Direct modulation and mode locking of 1.3 µm quantum dot lasers

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Abstract. We report 7 GHz cut-off frequency, 2.5 and 5 Gb s⁻¹ eye pattern measurements upon direct modulation of 1.3 µm quantum dot lasers grown without incorporating phosphorus in the layers. Passive mode-locking is achieved from very low frequencies up to 50 GHz and hybrid mode-locking is achieved up to 20 GHz. The minimum pulse width of the Fourier-limited pulses at 50 GHz is 3 ps, with an uncorrelated timing jitter below 1 ps. The lasers are optimized for high frequency operation by a ridge waveguide design that includes etching through the active layer and ridge widths down to 1 µm. The far-field shape for 1 µm is close to circular with a remaining asymmetry of 1.2.

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1. Introduction

Development of quantum dot (QD) lasers [1, 2] with 1.3 µm emission wavelength showing very low threshold current, large $T_0$, suppressed beam filamentation, and feasibility of 2.5 Gb s$^{-1}$ data transmission [3]–[6] presents a breakthrough towards the exploitation of nanotechnology for novel data and telecom applications. Promising dynamic properties of QD lasers such as large differential gain and cut-off frequency and small chirp were predicted and first reported for emission wavelengths 960–1160 nm [7]–[9]. Cut-off frequencies up to 23 GHz at room temperature at 1 µm [10] upon direct modulation were obtained using tunnel injection of carriers into the dots, indicating the potential of QD lasers for directly modulated 10 Gb s$^{-1}$ communication systems at 1.3 µm [11]. First eye-pattern measurements were recently reported by us [12].

For ultrahigh-frequency applications such as time domain multiplexing, optical-comb generators operating in the 10–40 GHz range are needed. Mode-locking of QD lasers at 1.3 µm was reported by Huang et al [13] at 7.4 GHz and by us with repetition rates up to 35 GHz [13]–[15].

We report here 7.4 GHz cut-off frequency of 1.3 µm QD lasers and 5 GHz open eye pattern. The lasers used are optimized with respect to their far-field symmetry. Furthermore, we report up to 20 GHz hybrid and low frequency to 50 GHz passive mode-locking at 1.3 µm. Fourier-limited pulses and an uncorrelated timing jitter below 1 ps are demonstrated.

This paper is structured as follows: section 2 gives details of growth and processing of the samples and their basic parameters. Section 3 presents the results on direct modulation of QD lasers, section 4 refers to the measurements on mode-locking and addresses some of the challenges for further improvement of mode-locked QD laser performance.

2. Growth, processing and cw parameters

The AlGaAs/GaAs laser structure incorporating a 5-fold stack of InGaAs QDs was grown by molecular beam epitaxy. Emission at 1.3 µm wavelength was achieved by overgrowth of the QDs with an InGaAs layer and by subsequent activated-phase alloy separation [16]. The wafers were then processed into ridge waveguide edge emitters with stripe widths from 1 to 4 µm. The ridges were dry-etched through the active layer to provide strong index guiding of the optical mode and suppression of current spreading. The strong index guiding combined with the small stripe width...
ensures a high-coupling efficiency into optical fibres. Suppression of current spreading in QD layers leads to an improvement of the electrical high-frequency characteristics of laser diodes by reducing parasitic capacitances, as will be shown in the next section.

The sides of the ridge were planarized with an insulating low refractive index material. Finally, the p-side contact metallization including bond pads was fabricated. The structure of the sample is shown in figure 1. Samples for mode-locking were processed into two-sectional devices by defining a metallization gap of 20 \( \mu \text{m} \) between the sections. In an additional processing step, the epitaxial contact layer in the gap was removed to ensure good electrical insulation (> 1 k\( \Omega \)).

Lasers with as-cleaved facets were mounted p-side up on a copper heat sink and were electrically connected to one (direct modulation) or two (mode-locking) SMA ports via stripe lines and short (< 400 \( \mu \text{m} \)) bond wires.

