2.3 mW. By inserting a suitable SESAM we readily achieved mode-locking. The laser generated a 9.63-GHz pulse train with an average output power of 10.1 mW at a pump power of 400 mW. The QML-threshold was at 246 mW pump power, which resulted in 2 mW output power. Above this level mode-locking was self-starting and stable. Figure 6.3 (left) shows the optical spectrum centered at 1531.9 nm with an optical bandwidth of 0.38 nm, which resulted in 6.9-ps (FWHM) pulses. The autocorrelation trace is shown in Figure 6.3 (right) together with the fit-curve for an ideal sech²-shaped pulse. The measured pulse parameters result in a time-bandwidth product of 0.33, which is 1.06 times the transform limit.

### 6.1.4 Conclusion

We have presented the first passively mode-locked Er,Yb:YAB laser with multi-GHz repetition rate. To the best of our knowledge this is to date the highest repetition rate achieved with an Er,Yb co-doped laser based on a crystalline gain material. Compared to the results achieved with Er,Yb:glass the performance of this laser has yet to be improved such that the results shown above should more be regarded as a proof of principle.

We analyzed the limiting factors: from the σ-polarized cross-sections shown in Figure 6.2, Tolstik et. al have calculated the inversion-dependent gain cross-section curves \( g(\lambda) \) shown in Figure 6.4, using \( g(\lambda) = \beta \sigma_{em} - (1 - \beta)\sigma_{abs} \), with the inversion parameter \( \beta \) being the ratio of the number of excited ions to the total number of ions. It is clearly visible, that for low inversion levels (dotted and dashed lines) the gain peak is located at 1602 nm, the same wavelength that we could observe in our cw experiments. For our work, output coupling mirrors with only one output coupling rate of 1.3% transmission were available, resulting in a low inversion of the gain medium. By inserting the etalon in cw operation we introduced higher losses leading to a higher inversion, which resulted in a shift of the gain peak to the desired wavelength. Tuning was not possible because the gain spectrum is not flat in this
spectral region. To shift the gain peak to the desired 1532 nm without an etalon, a higher output coupling rate would be necessary.

![Figure 6.4 Calculated $\sigma$-polarized gain coefficient curves for different inversion parameters $\beta$ [117].](image)

For low inversion, the gain peak is located at 1603 nm, for high inversion it is shifted to 1532 nm.

The SESAM that we used for mode-locking was optimized for a center wavelength of 1550 nm, as it can be seen from the dip in the linear reflectivity measurement in Figure 6.5 (left). At 1602 nm it has only a very small modulation depth (as indicated by the dotted vertical line), leading to a limited optical bandwidth and therefore comparably long pulses in the output. In addition we expect the saturation fluence to be increased at this long wavelength such that the absorber cannot be saturated sufficiently to cw-mode-lock the laser. When optimizing the laser for maximum output power we could verify that it was mode-locking Q-switched at 1602 nm with good output power of up to 25 mW. Figure 6.5 shows the optical spectrum (middle) and the microwave spectrum (right) during this operation. The microwave spectrum clearly indicates Q-switching. By moving the SESAM towards the end of the stability range, thereby introducing additional losses, the emission shifted to 1532 nm, where the SESAM has a low saturation fluence and sufficient modulation depth to cw-mode-lock the laser. Because of the additional losses, the laser is rather inefficient in this mode of operation. The stability range of
the SESAM with respect to its position along the optical axis at this point was only 15 µm, indicating a critical balance between induced losses and sufficient intensity on the SESAM to saturate the absorber. As a comparison, for an Er,Yb:glass laser, which has its intrinsic gain peak at 1535 nm, the stability range is in the order of 300 µm.

We believe that the laser performance can significantly be improved by adapted optical components. Output coupling mirrors with different transmission values have been ordered, to adapt the inversion and shift the gain maximum to the desired 1532 nm. Within the timeframe of this work, these mirrors were not yet available.

At MHz repetition rates up to 280 mW have been reported from Er,Yb:YAB lasers so far, while glass lasers have been limited to powers around 100 mW. We therefore believe, that the optimized Er,Yb:YAB laser will outperform the glass-laser results.

![Figure 6.5 Linear reflectivity of the SESAM used to mode-lock the Er,Yb:YAB laser (left). At 1602 nm the SESAM has only negligible modulation depth (vertical dotted line). When optimized for maximum output power, the laser emits at 1602.2 nm (center figure) in QML regime, as the microwave analyzer trace clearly indicates (right).](image)

6.2 QD-SESAM with lower $F_{\text{sat}}$

There are multiple ways to decrease the saturation fluence $F_{\text{sat}}$ of a SESAM. In a resonant SESAM, the enhanced field strength at the absorber position leads to a low saturation fluence [19], but at the same time, the modulation depth is equally increased. By changing the field enhancement, the product $F_{\text{sat}} \cdot \Delta R$ cannot be changed as this product is an intrinsic property determined by the density of states of the absorber. We can define $F_{\text{sat}} \cdot \Delta R$ as the transparency fluence of an absorber, describing at which fluence the absorption equals the stimulated emission of the transition. If one does not change the density of states, this product cannot be changed [118]. There are several possibilities, to reduce the density of states in an
absorber. For QWs, this can be achieved if the photon energy is close to the bandgap [119] or a material with a broad absorption edge like GaInNAs is chosen [120]. Still, for SESAMs operating at 1.5 µm wavelength, these attempts did not result in significant improvements compared to standard InGaAs-based QW-absorbers, which are typically used in this regime. One possible solution could be the implementation of QDs instead of QWs: the strong localization of the wave function in a quantum dot leads to an atom-like density of states. For an absorber the density of states then scales with the dot density and with it the modulation depth of the absorber, while the saturation fluence remains constant [111]. The additional degree of freedom, given by the variable dot density, allows to control the saturation fluence and the modulation depth of a SESAM independent of each other. The product $F_{sat} \cdot \Delta R$ can be reduced.

In the 1.5-µm spectral region SESAMs based on QD-absorbers have already been reported, but with properties that are not suitable for mode-locking high repetition rate lasers [112, 113]. In this section we want to introduce an attempt of a high-repetition rate QD-SESAM. To obtain a significant improvement over QW-SESAMs, our target specifications are a saturation fluence of 1 µJ/cm² and a modulation depth of 0.4-0.6%. The samples described in this chapter were grown by our collaborator, the University of Sheffield, within the framework of the EU-funded project “FastDot”.

### 6.2.1 QD-SESAM design

The design we use for our QD-SESAMs provides resonant and antiresonant samples from a single growth run. The basic design is a standard resonant structure, on which we grow two additional layers of AlAs and GaAs, to get an antiresonant device. The two top-layers can later be removed by selective wet-etching to obtain the original resonant design. As described in section 2.4.2, by adding dielectric coatings to the resonant device, we can continuously tune the properties to a desired intermediate state between the resonant and the antiresonant case.

We designed two different SESAM structures, implementing one and two QD-layers respectively (Figure 6.6). The absorber layers consist of GaInNAs-capped self-organized InAs QDs. To avoid strain induced dot-stacking in the two-layer device, which can lead to a wavelength shift due to the coupling of different layers [121], a thick enough GaAs strain relaxation layer was grown between the absorber layers.
The underlying DBR, consisting of 31 pairs of GaAs and Al$_{0.98}$Ga$_{0.02}$As layers, has a theoretical reflectivity of 99.99% at 1550 nm and was grown by metal-organic vapour phase epitaxy (MOVPE). The absorber section, in which the dot layers were placed in antinodes of the standing wave pattern of the electric field, was grown by molecular-beam epitaxy (MBE).

6.2.2 Post-growth processing by chemical etching

We first characterized the nonlinear reflectivity behaviour of the as-grown antiresonant devices. As we could not detect any nonlinear reflectivity (the response was rather flat with a constant reflectivity of about 99.4%), we etched away the two topmost layers, changing the structure to a resonant design. We first measured the linear reflectivity with a Cary 5E spectrophotometer from Varian Inc., and could detect resonant absorption dips in the reflectivity plateau (Figure 6.7), but the wavelength of the absorption maximum was shifted for both samples from the designed 1550 nm to 1573 nm and 1569 nm respectively. At the absorption minima we detected losses of 5.5% for the single dot-layer sample and 2.3% for the double layer device. The absorption behaviour of the samples was unexpected as the two-layer device should exhibit higher absorption losses. At 1534 nm (vertical dashed lines in Figure 6.7), which is the operation wavelength of our nonlinear reflectivity measurement setup, the absorption of both samples was too low, such that we again could not detect any nonlinear reflectivity behaviour, but obtained a flat response from both samples, again with a linear reflectivity of about 99.4%.
Figure 6.7 Linear reflectivity of resonant QD-SESAM samples. The maximum absorption (dip in the plateau) is shifted from the designed 1550 nm to 1573 nm and 1569 nm respectively. The vertical dashed line marks the operation wavelength of the nonlinear reflectivity setup, where the absorption is very low for both samples.

We therefore had to shift the resonance of the SESAM structure to obtain stronger absorption at the desired wavelength. This can be done by adapting the thickness of the topmost GaAs layer. By etching the SESAM surface, the thickness of this layer is reduced, thereby shifting the resonance to shorter wavelengths [122]. A change in the layer thickness of 10 nm results in a 13-nm shift of the center wavelength. We therefore need an etching process which is very slow, to achieve the required accuracy. Starting with etching solutions suggested in [122, 123] we obtained etch-rates which were about a factor of 50 higher compared to the cited ones, and therefore not suitable for our application. We optimized the etchant to get the following recipe for a slow etching process of GaAs (Table 6.1):

<table>
<thead>
<tr>
<th>GaAs etchant recipe ($\approx 0.4$ nm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen peroxide (30%)</td>
</tr>
<tr>
<td>citric acid (50%)</td>
</tr>
<tr>
<td>DI-water</td>
</tr>
</tbody>
</table>

Table 6.1 Etchant recipe for slow GaAs-etching. The etch-rate with this solution is about 0.4 nm/s. DI-water: de-ionized water.

The 50%-citric acid solution was obtained by dissolving 1 g of dry citric acid monohydrate in 1 g of de-ionized water.
Before etching the GaAs layer, we had to remove the oxide layer from the sample surface, which was done by using 37%-HCl diluted 1:1 with DI-water and a processing time of 1 minute. Figure 6.8 shows the incremental wavelength shift of the resonance dip in dependence of the applied etching time. To obtain a reasonable modulation depth at 1535 nm (the operation wavelength of the nonlinear reflectivity setup) the absorption dip was tuned to 1546 nm for the single QD-layer sample and to 1543 nm for the double QD-layer sample respectively.

Note that the underlying DBRs, which were designed for a center wavelength of 1550 nm, have a 25-nm offset towards longer wavelengths such that we are approaching the short wavelength edge of the DBR reflection band by moving the resonance dip.

![Figure 6.8 Incremental wavelength shift of the SESAM resonance with corresponding accumulated processing time. All reflectivity spectra are normalized to 100% reflectivity.](image)

6.2.3 Preliminary results

When measuring the nonlinear reflectivity behaviour of the wavelength-tuned resonant QD-SESAMs we again could not detect a significant increase in the reflectivity with increasing incident fluence (Figure 6.9). We consider the determined modulation depth of 0.05%, which is about the noise-level of the measurement setup, essentially as a flat response. The observed rollover-behaviour, indicating higher order absorption effects, is not an artifact introduced for example by a misalignment of the measurement setup. The measured reflectivity change of 0.4-0.6% can be well resolved with our setup as we have shown in Chapter 3, section 3.3.
The measured rollover was reproducible and comparative measurements with DBR-mirrors and QW-SESAMs with very low modulation depths did not show this reflectivity drop. We should note that the measured low linear reflectivity matches well with the data obtained from the spectrophotometer shown in Figure 6.7, but it is yet not clear where the strong linear absorption originates from.

