Experimental investigations on the suppression of *Q* switching in monolithic 40 GHz mode-locked semiconductor lasers

B. Hüttl,[a] R. Kaiser, Ch. Kindel, S. Fidorra, W. Rehbein, H. Stolpe, G. Sahin, U. Bandelow,[b] M. Radziunas,[b] A. Vladimirov,[a] and H. Heidrich
Fraunhofer-Institute for Telecommunications, Heinrich-Hertz-Institut, Einsteinufer 37, D-10587 Berlin, Germany

(Received 23 November 2005; accepted 3 May 2006; published online 30 May 2006)

Inherent *Q* switching as a source of intracavity 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 letter, 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 lasers are presented. Improved mode-locked lasers emit short optical pulses ($\leqslant$1.6 ps) with very low amplitude noise (1%–2%) and timing jitter (50–100 fs). © *2006 American Institute of Physics*. [DOI: 10.1063/1.2208277]

Mode-locked lasers have been designed for a number of applications.[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]]. 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., $\Delta t \leqslant 2$ ps, $A_N < 3\%$, and $\sigma_t, < 300$ fs in 160 Gbits/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.[3–6] This effect becomes even stronger if very short pulses (<2 ps) have to be achieved.

In this letter experimental investigations on the occurrence of amplitude noise caused by *Q* switching and its reduction by changing the number of quantum wells (N_{QW}) in monolithically integrated, InP-based 40 GHz mode-locked multiquantum 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.

The monolithic pulse sources are multisection 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 waveguides consist of a strained MQW and a GaInAsP bulk material, respectively. The active waveguide region integrates a gain section and a 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 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.

Q switching or intracavity 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,[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 nonresonant 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 ($s = E_{\text{sat,gain}}/E_{\text{sat,SA}}$), while κ is an optical attenuation factor for the nonresonant 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 $E_{\text{sat,gain}}$, by re-

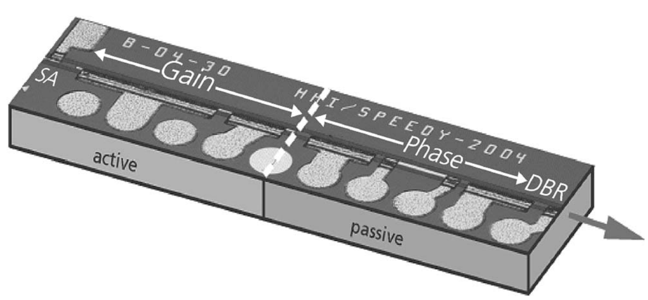

FIG. 1. Top view photo of a monolithic mode-locked 40 GHz MQW DBR laser (SA: saturable absorber; DBR: distributed Bragg reflector).

[a]Electronic mail: huettl@hhi.fhg.de
[b]Also at: Weierstrasse Institute for Applied Analysis and Stochastics, Mohrenstrasse 39, D-10117 Berlin, Germany.

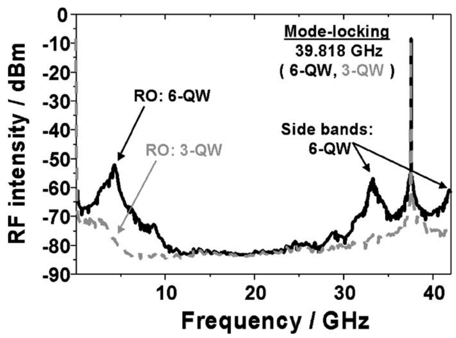

FIG. 2. Electrical rf spectrum of a 6-QW and 3-QW mode-locked 40 GHz MQW DBR laser with strong and suppressed QML, respectively, (RO: relaxation oscillations peak).

ducing the number of QWs in the active laser waveguide ($E_{\mathrm{sat,gain}}$ depends inversely proportional to the differential gain coefficient, which decreases with the N_{QW}). Thus, in our fabricated lasers with $N_{\mathrm{QW}}=1$, 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.[1]

The lasers were investigated under hybrid mode locking by applying an electrical rf signal onto the saturable absorber for synchronization. A rf power of only 12 dBm was necessary due to the implementation of a rf impedance-matching circuit within the characterized modules, similar to the circuit design described in Ref. 8.

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 on the 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 Figs. 3 and 4. Mode locking could be achieved for gain currents between 60 and 140 mA and reverse absorber voltages between 0.5 and 4 (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 the case of the 3-QW devices [Fig. 4(b)]. As expected, the 3-QW device has lower amplitude noise compared with the 6-QW [Fig. 4(a)], 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). Figure 5, which

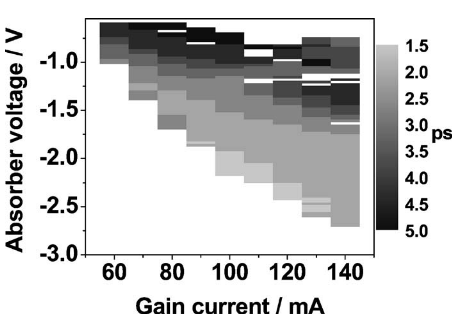

FIG. 3. Pulse width as a function of gain current and absorber voltage for a 3-QW laser.