The samples for direct modulation are about 1 mm long, the samples for mode-locking have lengths between 800 and 8000 \( \mu \text{m} \) corresponding to round trip frequencies of 5–50 GHz. All samples with length of 1 mm or below were high-reflectivity coated (95% reflectivity) on the rear facet.

All measurements were carried out at room temperature (297 K) and in continuous-wave mode.

From a series of devices with different length we determined internal losses of 5 cm\(^{-1}\), an internal quantum efficiency of 76% and a transparency current density of 95 A cm\(^{-2}\). These data are comparable to those of a similar series of lasers that have been processed with shallow mesas, thus indicating that the deep-mesa etching has not created a significant amount of defects within the active layer. Lifetime experiments have to corroborate this assumption.

Deep etching decreased the far-field asymmetry (ellipticity) from 10 to 3.5 for 4 \( \mu \text{m} \) stripe width. By reducing the ridge width to 1 \( \mu \text{m} \), we even achieved a symmetric far field with a 1/\( e^2 \) divergence of 60°. Figure 2 shows the improvement of the far-field symmetry for deep mesa lasers as a function of ridge width. Results on 4 \( \mu \text{m} \) wide stripe deep mesa lasers are presented in the following sections.
Figure 2. Far field of deep mesa-etched ridge waveguide QD lasers with ridge width of (a) 4 µm, (b) 2 µm and (c) 1 µm. The beam profile (c) has an asymmetry of 1.2.

3. Direct modulation

Prior to eye-pattern measurements, we investigated the small-signal modulation response of the lasers. An HP 8722C network analyser combined with a 50 GHz photodetector was used. Both the $S_{11}$ (reflection) and the $S_{12}$ parameters (transmission) of the laser were measured. The RC bandwidths derived from the reflection measurements at different currents were fitted to an electric equivalent circuit in order to derive the RC bandwidth of the device. The RC bandwidth increases up to 4 GHz, which is a factor of three higher than for shallow mesa samples (figure 3). The improvement is due to the strong reduction of the parasitic diffusion capacitance along with a moderate increase in the device resistance.

The transmission response curves ($S_{12}$) for different output powers were fitted with a transmission function in order to derive the resonance frequency and damping parameter. Plotting the damping versus the squared resonance frequency in figure 4 allows us to determine the $K$ factor and a $-3$ dB bandwidth of 5.6 GHz. The laser should therefore be capable of direct
Figure 3. Comparison of RC bandwidth of deep mesa-etched (d.e.) and shallow mesa-etched (sh.e.) QD lasers as a function of the drive current. The RC bandwidth of deep mesa lasers is a factor of three larger.

Figure 4. Damping parameter versus square of the resonance frequency as derived from the transmission response of a QD laser. The slope yields a maximum modulation bandwidth of 5.6 GHz. Note the high initial damping.

Modulation with 5 Gb s\(^{-1}\). The differential gain derived from the transmission measurement is \(g' = 2.3 \times 10^{-15}\) cm\(^{-2}\), a value comparable to our previous measurements [17].

Eye-pattern measurements were carried out with a bit pattern generator SHF BPG 4 \times 10, combined with a 20 GHz optical detector and an oscilloscope. The laser diode was coupled to the detector through a short single-mode optical fibre including an optical isolator. The diode was biased at \(7I_{th}\) (60 mA) by a low noise dc source. The average output power of the laser diode was 24 mW (both facets).
Figures 5 shows the measured 5 Gb s$^{-1}$ pattern generated with a 15 bit pseudo-random bit sequence and 1 V amplitude. A clear open eye with a signal-to-noise ratio of approx. 10 is observed. In agreement with the flat $S_{12}$ parameter (transmission) measurement, the eye pattern was quite symmetric with a small HI level overshoot of about 10%. The timing jitter was 16 ps. The inset of figure 5 shows the wavelength spectrum of the laser with a central wavelength of 1275 nm.

Results on 5 Gb s$^{-1}$ data transmission experiments and bit-error-rate measurements on these devices were published elsewhere [12].