### 6.2.4 Conclusion

The development of the 1.5-μm QD-SESAM is still work in progress. After the first iteration cycle of sample growths, we could only detect a negligible nonlinear reflectivity change which lies within the noise level of our measurement setup. The determined saturation fluences for both samples were below the target specification of 1 μJ/cm², but we consider this data more to be a numerical artifact.

The growth of QDs with an optical transition at 1.535 μm to 1.55 μm is still challenging, to date, most results are reported around 1.52 μm. Further investigations have to be performed by our collaborator, the University of Sheffield, who have grown the samples examined above, in order to optimize the optical properties of the QDs.
Chapter 7

Multi-wavelength source

Communication and data-transfer play an important role in today’s society. While people share photographs and other kinds of high-capacity data via social networks, the internet is also becoming a primary medium for the entertainment industry to distribute music, videos or high-definition television programs. To cope with the increasing demand in capacity, network operators have to upgrade existing fiber networks to increase their overall bandwidth. This can be done by increasing the data rates on existing transmission channels by means of optical time division multiplexing (OTDM) techniques or by adding new independent data channels with wavelength division multiplexing (WDM) techniques. WDM technology has attracted significant attention due to its potential for very high bandwidth capacity, while relaxing the requirements for ultra-high channel bit-rates which demand sophisticated high-bandwidth electronics, complex dispersion management systems and regeneration stages. For WDM systems, this complexity is currently transferred to the transmitter sub-system: in standard test and network architectures each data channel requires its own wavelength-stabilized continuous-wave laser. Usually distributed feedback (DFB) diode lasers are used in these systems, where each laser requires dedicated drive electronics. The wavelengths of the individual lasers have to be matched to a channel grid which is standardized by the International Telecommunication Union (ITU)[124], such that additional control electronics for wavelength monitoring and temperature stabilization is required for each individual laser. In case of failure of a single source, several tunable lasers have to be added for redundancy, covering together the whole transmission band. Figure 7.1 shows a simplified schematic of a standard WDM system.
Current dense WDM systems (DWDM) often operate in the spectral region between 1530-1565 nm (telecom C-band) with a channel spacing of 100 GHz or 50 GHz. To increase the bandwidth of a transmission system, in principle the channel spacing can be reduced, leading to more data channels within a fixed wavelength interval. Of course the minimal channel spacing is limited by the modulation frequency of the individual channels, as the generated modulation sidebands should not overlap. Still, the bandwidth of today’s DWDM systems, which typically operate at 10 Gbit/s, is limited by the selectivity and the steepness of the optical filters within the fiber network, limiting the spectral resolution. With improved system components, allowing tighter channel spacing, the number of individual sources within a transmitter will grow, leading not only to increasing installation costs but also to an increasing power consumption and space requirement. While the wavelength spacing decreases, the demands on the individual sources increase with respect to their wavelength stability and absolute accuracy. Currently installed DFB lasers might not match the enhanced tolerances and therefore eventually need to be replaced by new, improved versions, leading to additional costs.

7.1 Concept of a multi-wavelength source

One possibility to reduce the complexity and the overall costs of a DWDM transmission system would be an optical source capable of simultaneously generating a large number of different wavelengths with a defined spectral spacing through a single device. The output of such a source is de-multiplexed and the resulting individual cw-channels are encoded with data by a monolithically...
integrated multichannel modulator [125]. Figure 7.2 shows the simplified schematic of a transmission system deploying a multi-wavelength source (MWS). The transmitter still looks complex, but for DWDM systems the multiplexing components are highly integrated, purely passive devices which do not require sophisticated rf-electronics.

Figure 7.2 Simplified schematic of a WDM system deploying a multi-wavelength source. The transmitter consists of a single light source, passive multiplexing devices and a modulator array. DEMUX: de-multiplexer, MOD: modulator, MUX: multiplexer.

In the following we want to concentrate on the design of a MWS exploiting the properties of a mode-locked high repetition rate laser as it was described in Chapter 4. A detailed description of a complete WDM transmission system is beyond the scope of this text and can be found for example in [126]. The work described in this chapter was performed within an EU-funded project called “MultiWave” which is also the name for the final MWS and will be used to express properties of our specific system.

Mode-locked lasers naturally offer the spectral properties of a MWS: in the time domain mode-locked lasers produce trains of short pulses with a low timing jitter and high contrast ratio (Figure 7.3, left)[127]. In the frequency domain the phase-locked longitudinal modes of the fundamentally mode-locked laser cavity result in a stable comb-shaped optical spectrum with a high optical signal-to-noise ratio (OSNR), where the spacing of the individual wavelength-peaks is determined by the repetition rate of the laser (Figure 7.3, right).

The optical spectrum can be de-composed again into multiple cw-wavelength channels with this well defined spacing. Each cw-channel can then be encoded individually with data. When using a MWS in a DWDM transmission system, the source has to comply with additional technical prerequisites. The emitted different wavelengths have to match a standardized wavelength grid and the individual channels should exhibit similar power levels. In the optical spectrum in Figure 7.3
(right), out of the total number of displayed channels, only 18 lie within a 50% power range (-3 dB) of the maximum power. In this particular example the spacing of these channels is 25 GHz.

![Output of a 25-GHz modelocked laser in the time- and frequency domain. The equidistant pulse train in the time domain leads to an equally spaced wavelength-comb in the frequency domain. Each comb line can serve as a cw data-channel in a WDM transmission system.](image)

Commercially employed transmission systems usually rely on a channel spacing of 50 or 100 GHz, selecting every second or fourth channel respectively from the optical spectrum depicted in Figure 7.3. This reduces the number of usable channels to 9 for a 50 GHz spacing and to 4 for the 100 GHz grid, which in each case is only about 10% of the capacity of the C-band. The remaining dispensable wavelength-channels have to be suppressed to avoid disturbances within the system. To increase the overall number of generated channels, the optical comb of the laser can be spectrally broadened with a dispersion-engineered highly nonlinear photonic crystal fiber (PCF) to a so called supercontinuum (SC). The expression “supercontinuum” is somewhat misleading as the resulting spectrum is still comb-shaped and not continuous, and the comb spacing is still determined by the fundamental repetition rate of the pulse generating laser. With such a broadened spectrum a single MWS can cover a large number of transmission channels. Here we want to demonstrate a MWS covering the telecom S-, C- and L-band.

As described above, a complete MWS based on a mode-locked laser, consist of three fundamental building blocks: the initial pulse generating laser source, the supercontinuum generation and the spectral selection filter, determining the final
channel spacing. Figure 7.4 shows a diagram of these fundamental building blocks together with the evolution of the optical spectrum within the source.

![Diagram of fundamental building blocks](image)

Figure 7.4 Fundamental building blocks of a MWS, based on a mode-locked laser and the evolution of the optical spectrum within the source. The output of the MWS is a comb-shaped optical spectrum with a channel spacing matching the ITU grid. ERGO: Er,Yb:glass-oscillator, EDFA: erbium-doped fiber amplifier, PCF: photonic crystal fiber.

Key component is the fundamentally mode-locked, high repetition rate Er,Yb:glass oscillator (ERGO), determining the basic spectral properties of the MWS. The output of the laser is spectrally broadened with a highly nonlinear PCF. To enhance the width and the flatness of the broadened optical spectrum, the laser output is amplified by an erbium doped fiber amplifier (EDFA) before it is launched into the PCF. In the final stage, a Fabry-Pérot filter is used to suppress the dispensable channels such that the output of the MWS matches the channel spacing of the ITU grid. The Fabry-Pérot filter can be exchanged to adapt to different channel-spacings used in commercial test- and transmission systems.

In this chapter we describe in detail the development of a commercial MWS, based on a high repetition rate, fundamentally mode-locked Er,Yb:glass lasers. The following sections are dedicated to the individual components, to describe their function and their properties. We conclude with a section describing the overall system performance of the developed source. Due to the manifold of possible combinations of individual components with distinct properties, we will present only selected results in this text.
7.2 12.5-GHz and 25-GHz packaged ERGO lasers

Our main objective is to develop a reliable, highly integrated single optical source that delivers a large number of wavelength channels matching the specifications of the ITU grid. For today's WDM applications a channel spacing of 100 GHz between the individual lines is widely used. Therefore lasers with repetition rates directly matching the WDM channel spacing are particularly interesting, as every comb line of the optical spectrum can serve as a transmission channel and no spectral power is wasted. However, we found lasers operating at an integer fraction of the fundamental grid spacing, for example 12.5 GHz or 25 GHz, to be more efficient especially in the spectral broadening section. Compared to lasers with higher repetition rates, they generally offer higher peak powers leading to a better efficiency in the nonlinear PCF, because spectral creation is a highly nonlinear effect depending on the peak power. In addition, these lasers offer a higher potential bandwidth. With emerging ITU channel spacings of 25 GHz and 12.5 GHz, a MWS based on these fundamental repetition rates can easily be upgraded to offer the full system bandwidth simply by removing the Fabry-Pérot filter at the output of the source. Still, for our experiments we used an output-filter to enhance the channel spacing to the desired 100 GHz thereby complying with today’s standards.

Figure 7.5 Breadboard setup (left) and packaged version (right) of the same 12.5-GHz ERGO laser cavity. The packaged version is not only more compact but also less susceptible to environmental influences.
Starting from the optical layouts described in Chapter 4, and the corresponding flexible but sensitive and bulky lab-setups, the focus of this section is the development and the characterization of compact turn-key ERGO lasers as stable and reliable sources for the subsequent system components. Target specifications for these lasers are repetition rates of 12.5 GHz and 25 GHz, pulse durations of less than 2 ps and an optical output power of 10 dBm, in order to create a broad optical spectrum in the following spectral broadening section.

In the breadboard setup shown in Figure 7.5 (left), all optical components are mounted with five degrees of freedom, allowing maximum flexibility in the positioning of the components. With this setup, using standard XYZ-translation stages and mirror mounts, numerically found cavity parameters can quickly be investigated. The disadvantage of the setup, besides its size, is its susceptibility to environmental influences, leading to excessive noise in the laser output. Once the cavity parameters are found, a more robust laser cavity can be constructed, where the degrees of freedom for the individual components are reduced to a minimum, leading to an improved overall stability. In our construction, the components were attached to a solid stainless steel cage using specific holders. Because all dielectric cavity mirrors are strongly curved, a lateral movement of the mirrors is sufficient for the alignment of the resonator. Compared to standard tip-tilt mechanics, this alignment option allows for a better force closure once the components have to be locked to stay in place. The stainless steel cage containing the laser resonator is mounted in an enclosure on a temperature-stabilized baseplate. The enclosure also holds the fiber-coupled, high-brightness pump-diode. The output of the laser resonator is coupled through a free-space double-stage isolator with 60 dB isolation into a polarization-maintaining single-mode output fiber (PM-SMF). The power in the output fiber is split with a 95:5 ratio; the 5% signal can be used for external synchronization electronics, locking the repetition rate of the laser to an external clock. This is done by moving the SESAM, which is mounted on a piezo-element, along the optical axis inside the resonator, thereby changing the repetition rate of the laser.

We have build several integrated ERGO lasers with repetition rates of 12.5 GHz and 25 GHz, exhibiting an output power of about 10 dBm (10 mW) and a pulse
duration around 2 ps, to be used as fundamental sources for our MWS. In the following we give specific details about the properties of these lasers.