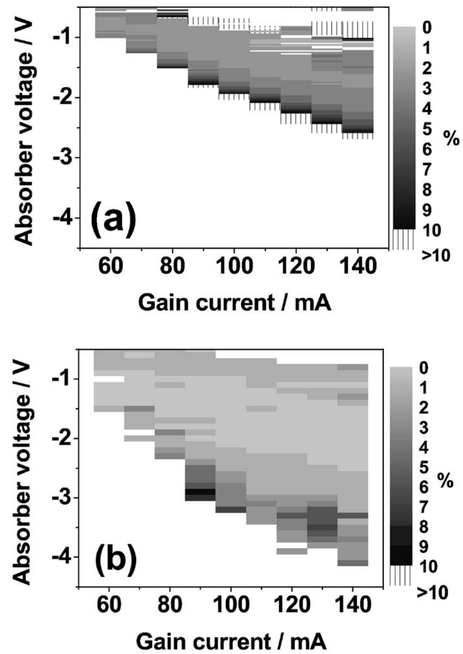

FIG. 4. Amplitude noise vs gain current and absorber voltage for 6-QW (a) and 3-QW lasers (b).

shows the achieved pulse width and amplitude noise level for each pair of applied gain current and absorber voltage, illustrates clearly the general tradeoff of amplitude noise and pulse width[3–5] and its dependency on N_{QW}: The amplitude noise is almost constant 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 ($\approx 1.2-1.6$ ps) and lower amplitude noise data ($\approx 1\%-1.5\%$). Figure 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 Table I together with other important performance data. The timing jitter improvement, as published by Yvind *et al.*[9] for a ridge waveguide structure, was not yet observable within the experimental investigations on our buried heterostructure lasers.

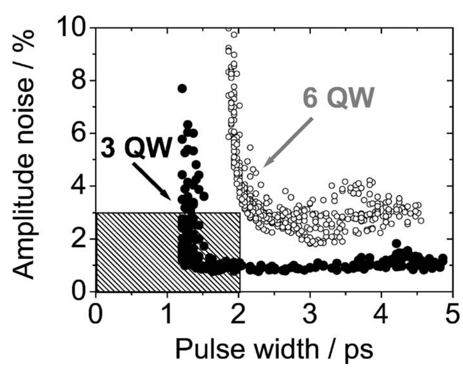

FIG. 5. Amplitude noise vs pulse width for a 6-QW and a 3-QW laser.

TABLE I. Performance data of 6-QW and 3-QW lasers in comparison ($\lambda = 1552$ nm: rf power: 12 dBm).

	6-QW	3-QW
Minimum pulse width (ps)	1.9–2.5	1.2–1.6
Minimum amplitude noise (%)	2.5–5	1–2.5
Timing jitter[a,b] (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

[a]Overall timing jitter, including synthesizer noise (35 fs).
[b]Offset from subcarrier: 100 Hz–10 MHz.

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. 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, meet already fundamental performance specifications. Successful system tests within 160 Gbits/s RZ-DPSK transmission experiments have been demonstrated very recently.[10]

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

[1]K. Williams, M. G. Thompson, and I. White, New J. Phys. **6**, 179 (2004).
[2]R. Ludwig, St. Diez, A. Ehrhardt, L. Küller, W. Pieper, and H. G. Weber, IEICE Trans. Electron. **E81-C**, 140 (1998).
[3]J. Palaski and K. Y. Lau, Appl. Phys. Lett. **59**, 7 (1991).
[4]C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16**, 46 (1999).
[5]D. Rachinskii, A. G. Vladimirov, U. Bandelow, B. Hüttl, and R. Kaiser, J. Opt. Soc. Am. B (in press).
[6]B. Huettl, R. Kaiser, W. Rehbein, H. Stolpe, Ch. Kindel, S. Fidorra, A. Steffan, A. Umbach, and H. Heidrich, Proceedings of 17th Indium Phosphide and Related Materials Conference (IPRM), Glasgow, Scotland, 2005, p. 5.
[7]R. Kaiser, B. Hüttl, H. Heidrich, S. Fidorra, W. Rehbein, H. Stolpe, R. Stenzel, W. Ebert, and G. Sahin, IEEE Photon. Technol. Lett. **15**, 634 (2003).
[8]S. Arahira and Y. Ogawa, Jpn. J. Appl. Phys., Part 1 **43**, 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**, 975 (2004).
[10]C. Schubert, S. Ferber, M. Kroh, C. Schmidt-Langenhorst, R. Ludwig, B. Hüttl, R. Kaiser, and H. G. Weber, Proceedings of European Conference on Optical Communication (ECOC), Glasgow, UK, 2005, Vol. 2, p. 167.