Weierstraß-Institut
für Angewandte Analysis und Stochastik

im Forschungsverbund Berlin e.V.

Preprint ISSN 0946 – 8633

Experimental Investigations on the Suppression of Q-Switching in Monolithic 40 GHz Mode-Locked Semiconductor Lasers

Bernd Hüttl[1], Ronald Kaiser[1], Christian Kindel[1], Sybille Fidorra[1], Wolfgang Rehbein[1], Heiko Stolpe[1], Gabriel Sahin[1], Uwe Bandelow[2], Mindaugas Radziunas[2], Andrei Vladimirov[2], and Helmut Heidrich[1]

submitted: 22nd March 2006

[1] Fraunhofer-Institute
for Telecommunications,
Heinrich-Hertz-Institut,
Einsteinufer 37,
D-10587 Berlin,
Germany,
E-Mail: huettl@hhi.fraunhofer.de
kaiser@hhi.fraunhofer.de

[2] Weierstrass Institute
for Applied Analysis
and Stochastics,
Mohrenstrasse 39,
D - 10117 Berlin,
Germany
E-Mail: bandelow@wias-berlin.de
radziuna@wias-berlin.de
vladimir@wias-berlin.de

No. 1112
Berlin 2006

WIAS

2000 *Mathematics Subject Classification.* 78A60.

Key words and phrases. monolithic semiconductor lasers, mode-locking, Q-switching.

1999 *Physics and Astronomy Classification Scheme.* 42.55.Px, 42.60.Fc, 42.60.Mi, 42.60.Gd.

Edited by
Weierstraß-Institut für Angewandte Analysis und Stochastik (WIAS)
Mohrenstraße 39
10117 Berlin
Germany

Fax: + 49 30 2044975
E-Mail: preprint@wias-berlin.de
World Wide Web: http://www.wias-berlin.de/

Abstract

Inherent Q-switching as a source of intra-cavity pulse energy modulations, i.e. unwanted amplitude noise, is still a challenging task in order to fabricate monolithic mode-locked semiconductor lasers in view of different commercial applications. In this paper, the results of experimental investigations on the influence of the quantum well number on the occurrence and suppression of Q-switching in 40 GHz mode-locked multiple quantum well buried heterostructure lasers are presented. Improved mode-locked lasers emit short optical pulses ($\leq$ 1.6 ps) with very low amplitude noise (1 – 2 %) and timing jitter (50 - 100 fs).

Mode-locked lasers have been designed for a number of applications (e.g. [1]). In particular, monolithically integrated mode-locked semiconductor lasers are very attractive as optical pulse sources due to their advantages in terms of compactness, handling, stability, robustness, and cost savings (e.g. within future Optical Time Division Multiplexing (OTDM) telecommunication networks [2] or measurement equipments based on high speed optical sampling techniques). For certain applications the pulse sources have to meet tight performance specifications on generated pulse width Δt, amplitude noise A_N, and timing jitter σ_t, (e.g. $\Delta t \leq 2$ ps, $A_N < 3$ %, and $\sigma_t < 300$ fs in 160 Gbit/s OTDM systems). But it is still a challenging task to meet all predetermined requirements simultaneously. Especially, the concomitance of Q-switching in mode-locked semiconductor lasers with an integrated saturable absorber (Fig. 1), generates so-called Q-switched mode-locking (QML), i.e. unwanted amplitude noise (e.g. [3, 4, 5, 6]). This effect becomes even stronger if very short pulses (< 2 ps) have to be achieved.

In this paper experimental investigations on the occurrence of amplitude noise caused by Q-switching and its reduction by changing the number of quantum wells (QW) in the pulse amplifying section of monolithically integrated, InP-based 40 GHz mode-locked multi-quantum well (MQW) distributed Bragg reflector (DBR) lasers (Fig. 1) are presented. Based on the achieved results improved monolithic lasers have been fabricated and packaged into fiber pigtailed modules, which already meet performance specifications on pulse width and noise.