### 7.2.1 Spectral properties

In this section we study the temporal and spectral characteristics of ERGO lasers operating at different repetition rates. The ERGO lasers were experimentally optimized for low noise operation and their performance in terms of optical signal-to-noise ratio (OSNR), spectral linewidth, relative intensity noise (RIN), and spectral long term stability were measured. The targeted specifications required for the MWS application are:

- optical signal to noise ratio OSNR >30 dB
- spectral linewidth <1 MHz
- relative intensity noise RIN <1 %
- long-term spectral stability <20 pm shift in absolute frequency over 1 hour

**Optical signal-to-noise ratio**

![Spectral intensity of a 12.5-GHz ERGO for a center wavelength of 1.551 µm. The measured OSNR > 40 dB is limited by the resolution of the optical spectrum analyzer (OSA). The dashed line displays the target specification.](image)

ERGO lasers provide excellent optical signal to noise ratio (see Figure 7.6). We measure more than 40 dB extinction ratio, which is limited by the resolution
bandwidth of the used optical spectrum analyzer. This performance is about 10 dB above the requirements of the MultiWave system, which are specified to have an extinction ratio of >30 dB.

**Spectral linewidth**

To determine the spectral linewidth of the individual comb lines in our optical spectrum, we used an optical beat measurement of two high repetition rate lasers operating at 12.5 GHz and 25 GHz. In addition we compared the beat signal from the two mode-locked lasers with a beat signal from a standard DFB laser, with a typical linewidth in the MHz-regime, and a 25-GHz laser. For this measurement we expect the high repetition rate laser to determine the achievable spectral resolution.

![Figure 7.7 Beating measurement principle, using two mode-locked lasers with slightly detuned repetition rate. The increasing frequency difference of the individual modes of the two laser spectra leads to a comb-shaped beating spectrum.](image-url)
In a standard beat measurement for cw-lasers, two lasers of slightly different optical frequency are superimposed. The resulting electrical field has an amplitude modulation, which corresponds to the optical frequency difference. Because the optical frequency is extremely high, a photo detector will measure only this low frequency intensity envelope, therefore the optical frequency is transferred to an electronically accessible rf-frequency range. A similar measurement technique is also possible for mode-locked lasers. Two mode-locked lasers, slightly detuned in repetition rate, will generate a comb shaped beating signal. As illustrated in Figure 7.7, the comb spacing of the two laser spectra will be slightly different according to the difference in the repetition rate. Assuming the first modes of both spectra have an identical frequency, this will result in a beating signal at $N$ times the difference of the repetition rate $\Delta f_{\text{rep}}$, where $N$ is the longitudinal mode number, starting from the identical mode.

In our case, the mode spacing of the beating comb is determined by the 25-GHz laser and only every second mode of the 12.5-GHz laser results in a beating signal. The rf-beating signal was measured with an rf-spectrum analyzer (Figure 7.8). Looking at a measured span of 50 GHz (Figure 7.8, top) one can clearly see the fundamental repetition rate and the harmonics of the 12.5-GHz and 25-GHz laser as well as the beating signals being symmetrically placed around the laser peaks. The observed fundamental beating-spectrum (Figure 7.8, bottom left) is similar to the theoretically expected one (Figure 7.7, bottom). At a reduced measurement span, a spectral linewidth of less than 200 kHz is observed (Figure 7.8, bottom right). Assuming that both lasers contribute equally to the linewidth of the beating signal, each laser mode would have less than 100 kHz optical bandwidth. Note that the beating signal has an offset of about 2.7 GHz and that the comb is not equidistantly spaced. This is due to the fact that the two lasers under test were not phase stabilized with respect to their carrier-envelope offset (CEO) phase [128, 129]. The absolute offset results from the CEO of the two lasers. During the measurement time of the rf spectrum, the beating comb was shifted by the varying CEO leading to differences in the mode spacing. This could clearly be observed on the rf spectrum analyzer. We will get back to this issue in more detail in section 7.6.1. In general the measured linewidth depends on the noise properties of a laser as well as on the measurement time.
In order to verify the detection method, an additional beating measurement of a 25-GHz laser and a DFB laser was recorded (Figure 7.9). As described above, the linewidth of the 25-GHz laser longitudinal modes is approximately 100 kHz, therefore this method allows characterization of the DFB spectrum. We recorded a spectral linewidth of 4-6 MHz, which matches the specifications of the DFB laser. Thus the spectral linewidth of the longitudinal modes of high repetition rate lasers is in the order of fifty times smaller than that of a standard commercially available DFB laser.
Figure 7.9 Beating measurement of a 25-GHz ERGO and a continuous-wave DFB laser with 4-6 MHz spectral bandwidth. According to the measurement shown in Figure 7.8, the linewidth of the 25-GHz lasers longitudinal modes is approximately 100 kHz, determining the measurement resolution. The measured spectral linewidth is therefore only determined by the DFB laser.

Relative intensity noise (RIN)

The RIN of a 25-GHz ERGO laser was measured with an rf-analyzer by integrating the power spectral density noise sidebands, centered at 25 GHz, from 5 kHz to 500 kHz offset (resolution bandwidth: 1.5 kHz). We obtained a RIN of 0.6% which is mainly determined by the accuracy of the rf-analyzer and amplifier, but also by technical noise, introduced through the voltage source driving the piezo-element inside the ERGO laser, as we will show in section 7.6.2. Still, the obtained result is about a factor of two lower than the specified 1%-requirement.
Long-term spectral stability

We characterized the long term spectral stability of a 25-GHz ERGO by measuring the spectrum with an optical spectrum analyzer as function of time. Over 18 hours we recorded the optical spectrum and compared it to an initial spectrum at time zero, tracking the maximal deviations. During this time, the maximum deviation was less than 3.4 pm, which is substantially lower than the targeted specification of 20 pm in one hour.

7.2.2 Wavelength tuning

Because the intrinsic emission wavelength of the ERGO laser is located at 1.535 µm, we have to implement wavelength tunability in order to coarsely tune the laser emission to match the ITU grid (which would require only a very small tuning range) and to match the laser output to the PCF and to the gain maximum of the EDFA (which requires a much broader tuning range). Target specification for the ERGO laser was a tuning range covering the full telecom C-band.

By inserting a low finesse solid etalon into the cavity and changing its tilt angle, the laser emission can be tuned over a large span of the gain bandwidth. The thickness of the etalon is crucial as it determines the free spectral range (FSR), which limits the maximal accessible tuning range. We used a fused silica etalon with a thickness of 20 µm, resulting in a FSR of about 40 nm. The finesse has to be adapted to provide sufficiently wide transmission bands supporting short pulse generation.
Still, due to the transmission characteristics of the etalon the effective gain bandwidth is reduced, leading to an increased pulse duration compared to the free running laser. For wavelength-tuning, a flat gain curve is desired from the laser gain medium as it broadens the accessible overall tuning range. As we have seen in section 4.2, a well adjusted gain inversion can maximize the tuning range. For wavelength-tunable lasers we used an output coupling mirror with 1.3% transmission, to obtain a rather flat gain profile. Figure 7.11 shows the pulse-width and the average output power together with the generated optical spectra of a 12.5-GHz laser. The tuning range covers almost the entire telecom C-band while the pulse duration remains reasonably low.

![Figure 7.11 Wavelength tuning performance of a 12.5-GHz laser: pulsewidth (dashed) and average output power (solid) is plotted versus the resulting emission wavelength. Bottom (grey shaded): respective optical spectra.](image)

7.2.3 Wavelength locking

In order to fully meet the specifications of the ITU grid with a MWS, not only the respective channel spacing has to be exactly matched but also the absolute position of the individual channels in the wavelength domain. With a solid etalon the frequency comb of an ERGO laser can be coarsely tuned over a broad wavelength range. For fine tuning to actively lock the comb to a pre-defined wavelength grid this is not a practical approach. As we will explain in more detail in section 7.6.1, the most practical approach to fine-tune the wavelength of the MultiWave system is to use the scheme of repetition-rate-tuning for the pulse generating laser: by slightly changing
the repetition rate of the laser, the wavelengths of the individual comb-lines can be slightly shifted. The ERGO laser is equipped with a piezo-element behind the backreflecting mirror which allows for changes in the repetition rate of the laser on a small scale with a high resolution of about 1 kHz, by changing its cavity length. Figure 7.12 shows a block diagram of an active feedback loop implemented to achieve stable wavelength locking.

For the experimental setup we use a stable 50-GHz air-spaced etalon as a wavelength reference. The etalon has a high finesse and meets the wavelength-specifications of the ITU grid. The transmission wavelengths can be slightly adjusted by tilting the etalon. As an input signal for the control loop, a 5% fraction of the ERGO's output is used, marked in the diagram as “sync out”. The transmission of the etalon is converted by a photodiode into an electrical signal and evaluated by a proportional-integral (PI) controller which finally gives a feedback signal to the ERGO laser, to control the repetition rate and therefore adjust the wavelength. We use a rather simple technique in this feedback scheme: the reference voltage of the PI controller is set to half of the maximum transmission signal of the etalon; the controller is tracking the rising slope of the etalon transmission curve. If the output wavelength of the ERGO laser changes, the intensity on the photodiode will change causing the PI controller to adjust the repetition rate of the laser to readjust the transmission back to the reference level. A similar scheme is successfully used to frequency-lock the output of ERGO lasers to external clock references. One has to note that this scheme does not track the position of a single line of the optical spectrum but rather integrates the complete optical spectrum of the generated
frequency comb, this way also giving a certain feedback about the maximum frequency deviations in the wings of the spectrum.

With this feedback-scheme we stabilized the output of a 12.5 GHz ERGO. Over a short time period of 1000 seconds we could measure the wavelength fluctuation of an individual wavelength channel (Figure 7.13, left) with an optical spectrum analyzer (Agilent 86142B). In this short-term measurement we determined a maximum wavelength deviation of ±1.3 pm with a standard deviation of 0.37 pm. To appreciate this result one has to put it into relation to the standard deviations of a commercial DFB laser which is specified to be ±2.5 GHz corresponding to ±20 pm.

To measure the signal over a longer time period, the measurement technique had to be changed: over 10 hours, we logged the transmission signal from the etalon which in contrast to the above short term measurement records the integrated wavelength fluctuations of the whole frequency comb (Figure 7.13, right). A proper calibration allowed us to convert the transmission signal to an equivalent wavelength deviation value. In this measurement we could determine a maximum peak-to-peak wavelength fluctuation of about 0.05 pm with a standard deviation of <0.01 pm. This is probably an underestimation of the wavelength deviation, since in this case we are looking at the error signal only. It still shows that the wavelength-locked laser is very stable over long time periods, tracking the reference etalon precisely.
7.2.4 *Lifetime and temperature cycling*

Because the developed MWS is targeting commercial applications in test- and transmission systems, the ERGO laser as the key component has to be tested for reliability with respect to time and also to environmental influences. The targeted specifications for the ERGO are

- Lifetime > 1000 h ("Lifetime" is defined by a power degradation of less than 20% or an increase of the driving current, to keep the output power constant, of less than 20%)

- Withstand temperature cycles between 10°C and 40°C (no further specifications were given in this requirement; we believe that power fluctuations of ±5% over the whole temperature range would be a good result, ±7% would still be acceptable).