In order to improve the modulation speed of QD lasers, p-doping of the active layer was proposed [18]. We investigated samples similar in growth and processing to the aforementioned devices except p-doping of $5 \times 10^{17}$ cm$^{-3}$ between the QD layers. The modulation response of these devices shows an improvement of the modulation bandwidth from 5.6 to 7.4 GHz (figure 6). This improvement is still smaller than expected and needs further investigation.

4. Mode-locking

Mode-locked lasers, like directly modulated lasers, are used for data communication. Since mode-locked lasers provide a regular optical pulse train, an optical modulator has to be added to provide the encoding of digital optical data. The maximum data rate is given by the round-trip frequency of the mode-locked laser and thus by its cavity length. We present results on mode-locking of samples with lengths between 800 and 8000 $\mu$m, corresponding to round trip frequencies between 5 and 50 GHz.

The two-section devices for mode-locking consisted of a long gain and a short absorber (typically 10–20% of the total length) section operated at reverse-bias levels between 0 and $-6$ V. Time-domain measurements were carried out with an autocorrelator.
Figure 6. Damping parameter versus square of the resonance frequency as derived from the transmission response of a QD laser with a p-doped active layer. The slope yields a maximum modulation bandwidth of 7.4 GHz.

Figure 7. Autocorrelation trace and deconvoluted pulse shape of a passively mode-locked QD laser at 5 GHz repetition rate. Inset, corresponding wavelength spectrum.

Figure 7 shows a typical auto and cross-correlation result for the 8000 \( \mu \text{m} \) device. The autocorrelation trace was deconvoluted assuming a Gaussian-pulse shape. The calculated pulse width for at full-width half-maximum (FWHM) was 9 ps. The peak power of the pulses was 64 mW.

Figure 8 shows results for the 1000 \( \mu \text{m} \) device. It shows both the autocorrelation (middle peak) and the cross correlation (side peaks) of the pulses. The FWHM pulse width at \(-6\) V absorber bias was 3.2 ps. This value is in good agreement with the Fourier limit \((\Delta \tau \Delta \nu = 0.44)\)
of 3 ps estimated from the spectral FWHM. The inset of figure 8 shows the spectrum of the mode-locked laser centred at a wavelength of 1273 nm.

In order to characterize the dependence of the pulses on parameters such as reverse bias, gain current and radiofrequency (RF) power, we performed a series of autocorrelation scans with a fully automated set-up. The lasers were hybridly/passively mode-locked at currents between \( I_{\text{thr}} \) and \( 2I_{\text{thr}} \) using reverse-bias voltages between \(-6\) and \(0\) V.

The results for passive mode-locking of the 1000 \( \mu \)m device (40 GHz) are depicted in figure 9. The diagram shows the different regimes of device operation versus reverse bias and gain current. The centre region, which corresponds to mode-locking operation, shows the colour-coded deconvoluted FWHM pulse width of the autocorrelation traces.

With increasing reverse bias, the onset of lasing shifts to larger currents, due to the increasing absorption within the waveguide. The onset of lasing occurred abruptly as mode-locking, and we observed no transition region. With increasing current, the pulses became broader, until we observed a cw offset, i.e. incomplete mode-locking. At even higher currents, we observed a transition region with all kinds of pulse patterns (e.g. self pulsation) until all intensity fluctuations flattened out to cw lasing.

The pulse widths ranged from 3 to 7 ps. As expected, the shortest pulses occurred at large reverse-bias voltages, where it was possible to go to larger gain currents with the laser still capable of mode-locking. The minimum pulse width was limited by the maximum reverse-bias voltage we estimated here to be not harmful for the device. It does not present a real lower limit. Similar characteristics were also found for all other devices at frequencies 5, 10, 20 and 50 GHz.