The monolithic pulse sources are multi-section DBR lasers, fabricated as a semi-insulating planar buried heterostructure (SIPBH) in an extended cavity configuration (cf. Fig. 1). The integrated active and passive laser waveguide consists of a strained MQW and a GaInAsP bulk material, respectively. The active waveguide region integrates a gain section (length: 660 μm) and a 55 μm long saturable absorber. The extended bulk cavity consists of three tunable phase sections for additional repetition rate fine tuning, and a DBR grating in order to meet predetermined wavelength allocations. More details on the laser architecture have been already reported elsewhere [7]. Lasers with different numbers of quantum wells (N_{QW}: 1, 2, 3 and 6) in the active device section were fabricated and experimentally investigated in order to achieve short optical pulses with low amplitude noise.

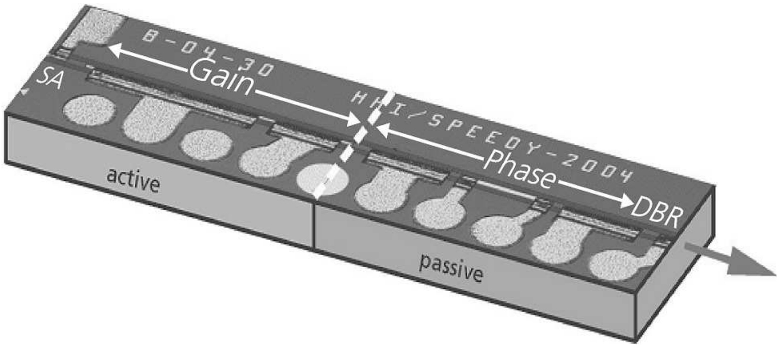


Figure 1: Top view photo of a monolithic mode-locked 40 GHz MQW DBR laser (SA: Saturable absorber, DBR: Distributed Bragg Reflector).

Q-switching or intra-cavity pulse energy modulation as a source for amplitude noise is caused by gain saturation. It follows the time behavior of carrier relaxation oscillations and corresponds to frequencies in the range of 1 – 5 GHz. The appearance of relaxation oscillations and the resulting modulation of the pulse amplitudes can be clearly seen from measurements taken with a radio frequency (RF) spectrum analyzer (cf. RF spectrum of laser with 6 QW in Fig. 2). QML has been suppressed in hybrid solid-state lasers in recent years by optimizing the saturation behavior of the integrated saturable absorber (e.g. [4]), but was not yet sufficiently achieved for monolithic mode-locked semiconductor lasers. Only some theoretical studies on semiconductor devices and laser design criteria have been published up to date [3, 5], which indicate the importance of non-resonant optical cavity losses and saturation energies.

According to a recent theoretical investigation [5], strong QML suppression is expected by achieving large products of the parameters κ and s. The parameter s represents the ratio of the saturation energies in the gain and absorber section ($s = E_{sat,gain}/E_{sat,SA}$), while κ is an optical attenuation factor for the non-resonant cavity loss per round trip ($\kappa = 1$: no losses, $\kappa = 0$: total absorption). Hence, QML can be suppressed by minimizing the optical losses within the cavity and/or by maximizing the s parameter. We followed the route to increase the parameter s, i.e. to increase $E_{sat,gain}$ by reducing the number of quantum wells (QW) in the active laser waveguide ($E_{sat,gain}$ depends inversely proportional to the differential gain coefficient, which decreases with the N_{QW}). Thus, in our fabricated lasers with $N_{QW} = 1$, 2, 3 and 6, the s parameter changes roughly by a factor of 50, 15, 5 and 1 with respect to the device with six QW (6-QW). Furthermore, a pulse width reduction is expected by reducing the quantum well number (e.g. [1]).