![Figure 7.14 Output power of an ERGO laser recorded over 1560 hours.](image)

To evaluate the life-time of the system, the power-degradation was measured over time in a time period of 1560 h. This test was performed under laboratory conditions which means under room temperature with maximum temperature deviations of ±3°C. The laser was operated with constant driving current, to measure a output-power-degradation over time. Figure 7.14 shows the output power in the examined time frame. Besides some minor fluctuations, no power-degradation could be observed. In addition, to verify the optical properties, an optical spectrum of the laser was taken once a week. The optical properties of the ERGO laser have not
changed over the observed time period. The laser therefore exceeded the required
demand of a lifetime of >1000h.

In addition to the lifetime data, the dynamic response of the free running laser
(no stabilization-scheme was applied) to continuous temperature changes was tested
from 10°C to 40°C. Output-power and repetition-rate of the laser were recorded over
temperature. For this test, the ERGO laser head was installed inside a climate
chamber, with the controller unit and the detection being placed outside. No
particular care was taken about humidity inside the chamber, which means that the
dew-point of the surrounding air was not stabilized in any way. The climate-
chamber could be programmed to run temperature cycles with defined temperature-
ramps and slopes of up to 3°K per minute in either direction. The laser was
dynamically tested with two temperature cycles, spanning the temperature range
from 10-40°C. Between the ramps, some stabilization-plateaus were implemented
into the program. For the data acquisition an additional, independent temperature
sensor was placed inside the chamber to record the ambient temperature near the
device under test (although the temperature distribution inside the chamber is fairly
even due to a fan at the back, circulating the air inside the chamber).

![Figure 7.15](image)

*Figure 7.15* Temperature dependent output power (left) and repetition rate
(right) of the unstabilized, free running laser. The output power changes by
maximal ±4%, the repetition rate by 1 MHz peak to peak. The dashed lines
indicate the targeted temperature interval of 10-40°C.

The temperature cycling test showed the following results: the output power of
the laser changes by approximately ±4% over the whole temperature range (Figure
7.15, left). Also the repetition rate scales with temperature and changes by
approximately 1 MHz peak to peak (Figure 7.15, right). During the test no
stabilization-scheme was implemented, neither repetition-rate nor wavelength-stabilization, both of which could compensate for this temperature dependence of the repetition rate. The temperature controller of the chamber was rather slow, which resulted in a strong under- respectively overshoot of the temperatures at the set limits. As such, an extended temperature interval, ranging from 8.5°C up to 42°C, was tested. Inside the ERGO-laser the pump diode and the laser cavity are temperature stabilized by thermo-electric coolers (TEC). The temperature controllers of the laser are able to provide ±4 A of drive current for the respective TECs. The maximum value reached in the tested temperature range was 1.3 A. Therefore it is expected that the laser could handle a larger temperature range as the performance of the TECs is limiting the operating conditions for the laser.

7.3 Integrated EDFA

The output power of MultiWave’s fundamental laser source is about 10 dBm. In order to create a broad optical spectrum in the spectral broadening section, the laser output is boosted with an integrated fiber amplification stage. To reduce the overall system costs, we split the output power of a single 600-mW single-mode fiber-coupled 976-nm laser diode to pump the ERGO laser and an EDFA. An ERGO laser in general needs about 300 mW of pump-power for stable cw mode-locked operation, the remaining 300 mW can be used to pump the amplifier.

To develop the amplifier section, we first built a self-contained version meaning that the amplifier was pumped by a separate, dedicated pump-diode. This allowed greater flexibility in the variation of the operation parameters to evaluate the characteristics and performance of the amplifier, as the pump power of the amplifier and the output power of the laser could be regulated independently. In a first step no special care is taken about dispersion management or particular noise properties.

7.3.1 Single-mode fiber amplifier

Limited by the available fiber splicing equipment, we used a highly doped standard single-mode fiber (Fibercore MetroGain M-12) for our EDFA design. The polarization management in this approach was done manually meaning that mechanical polarization controllers were used at the input and the output of the EDFA. To evaluate relevant design parameters like the pumping scheme (forward- or backward pumping), pump leakage, output power, gain length, amplified
spontaneous emission (ASE) and noise behavior, the simulation tool “Gainmaster” provided by Fibercore Inc. was used. The software allows to simultaneously simulate multiple source wavelengths for WDM systems. Figure 7.16 shows the schematic of a typical layout used in the graphical user interface of the simulation software. According to the output characteristics of the ERGO laser, for our simulations we assumed an optical source bandwidth of 3 nm consisting of 30 individual channels (channel spacing of 0.1 nm corresponding to 12.5 GHz) with a spectral power of 0.33 mW per channel, resulting in an overall power of 10 mW (10 dBm). Further we assumed 300 mW pump power at 976 nm and splicing losses of 0.2 dB. The simulations were carried out for two different center wavelengths namely 1535 nm, which is the intrinsic gain maximum of a free-running ERGO laser (without intracavity etalon), and 1550 nm.

The simulations showed qualitatively the same result with some variations in the gain-flatness at the different center wavelengths. Figure 7.17 shows selected simulation results for varying fiber lengths of the highly doped single-mode fiber and a center wavelength of 1550 nm. Figure 7.17 (right) shows that 2 m of active fiber would be sufficient to reach the specified output power with the available pump power of 300 mW, while 5 m of active fiber would exhibit the highest efficiency.
Based on the simulation results, a forward-pumped EDFA with an active fiber length of 5 m was built. This amplifier reached the specified output power of 100 mW (20 dBm) at a signal input power of 10.5 mW and a pump power of nominally 345 mW. An integrated design would provide only 300 mW pump power such that the amplifier would not fully meet the specifications. We attribute the reduced efficiency and the deviations compared to the simulations to increased splicing-losses between the passive and the active fiber. The loss-values that we estimated in the simulation are valid for splices of passive fibers only. Figure 7.18 shows the spectral properties at the input and the output of the amplifier. After amplification, the optical spectrum is clearly distorted (Figure 7.18, left) and the OSNR is reduced to about 10 dB as noise is building up around the laser pulses which is visible in the high dynamic range autocorrelation traces shown in Figure 7.18 (right). We attribute these effects to polarization issues in the SM fiber. The effects are clearly of linear nature as no additional spectral components are created. With the polarization controllers the spectral properties could be influenced but not be enhanced. We noticed that the amplifier in general was sensitive against environmental influences. As a conclusion, the SM-EDFA performed well with respect to power efficiency but the polarization management, which affects the spectral properties of the amplifier, has to be improved to adopt the EDFA in a MWS.
Figure 7.18 Measured spectral properties of an EDFA using 5 m of Fibercore MetroGain M-12 Erbium doped fiber. Top row: Gaussian shaped optical spectrum (left) and high dynamic range autocorrelation trace (right) at the amplifier input (equals output of the ERGO laser). Lower two rows: spectral properties at the EDFA-output at an output power of 50 mW and 100 mW respectively. The optical spectrum is clearly distorted (left) and the OSNR is reduced to less than 10 dB (right). The 20 dB-sidebands which are visible in the laser output (top right) originate from satellite pulses inside the laser cavity. The asymmetries in the autocorrelation are attributed to slight laser drifts over the measurement time of 20 minutes.
7.3.2 Polarization-maintaining fiber amplifier

The polarization management of an EDFA is crucial in order to get good spectral performance. Therefore we adapted the design of our stand-alone version of the EDFA such that the complete beam-guidance is done via PM fibers and components. According to results we obtained from new simulations that were carried out for Er-doped PM fiber (Figure 7.19), we used 15 m of DHB 1500-PM fiber from Fibercore for the active region to obtain good power efficiency and gain flatness.

![Figure 7.19 Simulation results for an EDFA implementing doped PM-fiber.](image)

Pump-absorption, gain, output power as well as the ASE noise-floor were calculated for varying lengths of the active fiber.

The active fiber DHB 1500-PM has stress bars in a bow-tie geometry, which could not be handled by our splicing equipment. Intermediate pieces of PANDA-fiber, spliced by an external supplier, were used to adapt the active fiber to the system components, increasing the overall number of splices and the associated losses. Therefore the overall power efficiency was about 2.3% lower compared to the SM-EDFA. The specified output power of 100 mW was reached at a signal input power of 12.9 mW with a pump power of nominally 375 mW. Figure 7.20 shows the power characteristics of both amplifiers in comparison.

In Figure 7.21 the improved spectral properties of the PM-EDFA are demonstrated: the optical spectrum is practically not distorted anymore (Figure 7.21, left). Also the noise buildup around the pulses in the time domain is substantially reduced (Figure 7.21, right). Some sidebands with an OSNR of about 30 dB evolve, while the main pulse remains almost unaffected. Only the pulse duration of the chirped input pulses is somewhat compressed from 1.5 ps to below 1.2 ps at 100 mW output power. As the dispersion data of the fiber are not available (proprietary data
of Fibercore Inc.) we cannot verify if the origin of the compression is simply dispersive or if other mechanisms also contribute.

![Graph showing EDFA output power for both design approaches, SM fiber and PM fiber.](image)

Figure 7.20  EDFA output power for both design approaches, SM fiber and PM fiber. The characteristics are comparable, with the SM-EDFA being slightly more efficient at high power levels.

To conclude, the spectral properties of the EDFA could be substantially improved by implementing an all PM design. There is no visible distortion on the optical spectrum anymore and the OSNR could be improved significantly. The continuous PM construction makes the whole fiber engine insensitive to environmental influences. The EDFA slightly compresses the pulses of the ERGO laser which is a positive and welcome side effect. Drawbacks of the PM design are the increased system costs, as PM fiber components in general and the long active PM-fiber in particular, are substantially more expensive than standard SMF counterparts.
Figure 7.21 Measured spectral properties of an EDFA using 15 m of Fibercore DHB 1500-PM polarization-maintaining Erbium doped fiber. The Gaussian shaped optical spectrum remains unaffected (left). The amplifier generates some additional noise sidebands with an OSNR of 30 dB as shown in the high dynamic range autocorrelation traces (right). The 20 dB-sidebands which are visible in the laser output (top right) originate from satellite pulses inside the laser cavity. The asymmetries in the autocorrelation are attributed to slight laser drifts over the measurement time of 20 minutes.
7.3.3 Performance of integrated design

For the transition from the self-contained EDFA to the integrated version in which
the EDFA and the ERGO laser are sharing the pump power of a single laser diode,
we use the PM-design because of its spectral properties and its overall stability. The
output of the laser diode is equally split by fiber-coupled power splitter. As the laser
oscillator and the amplifier are now driven by the same pump diode, the system has
to be operated at a fixed working point, as changing the pumping power strongly
influences the performance of the ERGO laser which can ultimately result in severe
damages of some of the optical components. The working point is chosen such that
the overall output power of the system is maximized; the ERGO laser already
exhibits an output power of 25.6 mW at this point. Note that a different ERGO laser
with lower sidebands and a pulsewidth of 1.2 ps (compared to 1.5 ps in the previous
experiments) was used for the integration. With the available pump power an
output power of 50 mW could be generated, which is an amplification of the input
signal of only 3 dB and significantly less than expected from the previous results.

Figure 7.22 Measured spectral properties of the PM-EDFA integrated into an
ERGO laser and sharing the same pump diode. The amplification of 3 dB
leads to a maximal obtained output power of 50 mW, which is clearly below
the expectations from the previous results.
Figure 7.22 shows the spectral properties of the integrated system. Again, noise sidebands with an OSNR of 20 dB built up, clearly degrading the quality of the input signal. The output pulses of the laser again were slightly compressed to a value of approximately 1 ps. We attribute the poor power efficiency as well as the spectral properties to low-quality splices and fiber-connector links within the system.