For hybrid mode-locking up to frequencies of 20 GHz, we applied an RF power of 20 dBm to the absorber section. The large RF power was necessary in order to compensate the strong damping of the electrical signal on its way to the laser diode as mentioned in section 3. For hybrid mode-locking, we observed quite similar results as for passive mode-locking except for a slight increase in the mode-locking regime towards larger currents (+5 mA). The pulse widths did not change significantly, which indicated that, as expected from the \( S_{11} \) measurements, most
Figure 9. Pulse-width dependence on reverse-bias voltage and gain current for a passively mode-locked QD laser at 40 GHz. Three modes of operation can be distinguished: no lasing, mode-locking (coloured squares) and incomplete mode-locking. The colour scale coded pulse FWHM shows an increase with both gain current and voltage.

Figure 10. Autocorrelation trace and wavelength spectrum of a passively mode-locked QD laser at 50 GHz repetition rate.

Of the RF power did not enter the device and thus did not contribute to absorption modulation. We characterized the influence of the RF power on the mode-locking frequency tuning range, i.e. the range of RF frequencies wherein the mode-locking frequency is pinned to the RF frequency. The maximum tuning range was 90 MHz (0.5% of the locking frequency).

The highest mode-locking frequency we achieved was 50 GHz. Figure 10 shows both the autocorrelation and the cross-correlation measurement of the laser pulses. The minimum pulse width we achieved with this device was 3 ps, which is again in agreement with the Fourier

New Journal of Physics 6 (2004) 181 (http://www.njp.org/)
The peak power from one facet of the mode-locked laser was 6 mW. Besides pulse shape and width, we also determined the timing and amplitude jitter of the pulses. Comparison of auto- and cross-correlation [19] allowed us to estimate the uncorrelated jitter to be less than 1 ps. However, we expect the main jitter contribution to be correlated jitter. Further investigations are required to clarify this question.

Figure 11 shows the reverse bias versus current scan of the autocorrelation traces and the corresponding FWHM pulse widths. In comparison to the results on the longer device shown in figure 9, we observed a much smaller region of mode-locking. Below $-4.5 \, \text{V}$ the laser does not turn on at all. This is due to the short gain section which saturates already at moderate absorber gain currents. We estimate the saturation absorption to be comparable to the saturation gain, i.e. $15 \, \text{cm}^{-1}$. Since the major part of the gain section has to compensate the front mirror and internal loss, the trade-off between absorber, gain and total length establishes the current pulse width limitation of 3 ps.

The ultimate limitation for the minimum pulse width of mode-locked lasers is the width of the gain spectrum. As we deployed only 2% of the intrinsic spectral width of the QD gain medium, there is still plenty of scope for reducing the pulse width to levels in the range or below 1 ps. Stacking of more QD layers or the insertion of an ion-implanted absorber for stronger absorption are the means to achieve this goal.

5. Conclusion

Open eye patterns of 5 GHz and cut-off frequency of 7.4 GHz for 1.3 $\mu$m QD lasers were presented. Deep-mesa etching of narrow waveguide lasers improves the electrical bandwidth without degrading their optical properties. P-doping of the active region has been shown to be beneficial for the modulation response. Hybrid and passive mode-locking of QD lasers at 1.3 $\mu$m
between 5 and 50 GHz repetition rate show Fourier-limited pulses. The minimum pulse width we achieved was 3 ps. The maximum locking range of the hybrid mode-locked laser was 0.5% of the locking frequency at 20 GHz. Uncorrelated jitter was below 1 ps at 50 GHz. Our results represent a large step towards the introduction of 1.3 $\mu$m QD lasers as directly modulated optical sources and high frequency optical comb generators in data and telecom systems.

Acknowledgments

Parts of this work were funded by the German Ministry for Education and Research (contract no. 1BC913), the European Union in the framework of the IST-Dotcom, NoE SANDIE, the state of Berlin in the framework of the Zukunftsfonds Berlin (TOB) and Nanosemiconductors GmbH. We are indebted to R Kaiser and U Niggebrügge (Heinrich-Hertz-Institut Berlin) for helpful discussions and assistance with dry etching, respectively.

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