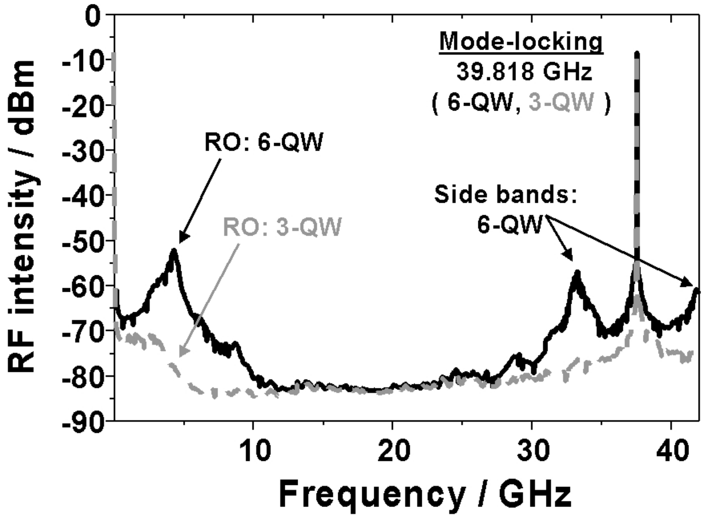


Figure 2: Electrical RF spectrum of a 6-QW and 3-QW mode-locked 40 GHz MQW DBR laser with strong and suppressed QML, respectively (RO: relaxation oscillations peak).

The lasers were investigated under hybrid mode-locking by applying an electrical RF signal onto the saturable absorber for synchronization. A very low RF power of only 12 dBm was necessary due to the implementation of an advanced electrical narrowband RF impedance-matching circuit within the characterized modules, similar to the circuit design described in Ref. [8]. The external RF frequency was matched to the internal round trip frequency of the laser for each bias condition.

Only unstable or almost no mode-locking was achievable with the 1- and 2-QW devices, due to the rather low net modal gain in the gain section with a fixed length of 660 μm on one hand, and the existing optical losses in the cavity on the other. The obtained results on pulse width and amplitude noise of 6-QW and 3-QW devices are shown in Fig. 3 and Fig. 4 for a large range of absorber and gain bias conditions. Mode-locking could be achieved for gain currents between 60 mA and 140 mA and reverse absorber voltages between 0.5 V and 4 V (3-QW) or 2.5 V (6-QW).

In comparison with the 6-QW laser, a much larger area of applicable bias conditions for mode-locking is achievable in case of the 3-QW devices (Fig. 4b). As expected, the 3-QW device has lower amplitude noise compared with the 6-QW (Fig. 4a), even for shorter pulse widths. The evidence for amplitude noise reduction due to stronger Q-switching suppression in the 3-QW laser was further proven by measurements with an electrical spectrum analyzer. The recorded spectra show almost no relaxation oscillation peaks, and therefore no side bands around the mode-locked pulse frequency (cf. 3-QW device in Fig. 2). Fig. 5, which shows the achieved pulse width and amplitude noise level for each pair of applied gain current and absorber voltage, illustrates clearly the general trade-off of amplitude noise and pulse width [3, 4, 5] and its dependency on N_{QW}: The amplitude noise is almost constant