To conclude, the overall efficiency and the spectral properties of the integrated system is not sufficient to meet the desired specification. We will see in section 7.4.1, that the nonlinear efficiency of the highly non-linear PCF in the spectral broadening section was overestimated in the initial specifications. A single stage 20-dBm amplifier is not sufficient to create the desired spectral bandwidth with the available PCF. For the final MWS a commercial 26-dBm double-stage amplifier has to be used.

### 7.4 Spectral broadening

The generation of broad optical spectra, also often referred to as supercontinuum (SC) generation, by propagation of high intensity laser pulses through nonlinear media was first observed in 1970 by Alfano and Shapiro [130, 131]. Since then, highly specialized media in form of highly non-linear fibers (HNLF) have been developed to enhance the broadening effect while reducing the demands on the initial laser source. The nonlinear effects involved in the spectral broadening are highly dependent on the dispersion of the fiber. A properly designed dispersion can therefore significantly reduce the power requirements. Wide spectra can be generated if the pump pulses are spectrally close to the zero-dispersion wavelength of the non-linear fiber and the dispersion profile of the fiber is rather flat. Photonic crystal fibers offer an outstanding design freedom to obtain such properties.

#### 7.4.1 Properties of highly nonlinear photonic crystal fiber

Photonic crystal fibers (PCF) were first demonstrated in 1996 [132] and have generated much attention since that time, because they allow unprecedented control over fiber properties like nonlinearity and dispersion. PCFs are optical fibers that employ a microstructured arrangement of low-index material in a background material of higher refractive index. The background material is typically undoped silica and the low index region is typically provided by air voids running along the length of the fiber.
For the MultiWave system, to obtain a flat dispersion profile with the zero-dispersion wavelength around 1550 nm, the hybrid PCF NL-1550-POS-1 from NKT Photonics (former Crystal Fiber A/S) was chosen. According to the manufacturer, this fiber has a nonlinear coefficient of $\gamma = 11.2 \text{ (W km)}^{-1}$ and an effective mode field diameter of $2.8 \pm 0.5 \mu\text{m}$ at 1550 nm. The attenuation between 1520 nm and 1620 nm is $< 9 \text{ dB/km}$, and the dispersion between 1480 nm and 1620 nm is between 0.5 and $1.5 \text{ ps/(nm\cdot km)}$ with a slope of about $-2 \cdot 10^{-2} \text{ ps/(km\cdot nm}^2)$ at 1550 nm (Figure 7.23, right). This can be achieved by a three-fold symmetric hybrid core region, comprising a germanium-doped center element surrounded by three fluorine-doped regions embedded in a standard air/silica cladding structure (Figure 7.23, left). The hybrid core offers additional design parameters for the dispersion profile: the negative waveguide dispersion, which can be varied by changing the pitch and the hole-size of the photonic crystal structure, can be balanced with the positive contribution from the fluorine-doped regions, such that a desired dispersion profile can be engineered [133]. Because of its mode field diameter and the numerical aperture of $0.4 \pm 0.05$ the fiber can be spliced to standard step-index fibers with a loss of approximately 0.25 dB.

![Microstructured region of the used PCF](133). The solid doped hybrid core elements are graphically enhanced. Right: the fiber’s dispersion profile (data courtesy of NKT Photonics).

### 7.4.2 Broadening-results for a 12.5 GHz comb

The 9.9-dBm (9.8 mW) output of the 12.5-GHz ERGO laser, centred at 1550 nm with 1.9-ps pulses was amplified with a commercial EDFA to 26 dBm (400 mW) before it was launched into two consecutive 50-m spans of the highly nonlinear PCF. Because we found the efficiency of the spectral broadening to sensitively depend on the
polarization state of the pump pulses, the polarization was manually adjusted before the EDFA, re-adjusted before first fiber-span and once more between the two PCF-spans to optimize the result. At the output of the PCF-fiber spans we got an average power of 22 dBm (159 mW) due to absorption and splicing losses. The obtained generated spectrum shown in Figure 7.24 covers the S-, C- and L-bands (Figure 7.24, left) but is slightly asymmetric with a significant drop of the spectral intensity particularly in the S-band. In the commercially more important C- and L-bands, we obtained very good spectral flatness of 7.8 dB for the C-band and 4 dB for the L-band (Figure 7.24, right). We should note that the generated spectrum appears to be continuous due to the limited resolution of the optical spectrum analyzer. With enhanced resolution we could clearly resolve the discrete nature of the spectrum consisting of individual lines spaced by 12.5 GHz. We therefore have generated more than 1000 wavelength channels on a 12.5-GHz grid with an overall spectral flatness <9 dB.

Figure 7.24  Broadened optical spectrum from a 12.5-GHz ERGO laser. Left: the spectrum covers the telecommunication S-, C- and L-bands. Right: the spectral flatness is 7.8 dB over the C-band and 4 dB over the L-band.

7.4.3 Broadening-results for a 25 GHz comb

The 10-dBm output of the 25-GHz ERGO laser was also amplified to 26 dBm average output power before it was launched into the same two 50-m spans of highly nonlinear PCF. The resulting broadened spectrum is shown in Figure 7.25 (left). The amplitude variations are currently larger than for the 12.5-GHz system (about 30 dB for the whole spectrum and 24 dB for the C- and the L-band). This is due to the twice as high repetition rate at comparable pulse duration (2.1 ps), which results in a
reduction of the input pulse energy and the pulse peak power by a factor of two at similar average power. With 12 dB the spectral flatness in the C-band is still good, while for the L-band this value is already increased to 16.5 dB.

Figure 7.25 Broadened optical spectrum from a 25-GHz ERGO laser. Due to the lower pulse energy and resulting peak power of the 25-GHz laser, the spectrum is not as flat as in the 12.5-GHz case. The spectral flatness is 12 dB over the C-band and 16.5 dB over the L-band. The spectrum for the C-band starts to resolve the individual wavelength channels.

7.4.4 Conclusion
With the currently used highly nonlinear PCF we could broaden the output of the 12.5-GHz and 25-GHz ERGO lasers to cover the telecom S-, C- and L-bands. Especially in the case of the 12.5-GHz laser the spectral flatness of the generated spectra was very good for the C- and the L-band. Therefore we want to concentrate in the following on the 12.5-GHz system operating in the C- and the L-band. In general the quality of the generated spectra strongly depends on the polarization at the input of each fiber, such that a good polarization management is crucial at this point.

7.5 Mode selection
The bandwidth of today’s WDM systems is limited by the selectivity and the steepness of the optical filters within the fiber network, such that commercial WDM systems to date usually operate on the ITU 50 GHz or 100 GHz channel grid. To comply with the current requirements, the output of a MWS, operating with a fundamental channel spacing of 12.5 GHz, has to be spectrally filtered to suppress dispensable channels not matching the respective channel grid with a specified
extinction ratio of 30 dB. This can be done with a Fabry-Pérot filter, which offers an equally spaced, comb-shaped transmission function that can be designed to exhibit a high extinction ratio. For this scheme to work, the fundamental repetition rate of the mode-locked laser and the narrow transmission function of the Fabry-Pérot filter, which will be an integer multiple of the laser’s fundamental repetition rate, have to be closely matched to each other and to the ITU grid. Bulk Fabry-Pérot filters can be manufactured with a mirror spacing accuracy of ±100 nm, corresponding to a frequency offset of ±6.67 MHz for a 100 GHz filter. The 12.5-GHz ERGO laser can be frequency fine-tuned over a range of 7.75 MHz which is not sufficient to compensate for any manufacturing deviation. Additional tuning capabilities of the filter are needed to compensate for the remaining offset.

7.5.1 Fabry-Pérot filters

In its simplest form a Fabry-Pérot filter, also often referred to as etalon, is an interferometer consisting of two planar, parallel, equally reflective surfaces, constituting an optical cavity. The transmission of an ideal etalon under normal incidence can be expressed through the Airy function as

$$T = \frac{1}{1 + F \cdot \sin^2 \left( \frac{2\pi \cdot n \cdot d}{\lambda} \right)}$$

(7.1)

with $n$ being the refractive index of the material between the reflective surfaces, $d$ the distance between these two surfaces, $\lambda$ the respective wavelength and $F$ the finesse given by

$$F = \frac{4R}{(1 - R)^2}$$

(7.2)

which again is a function of the intensity reflectivity $R$ of the etalon’s surfaces. Strictly, the Airy function is only valid for perfectly flat and parallel mirrors free of absorption and a perfectly collimated beam under normal incidence. Figure 7.26 (left) shows the transmission through an ideal 100-GHz etalon in dependence of the finesse and the 30-dB suppression of dispensable wavelength channels through an etalon in a MWS (right).
Figure 7.26 Left: transmission function of an ideal, air-spaced ($n=1$) 100-GHz etalon for different reflectivities. The reflectivity of 82% corresponds to a finesse of 100. Right: calculated 30-dB suppression of 12.5-GHz laser lines by a 100-GHz etalon (dashed line).

The transmission maxima of an ideal etalon are evenly spaced in frequency, separated by the free spectral range (FSR), which is given in wavelength- or frequency units by

$$\text{FSR}_\lambda = \frac{\lambda^2}{2 \cdot n \cdot d \cdot \cos \theta} \quad \text{FSR}_\nu = \frac{c}{2 \cdot n \cdot d \cdot \cos \theta}$$

(7.3)

with $c$ expressing the vacuum speed of light and $\theta$ the angle of incidence. When using bulk precision-etalons, to exactly match a given wavelength grid, the transmission function can be fine-tuned by tilting the etalon. As we can see from equation (7.3), by tilt-tuning the transmission function, the FSR is changed simultaneously. For a broad wavelength-comb, this can lead to a mismatch between the filter transmission, the ITU grid and the incident wavelength comb from the mode-locked laser. In section 7.6.1, we will examine in more detail the analogous case of wavelength-tuning the output of the ERGO laser by changing its repetition rate. There we will explain that the obtained mismatch usually has only a negligible effect in our application.

However, because the properties of real etalons deviate from the ideal case in different aspects, we still have to address another issue which is also leading to a mismatch: real etalons always show dispersion, either introduced by the spacer material (which can be avoided by using air-spaced etalons) or by the dielectric reflective coatings. This leads to a wavelength dependent optical path length of the etalon, resulting in non-uniform transmission spacing and therefore to a slowly
increasing mismatch compared to a fixed wavelength grid. Because of this effect, the transmission bandwidth of the etalon has to be large enough to tolerate this mismatch. At the same time, to meet the specified extinction ratio of 30 dB, an etalon with a high finesse is required which drastically reduces the transmission bandwidth, as it is shown in Figure 7.26. The latter effect can be reduced by double-passing an etalon with reduced finesse: the transfer function of the double-pass scheme is equal to the squared transfer function of the single pass, thus providing adequate extinction without drastically reducing the filter bandwidth [134].

Another effect we have to be aware of is the fact that the effective finesse of an etalon is significantly reduced when tilted. Even for quite small tilt angles, the extinction of the filter is therefore drastically degraded. This can be avoided by using a fiber Fabry-Pérot filter as it is provided for example from Micron Optics: the cavity of this etalon can be longitudinally tuned by piezo-ceramics with high precision, such that no tilting effects occur.

In the MultiWave system we used precision bulk-etalons provided by SLS-Optics as well as fiber Fabry-Pérot filters from Micron Optics for spectral selection of the desired wavelength channels.

### 7.5.2 Results of filtered frequency combs

To enhance the channel spacing of the 12.5-GHz frequency comb described in section 7.4.2, the output of the PCF fiber was launched into a 100-GHz fiber Fabry-Pérot filter with a finesse of 200. The repetition rate of the laser was fine-tuned to 12.49975 GHz in order to match the exact FSR of the Fabry-Pérot filter. The generated 100-GHz frequency comb showed a spectral flatness of 4 dB over the commercially most relevant C-band (Figure 7.27, left) and 28.5 dB suppression of the unwanted spectral lines. Obviously the Fabry-Pérot flattened the spectrum obtained directly from the PCF. In section 7.6.2 we look in more detail at the spectral properties of this frequency comb.

A channel upgrade to the 50-GHz grid was achieved simply by replacing the 100-GHz filter with a 50-GHz fiber Fabry-Pérot, which in our implementation had a finesse of 100 (Figure 7.27, right). Because the 50 GHz filter follows the amplitude of the original 12.5-GHz comb more closely, the spectral flatness of the resulting spectrum is degraded to become 8.5 dB over the C-band. Suppression of the
undesired 12.5-GHz channels was reduced to 23 dB due to the lower finesse of the 50-GHz filter.

Both fiber Fabry-Pérot filters were wavelength tuned by means of a temperature controller, to closely match the ITU grid. We should note again, that both spectra shown in Figure 7.27 can be de-composed into their cw-components again, such that we obtain 44 DWDM wavelength channels for the 100-GHz grid and 88 channels for the 50-GHz grid within the C-band. In section 7.6.3 we will isolate individual channels and use them as carriers in data transmission experiments.

Figure 7.27 Optical spectrum over the C-band of the spectrally filtered MWS output with a mode spacing of 100 GHz (left) and 50 GHz (right).

7.6 System performance

7.6.1 Comb control and wavelength locking of MWS

Mode-comb properties

So far, we were focusing on stable and reliable laser sources for the generation of frequency combs with a distinct channel spacing, furthermore on the spectral broadening of these frequency combs and the filtering of the obtained broad spectra in order to meet the commonly used channel spacing specifications of the DWDM ITU grid. In order to fully meet the specifications of the ITU, not only the channel spacing has to be controlled but also the absolute position of the individual channels of the frequency comb in the frequency domain. It seems to be obvious that by matching the exact channel spacing, the absolute position of the individual channels is also fixed and therefore always matches the ITU specifications. Here we assume
that an ultra-broad frequency comb always starts with its first channel at the fundamental repetition-rate frequency (in our case 12.5 GHz) with no offset towards 0 Hz. All other channels are integer multiples of this fundamental frequency $n \cdot f_{\text{rep}}$ up to the frequencies in the desired communication bands between 186 THz and 201 THz. This assumption of a zero-offset, however, is in general not valid for the optical spectrum of a mode-locked laser due to the carrier-envelope offset (CEO) frequency.

**Carrier envelope offset (CEO) frequency**

In a fundamentally mode-locked laser (like the ERGO laser) the emitted pulse-train is generated by a single pulse travelling inside the laser cavity emitting an attenuated copy of itself every time it hits the output coupler. The electric field of the emitted pulses can be decomposed into the rapidly oscillating carrier, travelling with the phase velocity and the slower varying envelope, travelling with the group velocity of the pulse. If there are dispersive elements inside the cavity (which is almost always the case) there will be a phase offset $\Delta \phi_{\text{CEO}}$ between the carrier and the envelope as it is shown in Figure 7.28, which is constantly adding up for each roundtrip of the pulse inside the cavity,

![Figure 7.28 Carrier frequency (solid) and envelope (dashed) of three successive pulses from an oscillator, shown for a CEO phase slip of $\pi/2$.](image)

Therefore, every emitted pulse will have a different carrier-envelope phase (CEP) offset which in absolute values can be quite large; for the emitted pulse-train only the phaseshift modulo $2\pi$ is relevant. The CEP can be used to define the carrier envelope offset frequency $f_{\text{CEO}}$ as:

$$f_{\text{CEO}} = \frac{\Delta \phi_{\text{CEO}} \mod 2\pi}{2\pi} \cdot f_{\text{rep}}$$  \hspace{1cm} (7.4)
which basically describes the periodic re-occurrence of a particular phase relation between the carrier and the envelope. Because of this frequency, the optical frequencies \( f_n \) for the individual longitudinal modes in the spectrum of a pulse train are shifted by \( f_{\text{CEO}} \) and can be written as

\[
f_n = n \cdot f_{\text{rep}} + f_{\text{CEO}}
\]

with \( n \) being the mode number of the longitudinal mode. This means that a generated frequency comb has not only one but two degrees of freedom, namely the comb spacing \( (f_{\text{rep}}) \) and the frequency offset \( (f_{\text{CEO}}) \) as it is shown in Figure 7.29. In order to fully meet the ITU specifications, this frequency offset has to be corrected.

**Comb control**

As we can see from equation (7.4), \( f_{\text{CEO}} \) has a value between zero and \( f_{\text{rep}} \). Hence the appropriate approach would be to tune \( f_{\text{CEO}} \) either to zero or to \( f_{\text{rep}} \). In fact \( f_{\text{CEO}} \) depends sensitively on factors such as laser power and resonator alignment, such that a stabilization can be realized for example by tuning the lasers pump power or changing the intracavity dispersion. What is more of an issue for stabilization, is to obtain an appropriate feedback signal. It is not possible to directly measure \( f_{\text{CEO}} \) with the required accuracy, as there the offset frequency is usually several order of magnitude below the optical frequencies of the actual comb lines. To precisely

![Figure 7.29 The absolute position of the equidistantly spaced frequency comb lines of a mode-locked laser is shifted by \( f_{\text{CEO}} \). The spacing of the comb lines is determined by \( f_{\text{rep}} \).](image-url)
determine $f_{\text{CEO}}$ one needs different phase-stable harmonics $N(n_1 \cdot f_{\text{rep}} + f_{\text{CEO}})$ and $M(n_2 \cdot f_{\text{rep}} + f_{\text{CEO}})$ from different parts of the coherent optical spectrum. These harmonics have to spectrally overlap such that $N \cdot n_1 = M \cdot n_2$. If both frequencies are detected with the same photo detector, the difference frequency will automatically be generated leading to $f_{\text{det}} = (M - N) \cdot f_{\text{CEO}}$. In the simplest case where $N = 1$ (fundamental wave) and $M = 2$ (second harmonic), $n_1 = 2 \cdot n_2$ which means that one needs an octave spanning spectrum to get the spectral overlap. This requirement on the spectral width could be relaxed by using higher harmonics, but practically all of these schemes are difficult to implement with a low power picosecond laser.

For our application, a simpler approach is more suitable to compensate for the frequency shift caused by the carrier envelope offset. As there is a second degree of freedom, namely the comb spacing (= $f_{\text{rep}}$), one can slightly detune the repetition rate by $\Delta f_{\text{rep}}$ and with that perfectly match one longitudinal mode (which ideally would be placed in the center of the emitted optical spectrum) to the ITU grid, completely ignoring the CEO frequency:

$$f_n = n \cdot (f_{\text{rep}} + \Delta f_{\text{rep}}) + f_{\text{CEO}} \quad (7.6)$$

In order to remove the CEO frequency offset one has to detune the repetition rate by

$$\Delta f_{\text{rep}} = \frac{f_{\text{CEO}}}{n}. \quad (7.7)$$

By varying $\Delta f_{\text{rep}}$ from $-\frac{f_{\text{rep}}}{2n}$ to $+\frac{f_{\text{rep}}}{2n}$ (instead of 0 to $\frac{f_{\text{rep}}}{n}$) we can compensate for any value of $f_{\text{CEO}}$ and reduce the maximum frequency offset by a factor of 2. With the mode number $n = \frac{c}{\lambda_0 \cdot f_{\text{rep}}}$ one gets

$$\Delta f_{\text{rep}} \leq \frac{f_{\text{rep}}^2 \cdot \lambda_0}{2c}. \quad (7.8)$$

For a center wavelength of $\lambda_0 = 1550\text{ nm}$ and a repetition rate of $f_{\text{rep}} = 12.5\text{ GHz}$ this leads to a maximum frequency detune of $\Delta f_{\text{rep}} \leq \pm 0.4\text{ MHz}$, which is 0.003% of the nominal repetition rate. This frequency detune leads to an error in the comb spacing such that with increasing differential mode number (compared to the mode, which is exactly matched to the frequency grid) the absolute frequency shift will linearly
increase. A frequency comb with a 12.5 GHz spacing has 352 channels within the telecom C-band. If the center comb line is matched to the ITU grid, the maximum deviation at the edge of the band is 70.4 MHz which corresponds to a relative error of 0.56%. As a comparison, the standard frequency deviations of commercially available DFB lasers are specified to be around ±2.5 GHz. In a 100-GHz grid, a fundamental repetition rate of 12.5 GHz instead of directly 100 GHz is actually favorable for this tuning scheme as the maximum frequency detune is reduced by a factor of 8 compared to the 100 GHz grid spacing, leading to a relative error of maximum 0.07% for the full C-band (with the same assumptions as mentioned above). This is due to the fact that the frequency detuning directly scales with the fundamental repetition rate.

**Wavelength locking**

As we have seen above, to match the frequency comb of the MultiWave system to the ITU grid, the most practical approach is to use the scheme of repetition-rate-tuning. To achieve stable wavelength locking we implemented the same active feedback loop as described in section 7.2.3. Figure 7.30 shows a block diagram of the complete system. For the experimental setup we used the same 50 GHz air spaced etalon that we used for stabilizing the ERGO laser only and which is matched to the ITU grid. As an input signal for the control loop only a 5% fraction of the ERGO’s output is used marked in the diagram as “sync out”. The transmission of the etalon is converted by a photodiode into an electrical signal and evaluated by a PI controller which finally gives a feedback signal to the ERGO laser, to control the repetition rate and therefore adjust the wavelength. The ERGO laser is equipped with a piezo-element behind the back-reflecting mirror which allows for slight changes in the repetition rate of the laser by changing its cavity length. At the output of the MWS, a temperature stabilized fiber Fabry-Pérot filter is used as the channel selection module. This filter was manually matched to the repetition rate of the ERGO laser. In a final product, the ERGO laser would directly be locked to the output-filter of the MWS as it is indicated by the dashed line in Figure 7.30. The filter then has to serve as the wavelength-reference in addition. With this locking scheme, the system is then inherent stable with respect to its output power. One should note that this scheme in general integrates over the transmission of the complete generated
frequency comb, thereby also taking into account the frequency deviations in the wings of the spectrum.

Figure 7.30 Block diagram of the complete MWS with integrated wavelength locking. The reference etalon is the same that was used for stabilizing the ERGO laser. In a final system setup, the laser would directly be locked to the output filter instead of a separate reference as it is indicated by the dashed line.

Figure 7.31 Wavelength deviation measurement of a wavelength locked MultiWave system on timescale of two hours. We could determine a maximum wavelength deviation of ±1.43 pm.

According to the feedback-scheme which is using a separate reference etalon, we stabilized the output of the MultiWave system and recorded a single line of the optical spectrum (extracted before the reference etalon) with an optical spectrum
analyzer (Ando AQ6319) over time (Figure 7.31). We could determine a maximum deviation of ±1.43 pm with a standard deviation of 0.67 pm. As a comparison, a standard telecom DFB laser has a specified wavelength deviation of ±2.5 GHz which corresponds to ±20 pm.

7.6.2 Spectral properties of MWS

Analogous to section 7.2.1, where we have determined the spectral properties of the developed ERGO lasers, we want to investigate the complete MWS to analyze if the spectral properties are degraded by any of the system components. Because of the manifold of possible combinations between different system components, we will not document all achieved results in detail. We rather give significant data for system-configurations that might be relevant for commercial use.