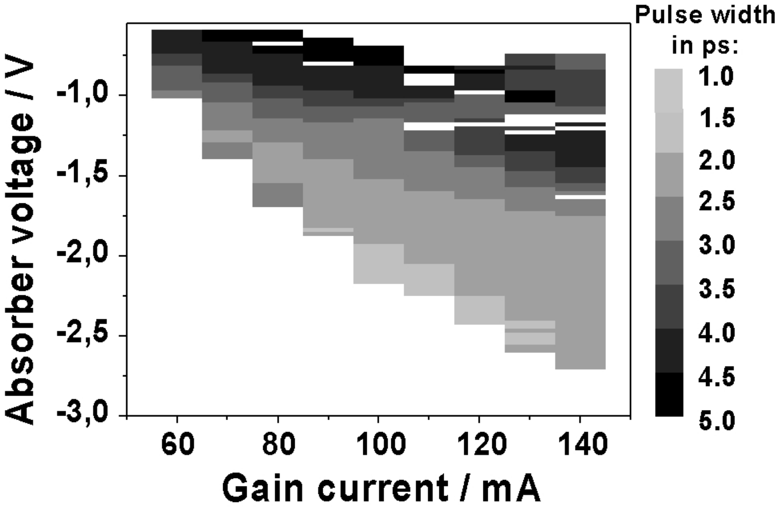
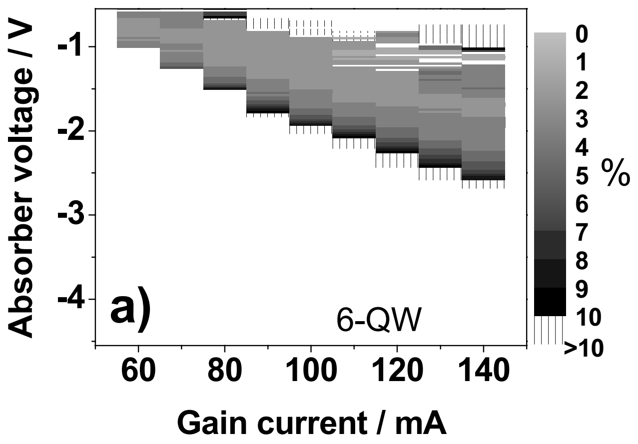


Figure 3: Pulse width as a function of gain current and absorber voltage for a 3-QW laser.

with decreasing pulse width down to a certain width and experiences abruptly a very strong increase up to > 10 % below this value. This behavior is qualitatively the same for the 3-QW laser but significantly shifted towards shorter pulse widths (≈ 1.2 - 1.6 ps) and lower amplitude noise data (≈ 1 - 1.5 %). Fig. 5 demonstrates clearly the importance of QW design for a comprehensive optimization of monolithic semiconductor mode-locked lasers.

The achieved improvements on minimum pulse width and amplitude noise by reducing the number of QW from six down to three are summarized in Tab. 1 together with other important performance data measured from fiber pigtailed pulse laser modules. The timing jitter improvement, as published by Yvind [9] for a ridge waveguide structure, was not yet observable within the experimental investigations on our buried heterostructure lasers.

In conclusion amplitude noise caused by Q-switching instabilities of mode-locked 40 GHz SIPBH MQW DBR lasers could be suppressed by a proper choice of the QW design. For this purpose the influence of QW number on amplitude noise was experimentally investigated. Improved monolithic 3-QW devices have been presented, which emit 1.2 - 1.6 ps short optical pulses with very low amplitude noise (1 – 2 %) and phase noise levels (50 - 100 fs) within a large range of bias conditions. Fiber pigtailed pulse laser modules, which consist of a 3-QW laser and an optimized electrical RF matching circuit, meet already most of given performance specifications with the need of only 12 dBm electrical RF power for external synchronization. Successful system tests within 160 Gb/s RZ-DPSK transmission experiments have been demonstrated very recently [10].



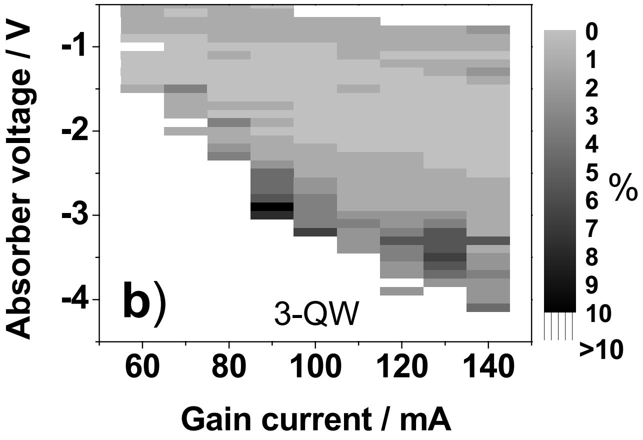


Figure 4: Amplitude noise vs. gain current and absorber voltage for 6-QW (a) and 3-QW laser (b).