The targeted specifications for the full MWS are

- optical signal-to-noise ratio OSNR >30 dB (per channel)
- spectral linewidth <1 MHz (per channel)
- relative intensity noise RIN <1 %

Optical signal-to-noise ratio

As we have seen in section 7.2.1 the OSNR of the ERGO laser, which is the key component of the MWS, exceeds 40 dB, limited by the resolution of the used optical spectrum analyzer. The output of the complete MultiWave system is specified to have an extinction ratio of >30 dB. Of major importance for this specification is the extinction ratio of the output Fabry-Pérot filter, that enhances the channel spacing from the fundamental 12.5 GHz or 25 GHz of the ERGO laser to the desired 50 GHz or 100 GHz of commercial telecom grids. Figure 7.32 (left) shows a section of a 100-GHz frequency comb generated with a MultiWave system based on 12.5-GHz fundamental channel spacing. The spectrum, which covers a large part of the telecom L-band, is fully generated through MultiWave’s spectral broadening and does not contain channels from the generating laser itself. In this spectrum we can determine an OSNR>30 dB. Looking at individual comb-lines in detail (Figure 7.32, right) reveals the fundamental channels which were suppressed by the output filter with an OSNR>28.5 dB.
Spectral linewidth

In order to determine the spectral linewidth, we used an optical beat measurement similar to the one described in section 7.2.1. The channel linewidth was evaluated for different system configurations. To separate the influence of the individual building blocks to the output, we first measured the spectral linewidth of a MultiWave source based on a 12.5 GHz fundamental repetition rate without the final channel selection filter. In order to evaluate the performance across the full C-band, the 25-GHz reference laser was tuned to 3 different optical wavelength (1536 nm, 1550 nm, and 1564 nm). The measurements were repeated with MultiWave sources based on 12.5 GHz and 25 GHz fundamental repetition rates, using channel selection filters with a channel spacing of 50 GHz and 100 GHz respectively. In all cases a spectral linewidth of less than 200 kHz is observed. Assuming that the noise is equally introduced by both independently fluctuating sources, each mode would have less than 100 kHz optical bandwidth.
As an example for one particular configuration Figure 7.33 shows the setup used to measure the beat signal of a mode-locked 25 GHz ERGO laser with the output of a 50 GHz MultiWave source with 12.5 GHz fundamental repetition rate. In this case, only every second mode of the 25 GHz ERGO results in a beating signal as the number of beating modes is determined by the 50-GHz MWS. The rf-beating signals shown in Figure 7.34 were measured with an rf-spectrum analyzer. On the right hand side of Figure 7.34 a single beating signal is shown, exhibiting a linewidth of less than 200 kHz.

Figure 7.34 Beating measurement of a 25 GHz laser and a 50 GHz MultiWave source with a fundamental repetition rate of 12.5 GHz. Full beating-comb (left) and one individual beating line (right). Less than 100 kHz spectral linewidth of the individual modes is observed (assuming equal contributions from both sources). Note that the different center frequencies result from a movement of the beating comb between the two individual measurements.
The result is similar to the one obtained from the direct beating signal between the 12.5-GHz laser and the 25-GHz laser, therefore it can be concluded that the spectral creation stage and the channel selection stage do not introduce significant broadening of the individual optical channels. The measured spectral bandwidth of less than 100 kHz is well below the 1 MHz specification for the MultiWave system. One should add for completeness that in fiber-optical transmission systems a very narrow linewith of individual transmission channels can lead to problems due to stimulated Brillouin scattering [135]. As we could confirm in transmission experiments shown in section 7.6.3, we believe that the channels of the MultiWave system do not experience these effects.

Relative intensity noise

To determine the noise properties of the generated continuous-wave optical channels, the output of a MultiWave source was filtered through a 0.6 nm bandpass filter followed by a 290 MHz bandwidth Fabry-Pérot Filter. By this, individual optical channels across the whole generated spectrum could be addressed. The RIN was measured with an rf-analyzer by integrating the power spectral density noise sidebands, centered at the respective channel frequency, from 10 kHz to 500 kHz offset (resolution bandwidth: 300 Hz, video bandwidth: 300 Hz). To match the transmission of the main channel selection Fabry-Pérot filter, the repetition rate of the ERGO laser source had to be tuned with the internal piezo element, which changes the laser cavity length. The piezo was first driven with a regular voltage source, leading to strong noise sidebands in the regime from 10 kHz to about 200 kHz (Figure 7.35, left). The observed noise sidebands are of technical origin, introduced by the piezo voltage source. By changing the voltage source driving the piezo to a battery-based system, which should not introduce additional technical noise, these noise-sidebands could be efficiently suppressed (Figure 7.35, right). Integrating the power spectral density in this case resulted in a RIN of <0.1% which is a factor of 10 better than the target specification of RIN<1%, although the result is mainly determined by the accuracy of the rf-analyzer and amplifier. The origin of the pronounced noise-peaks at 94.9 kHz and 129.2 kHz in this measurement remains unknown. The 94.9-kHz peak is also visible in the left noise spectrum but less pronounced.
As an important result from these measurements we conclude that for a commercial MWS it is of major importance to reduce sources of technical noise within the system. The use of low-noise voltage drivers within the feedback-loop for wavelength stabilization is recommended.

![Figure 7.35 Relative intensity noise (RIN) of one isolated channel of a 100-GHz MultiWave source measured with an rf spectrum analyzer. In the left measurement technical noise is introduced by a power supply controlling the piezo element inside the ERGO laser. In the right measurement the power supply is replaced by batteries.](image)

7.6.3 Results of transmission experiments

In order to assess the performance of the complete MultiWave source and to verify that the generated cw-channels are appropriate for use as WDM sources, each channel was modulated in a Ti:LiNbO$_3$-modulator at 10 Gb/s, with a $2^{31}$-1 pseudo-random binary sequence (PRBS) data pattern, and eye diagrams as well as bit-error-rates (BER) were recorded and evaluated. Figure 7.36 shows the obtained results for the 100 GHz (left) and 50 GHz (right) grid respectively. Selected channels within the C-band are presented, covering a range of 34 nm. The results show similar performance between adjacent and distant channels. The BER also shows that even two adjacent channels perform equally well. A commercially available DFB laser was used as a reference and showed similar BER performance, proving the high quality of the cw channels generated by our MWS.
Figure 7.36  MWS performance for 100-GHz grid (left) and 50-GHz grid (right). Eye-diagrams (top row, scale: 20 ps/div.) and BER measurement (bottom row) for a $2^{31}-1$ PRBS. For comparison, the corresponding results of a commercial DFB laser are included.
7.6.4 Failure modes of the MultiWave source

When we examined the response of the MultiWave system to changing environmental conditions, analogous to the tests we performed for the ERGO lasers described in section 7.2.4, we identified some system failure modes, which we briefly want to describe in this section.

Wavelength offset between laser output and channel selection filter

Over time or due to changes of environmental conditions, it is possible that an offset occurs between the frequency comb, emitted by the laser, and the transmission function of the channel selection filter, as both components are in principle susceptible to temperature changes. Therefore they are actively temperature stabilized, but a change in the ambient temperature can still be transferred in an attenuated manner to the stabilized component. This can lead to thermal expansion or contraction respectively, which will lead to a change in size for these interferometrically precise devices. Depending on the local temperature or a difference in the thermal expansion coefficient, a mismatch of the former precisely matched components can occur.

To avoid such an offset, the output of the ERGO laser should be wavelength-locked to the transmission function of the channel upgrade module as it was already indicated in Figure 7.30 by the dashed line. When we demonstrated wavelength locking of the ERGO laser and the MWS in sections 7.2.3 and 7.6.1 respectively, we locked the respective device to an external fixed wavelength reference, to precisely match the ITU grid. In contrast, the above described locking scheme would result in a MWS which is inherently stable with respect to its output power as the pulse generating laser (PGL) will always be tuned for maximum transmission through the channel selection filter. Now, in addition, special care has to be taken to match the desired wavelengths of the ITU grid. This could be done by replacing the fiber-Fabry-Pérot filter at the output of the MWS by a highly stable free-space reference, which is matched to the ITU grid.

Polarization management

As we have briefly mentioned in section 7.4.2 about spectral broadening at 12.5 GHz and also in section 7.3 about the design of an EDFA, polarization-management is a
crucial issue for the MWS to work in a stable and reliable manner. Changes of the polarization state especially at the input of the fiber-amplifier and the nonlinear fiber-stages have a huge impact on the efficiency and the noise properties of the system.

According to our results, a final MWS, as a commercial product, should exhibit a complete PM-architecture. The system would then be less susceptible to any kind of external temperature perturbations. Due to the results of our research conducted during the MultiWave project, the partner NKT Photonics has started to develop a polarization-maintaining photonic-crystal fiber (PM-PCF). In addition to the PM-PCF, a high-power PM-EDFA would be needed for the system to be complete. Er-doped PM-fibers are available, but so far, to the best of our knowledge, there is no suitable commercial high-power PM-EDFA available on the market.
Chapter 8

Conclusion and outlook

In this thesis we investigated passively mode-locked multi-GHz solid-state lasers emitting in the spectral region around 1.5 µm, and described their application in a novel multi-wavelength telecom source to be used in broadband fiber-optical transmission systems. This source has the potential to reduce the complexity and the overall installation costs of commercial DWDM systems or to upgrade the bandwidth of already installed fiber networks in a cost efficient way.

Multi-GHz pulse sources are highly desired for numerous applications in science and technology. Out of many different approaches, passively mode-locked Er,Yb:glass lasers represent a simple way to generate high repetition rate 1.5-µm ps-pulse trains with excellent pulse quality. To initiate and sustain the pulse generation, a semiconductor saturable absorber mirror (SESAM) is used, which is a highly flexible device that can be adapted to many different laser parameters. However, the small emission cross section of the Er,Yb:glass leads to a strong tendency towards Q-switched mode locking, which in most applications is not desired. Especially at very high repetition rates, to suppress Q-switched mode-locking is a major challenge. Based on the stability criterion for stable mode-locking introduced by Hönninger et al. [22] (also referred to as QML-threshold), we have discussed SESAM designs and general laser design considerations for mode-locking at high repetition rates. For the SESAM, an antireflection-coated resonant device offers a good balance between a moderate saturation fluence, which simplifies the cavity design, and a reasonably low modulation depth, leading to a reduced QML-threshold. We also discussed that
the effect of inverse saturable absorption of a SESAM additionally relaxes the requirements for stable mode-locking.

Because the precise knowledge of the nonlinear reflectivity change is crucial to optimize SESAMs for self-starting, passive mode-locking at record high repetition rates, we have built a setup for wide dynamic range nonlinear reflectivity measurements, according to [50]. With this setup we achieve an accuracy of 0.05% for the measured reflectivity, for an incident pulse fluence varied over 3.5 orders of magnitude. We were able to measure SESAMs with a modulation depth down to 0.16%, which was not possible with our previously existing 1.5-µm setup as its resolution was limited to 0.3%.

We have demonstrated a fundamentally SESAM mode-locked Er:Yb:glass laser with a repetition rate of 101 GHz at 1534.2 nm and an average output power of 35 mW in 1.6-ps pulses. By systematically varying the SESAM design, we could reduce the pulse duration by about 30% to get 1.1-ps pulses with an average output power of 30 mW. The mode locking of all demonstrated lasers was self-starting and stable. To the best of our knowledge, this is the highest repetition rate generated directly from a passively mode-locked solid-state laser oscillator operating in the 1.5-µm telecom window. The high average output power at high repetition rate, the good pulse quality and pulse-to-pulse phase stability, and the compact and simple setup make this laser a competitive alternative to harmonically mode-locked fiber lasers [65], semiconductor lasers [59] and distributed feedback (DFB) lasers [96] for high-speed data-transmission applications.

As an intermediate conclusion, we summarized our design considerations and the experience we gained through our experimental setups in some practical guidelines for the design of passively mode-locked high repetition rate lasers (section 4.7).

Within our work on Er,Yb:glass lasers we could experimentally confirm beam quality deteriorations which arise from frequency degenerate higher order spatial modes. They have to be considered when building a passively mode-locked laser, as they can resonantly couple to the fundamental transverse mode, leading to instabilities in the mode-locking process and even to a complete laser shut-off. In general, it is not possible to fully suppress these degeneration effects. To reduce the
effective number of contributing modes, it is good practice to pump with a smooth and symmetric beam profile and to avoid misalignments and any kind of asymmetries inside the laser cavity. For an ideal circular symmetry the coupling between the fundamental Gaussian mode and Hermite-Gaussian modes with an odd index will vanish and no energy will be transferred [104]. With the cavity single-pass matrix, it is possible to calculate cavity configurations at which degeneracies occur. This is highly interesting for lasers operating at MHz repetition rates, as they often offer a large stability range with respect to the axial position of their components, and the spacing of the individual degenerate points is rather large as well. Therefore there is enough freedom for optimizing the laser cavity to operate in a stable regime. For high repetition rate cavities, it is more difficult. Usually the stability range of the cavity is in the order of only a few 100 µm and even more limited by the operating parameters of the SESAM to achieve cw-modelocking. Because the geometric cavity parameters are usually not precisely known for these lasers, it is also difficult to accurately determine the degeneration points in advance. Still, it is important to be aware of the existence of such degeneracies and their effects on the laser dynamics.

A fundamentally mode-locked laser with a substantially higher pulse repetition rate than the one presented in this thesis would require a different mechanical setup such as a monolithic approach, in which the gain medium and the saturable absorber are bonded together to form a simple straight cavity. With such a design not only the repetition rate could potentially be increased but also the assembly of commercial laser versions could be simplified substantially, such that multi-GHz solid-state lasers in general could become a cost-effective solution for many applications. However, monolithic approaches require equal mode sizes in the gain medium and on the absorber (1:1 mode-locking), such that stable mode-locking is not feasible with the currently available components. To obtain stable 1:1 mode-locking in the 1.5-µm spectral region, gain media with substantially higher interaction cross sections compared to Er,Yb:glass and saturable absorbers with very low saturation fluence, low modulation depth and flat GDD are needed.

With Er,Yb:YAB a new Er,Yb-doped crystalline material with very good optical quality and improved thermal properties has recently been reported, together with corresponding laser results. It has the noticeable feature that it offers a four times
higher emission cross section compared to Er,Yb-doped phosphate glasses, which makes it highly attractive to be used in 1.5-µm multi-GHz lasers. We have presented the first passively mode-locked Er,Yb:YAB laser with multi-GHz repetition rate. To the best of our knowledge this is to date the highest repetition rate achieved with an Er,Yb co-doped bulk laser based on a crystalline gain material. Compared to the results achieved with Er,Yb:glass the performance of this laser has yet to be improved such that the achieved results should more be regarded as a proof of principle. We believe that the laser performance can significantly be improved by adapted optical components, such that the optimized Er,Yb:YAB laser will outperform the glass-laser results.

To reduce the saturation fluence of the SESAM while maintaining a low modulation depth and a flat GDD, we tried to implement a design based on quantum-dots rather than quantum wells to be used as saturable absorbers. By varying the dot density, QD-SESAMs offer an additional degree of freedom to control the saturation fluence and the modulation depth independent of each other. In other wavelength regimes, QD-SESAMs have been demonstrated exhibiting a significantly lower saturation fluence compared to their QW-counterparts. However, the growth of QDs with an optical transition between 1.535 µm and 1.55 µm is still challenging. To date, most results are reported around 1.52 µm, which is below our laser transition. Further investigations have to be performed by our collaborator, the University of Sheffield, to optimize the optical properties of the QDs, such that the development of the 1.5-µm QD-SESAM is still work in progress. After the first iteration cycle of sample growths, we could only detect a negligible nonlinear reflectivity change which lies within the noise level of our measurement setup.

Furthermore, we have demonstrated a cost-effective and viable multi-wavelength source, capable of generating a large number of ITU compatible DWDM channels within C- and L-band. The source is exploiting the physical properties of fundamentally mode-locked lasers, photonic crystal fibers and high-finesse Fabry-Pérot filters. The demonstrated performance of the 100 GHz multi-wavelength source is ideally suited for the use in DWDM transmitter systems; besides the mere optical properties, BER measurements and eye diagrams revealed that the generated channels exhibit a performance comparable to commercial DFB lasers. In addition, the proposed concept offers a simple upgrade path to increase its channel count: by
changing the Fabry-Pérot filter at the output, different ITU grid spacings can be generated, reaching down to the fundamental spacing of 12.5 GHz.

We have demonstrated, that the core component of our source, an engineered and packaged Er,Yb:glass laser, is a reliable, long-term stable system, which did not show any power- or optical degradation over a time period of more than 1500 hours. It also did not show any failure when tested over an extended temperature range. Its long-term stability as well as its predictable behaviour under demanding environmental conditions make it an ideal system for telecom applications.

The multi-wavelength source as a system exceeded our expectations with its performance under laboratory conditions. Nevertheless, for long-term stability and more demanding environmental conditions, additional work has to be done in the future to enhance the system to become a competitive product for the telecom market. We identified the critical failure modes and suggested solutions. With an all-PM-architecture, we believe that the presented source can become an interesting alternative to conventional DFB laser arrays, to be used in commercial transmission systems.

Potential future applications of multi-GHz solid-state lasers include phase stabilized frequency combs to be used in frequency metrology. Such combs have already been presented based on high repetition rate Ti:Sapphire lasers [136]. However, these lasers are expensive and have a low wall plug efficiency (which is important for space applications for example). Further, their frequency combs are usually centered around 800 nm and therefore not suitable for long-haul fiber distribution. Recently very promising results have been reported on the first carrier-envelop-offset (CEO) frequency signal from a spectrally broadened 75-MHz Er,Yb:glass laser. The f-to2f CEO frequency beat signal had an extinction ratio and a linewidth that were significantly better than typically obtained from ultrafast fiber lasers [137]. It is highly anticipated to increase the mode-spacing of these frequency combs into the GHz regime. Here spectral broadening is a critical issue. With our MultiWave source we obtained a -30-dB optical bandwidth of about 250 nm, which is sufficient for telecom applications. To obtain an octave spanning spectrum, which is required for the detection of the CEO frequency, the pulse duration of GHz solid-state lasers has to be reduced from picoseconds into the fs-regime. Further, highly nonlinear fibers with increased nonlinear coefficient and flat dispersion are required.
Appendix

ABCD-matrices used for theoretical calculations of mode degeneracies in a 100-GHz laser cavity.

Flat/Brewster gain prism

Derived from general prism given in [138].

Propagation from flat to Brewster interface (for counter-propagation indices 1 and 2 have to be exchanged):

\[
\begin{align*}
\text{tangential:} & \quad M_{\text{prism},t} = \begin{vmatrix}
\cos \Theta_2 & L \cos \Theta_2 \\
\cos \Theta_1 & n \cos \Theta_1 \\
0 & \cos \Theta_1 / \cos \Theta_2
\end{vmatrix} \\
\text{sagital:} & \quad M_{\text{prism},s} = \begin{vmatrix}
1 & L/n \\
0 & 1
\end{vmatrix}
\end{align*}
\]

Refractive index of prism: \( n = 1.521 \) at 1535 nm.

\text{Tilted curved folding-mirror}

\[
\begin{align*}
\text{tangential:} & \quad M_{\text{FM},t} = \begin{vmatrix}
1 & 0 \\
-2 / R \cos \theta & 1
\end{vmatrix} \\
\text{sagital:} & \quad M_{\text{FM},s} = \begin{vmatrix}
1 & 0 \\
-2 \cos \theta / R & 0
\end{vmatrix}
\end{align*}
\]

\( \theta \): folding angle

\( R \): radius of curvature
Thermal lens

\[ M_{TL} = \begin{bmatrix} 1 & 0 \\ -\frac{f}{1} & 1 \end{bmatrix} \]

Free-space region

\[ M_{FS} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \]

Single-pass matrices
(without thermal lens)

tangential:

\[
\begin{vmatrix}
A_{1,t} & B_{1,t} \\
C_{1,t} & D_{1,t}
\end{vmatrix} = \begin{bmatrix}
\cos \Theta_2 & \frac{L_1 \cos \Theta_2}{n \cos \Theta_1} \\
-\frac{\cos \Theta_2}{\cos \Theta_1} & \frac{L_1 \cos \Theta_2}{\cos \Theta_1}
\end{bmatrix} \begin{bmatrix}
1 & L_2 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
-\frac{2}{R \cos \Theta_3} & 1
\end{bmatrix} \begin{bmatrix}
0 & 1 \\
1 & L_3
\end{bmatrix}
\]

\[ A_{1,t} D_{1,t} = 1 - \frac{2 \left( \frac{L_1}{n} + L_2 + L_3 \right)}{R \cos \Theta_3} + \frac{4L_3 \left( \frac{L_1}{n} + L_2 \right)}{R^2 \cos^2 \Theta_3} \]
The terms $A_{1,t}D_{1,t}$ and $A_{1,s}D_{1,s}$ can now be inserted in equation (5.5) to calculate the cavity’s resonance frequencies and to identify degeneracies.
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Weiterhin in alphabetischer Reihenfolge (diesmal nach Nachnamen sortiert), wie auch im täglichen Umgang unter Vernachlässigung von Titeln: Cyrill Bär, Yohan Barbarin, Aude-Reine Bellancourt („Isch ‘ab lieber Pizza…“), Claudio Cirelli, Petrissa Eckle, Anna Enquist (Yes, computer monitors are eye-safe), Christian Erny, Birgit Gallmann-Schenkel, Lukas Gallmann, Matthias Golling, Rachel Grange, Annalisa Guadalini, Shigeki Hashimoto (World’s best Sushi…), Oliver Heckl („Ich brauch ’nen kleineren Gang – ich kauf mir ’n neues Rrad“), Clemens Heese (Mr. Spitzer), Arne Heinrich, Martin Hoffmann (hat schon mehrere schweizer Pässe…), Mirko Holler, Christian Kränkel, Valeria Liverini, Reto Locher, Dirk Lorenser (danke für Deran’s tollen „Dirk“), Sergio Marchese, Konstantinos Moutzouris, Paolo Navaretti, Rüdiger Paschotta (für den Hinweis auf die Moden-Entartungen), Wolfgang Pallmann, Adrian Pfeiffer (mit drei f), Thomas Remetter, Benjamin Rudin, Andreas Rutz, Clara Saraceno, Florian Schapper, Sandra Schmid, Mohammad Shafiei („Ohhh, I looove Satriani!“), Oliver Sieber (früher oder später kriegen wir sie alle…), Matthias
Smolarski, Heiko Unold, Matthias Weger, Valentin Wittwer („Hmm, legger Schoggohörnsche!!“) und Amelle Zaïr („MmmHmmm…“).

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