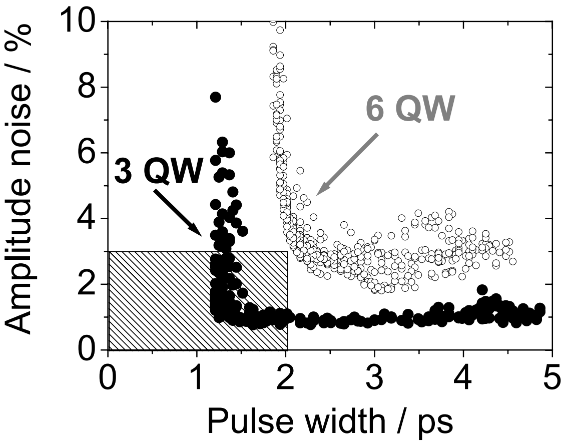


Figure 5: Amplitude noise vs. pulse width for a 6-QW and a 3-QW laser.

	6 QW	**3 QW**
Min. pulse width / ps	1.9 - 2.5	1.2 - 1.6
Min. amplitude noise / %	2.5 - 5	1 - 2.5
Timing jitter^{I,II} / fs	50 - 100	50 - 100
Time-bandwidth product	0.32 - 0.55	0.35 - 0.6
Optical power (in fiber) /mW	1 - 2	0.5 - 1

Table 1: Performance data of 6-QW and 3-QW lasers in comparison [$\lambda =$ 1552 nm, RF power: 12 dBm, $^{I)}$ overall timing jitter, incl. synthesizer noise (35 fs),$^{II)}$offset from subcarrier: 100 Hz – 10 MHz].

The work was supported by the State of Berlin and the European Union (framework project: TeraBit Optics Berlin).

References

[1] K. Williams, M.G. Thompson, and I. White, New J. Phys., **6**, article 179 (2004).

[2] R. Ludwig, St. Diez, A. Ehrhardt, L. Küller, W. Pieper, and H.G. Weber, IEICE Trans. Electron., **E81-C**, no. 2, 140 (1998).

[3] J. Palaski, K.Y. Lau, Appl. Phys. Lett., **59**, no. 1, 7 (1991).

[4] C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16**, no. 1, 46 (1999).

[5] D. Rachinskii and A.G. Vladimirov, U. Bandelow, B. Hüttl, and R. Kaiser, accepted for publication in J. Opt. Soc.Am. B. (2005).

[6] B. Huettl, R. Kaiser, W. Rehbein, H. Stolpe, Ch. Kindel, S. Fidorra, A. Steffan, A. Umbach, H. Heidrich, in Proc. of 17th Indium Phosphide and Related Materials Conference 2005"(IPRM), Scotland Glasgow, paper Tu / Optoelectronics 5 (2005).

[7] R. Kaiser, B. Hüttl, H. Heidrich, S. Fidorra, W. Rehbein, H. Stolpe, R. Stenzel, W. Ebert, G. Sahin, IEEE Photon. Technol. Lett. **15**, no. 5, 634 (2003).

[8] S. Arahira, Y. Ogawa, Jpn. J. Appl. Phys. **43**, no. 4B, 1960 (2004).

[9] K. Yvind, D. Larsson, L.J. Christiansen, C. Angelo, L.K. Oxenløwe, J. Mørk, D. Birkedal, J.M. Hvam, and J. Hanberg, IEEE Photon. Technol. Lett. **16**, no. 4, 975 (2004).

[10] C. Schubert, S. Ferber, M. Kroh, C. Schmidt-Langhorst, R. Ludwig, B. Hüttl, R. Kaiser, H.G. Weber, in Proc. of European Conference on Optical Commun.2005 (ECOC), Glasgow (UK), **vol. 2, paper Tu 1.5.3**, 167(2005).