Dual-wavelength passive and hybrid mode-locking of 3, 4.5 and 10 GHz InAs/InP(100) quantum dot lasers

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Dual-wavelength passive and hybrid mode-locking of 3, 4.5 and 10 GHz InAs/InP(100) quantum dot lasers

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Abstract: We present an investigation of passive and hybrid mode-locking in Fabry-Pérot type two-section InAs/InP(100) quantum dot lasers that show dual wavelength operation. Over the whole current and voltage range for mode-locking of these lasers, the optical output spectra show two distinct lobes. The two lobes provide a coherent bandwidth and are verified to lead to two synchronized optical pulses. The generated optical pulses are elongated in time due to a chirp which shows opposite signs over the two spectral lobes. Self-induced mode-locking in the single-section laser shows that the dual-wavelength spectra correspond to emission from ground state. In the hybrid mode-locking regime, a map of locking range is presented by measuring the values of timing jitter for several values of power and frequency of the external electrical modulating signal. An overview of the systematic behavior of InAs/InP(100) quantum dot mode-locked lasers is presented as conclusion.

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References and links
1. R. Nötzel, S. Anantathanasarn, R. P. J. van Veldhoven, F. W. M. van Otten, T. J. Eijkemans, A. Trampert, B. Satpati, Y. Barbarin, E. A. J. M. Bente, Y.-S. Oei, T. de Vries, E. Geluk, B. Smalbrugge, M. K. Smit, and J. H. Wolter, “Self assembled InAs/InP quantum dots for telecom applications in the 1.55 µm wavelength range: wavelength tuning, stacking, polarization control, and lasing,” Jpn. J. Appl. Phys. 45(8B), 6544–6549 (2006).
2. F. Lelarge, B. Dagens, J. Renaudier, B. Brenot, A. Accard, F. Djik, D. Make, O. L. Gouezigou, J.-G. Provost, F. Pointg, J. Landreau, O. Drisse, E. Derouin, B. Rousseau, F. Pommereau, and G.-H. Duan, “Recent advances on InAs/InP quantum dash based semiconductor lasers and optical amplifiers operating at 1.55µm,” IEEE J. Sel. Top. Quantum Electron. 13(1), 111–124 (2007).
3. B. W. Tilma, M. S. Tahvili, J. Kotani, R. Nötzel, M. K. Smit, and E. A. J. M. Bente, “Measurement and analysis of optical gain spectra in 1.6 to 1.8 µm InAs/InP (100) quantum-dot amplifiers,” Opt. Quantum Electron. 41(10), 735–749 (2009).
4. B. W. Tilma, Y. Jiao, J. Kotani, B. Smalbrugge, H. P. M. M. Ambrosius, P. J. Thijs, X. J. M. Leijtens, R. Ntzel, M. K. Smit, and E. A. J. M. Bente, “Integrated tunable quantum-dot laser for optical coherence tomography in the 1.7µm wavelength region,” IEEE J. Quantum Electron. 48(2), 87–98 (2012).
5. X. Huang, A. Stintz, H. Li, L. F. Lester, J. Cheng, and K. J. Malloy, “Passive mode-locking in 1.3 µm two-section InAs quantum dot lasers,” Appl. Phys. Lett. 78(19), 2825–2827 (2001).
6. E. U. Rafailov, M. A. Cataluna, W. Sibbett, N. D. It’inskaya, Y. M. Zadiranov, A. E. Zhukov, V. M. Ustinov, D. A. Livshits, A. R. Kovsh, and N. N. Ledentsov, “High-power picosecond and femtosecond pulse generation from a two-section mode-locked quantum-dot laser,” Appl. Phys. Lett. 87(8), 081107 (2005).
7. M. G. Thompson, A. R. Rac, M. Xia, R. V. Penty, and I. H. White, “InGaAs quantum-dot mode-locked laser diodes,” IEEE J. Sel. Top. Quantum Electron. 15(3), 661–672 (2009).
8. M. J. R. Heck, E. A. J. M. Bente, B. Smalbrugge, Y. S. Oei, M. K. Smit, S. Ananthanarayanan, and R. Nötzel, “Observation of Q-switching and mode-locking in two-section InAs/InP (100) quantum dot lasers around 1.55 µm,” Opt. Express 15(25), 16292–16301 (2007).

9. M. J. R. Heck, A. Renault, E. A. J. M. Bente, Y.-S. Oei, M. K. Smit, K. S. E. Eikema, W. Ubachs, S. Ananthanarayanan, and R. Nötzel, “Passively mode-locked 4.6 and 10.5 GHz quantum dot laser diodes around 1.55 µm with large operating regime,” IEEE J. Sel. Top. Quantum Electron. 15(3), 634–643 (2009).

10. W. M. Yee and K. A. Shore, “Multimode analysis of self locked FM operation in laser diodes,” IEE Proc.-J. Optoelectron. 140, 21 (1993).

11. J. P. Tourrenc, A. Akrou, K. Merghem, A. Martinez, F. Lelarge, A. Shen, G. H. Duan, and A. Ramdane, “Experimental investigation of the timing jitter in self-pulsating quantum-dash lasers operating at 155 µm,” Opt. Express 16(22), 17706–17713 (2008).

12. S. Ananthanarayanan, R. Nötzel, P. J. van Veldhoven, F. W. M. van Otten, Y. Barbarin, G. Servanton, T. de Vries, E. Smalbrugge, E. J. Geluk, T. J. Eijkemans, E. A. J. M. Bente, Y. S. Oei, M. K. Smit, and J. H. Wolter, “Lasing of wavelength-tunable (1.55 µm region) InAs/InGaAsP/InP (100) quantum dots grown by metal organic vapor-phase epitaxy,” Appl. Phys. Lett. 89(7), 073115 (2006).

13. S. Arahira and Y. Ogawa, “Repetition – frequency tuning of monolithic passively mode-locked semiconductor lasers at 1.56 microm,” Appl. Opt. 36, 6764–6771 (1997).

14. Z. Zhang and T. Yagi, “Dual-wavelength synchronous operation of a mode-locked Ti:Sapphire laser based on self-spectrum splitting,” Opt. Lett. 18(24), 2126 (1993).

15. Z. Cong, D. Tang, W. De Tan, J. Zhang, C. Xu, D. Luo, X. Xu, D. Li, J. Xu, X. Zhang, and Q. Wang, “Dual-wavelength passively mode-locked Nd:LuYSiO5 laser with SESAM,” Opt. Express 19(5), 3984–3989 (2011).

16. K. Veselínov, F. Grillot, C. Cornet, J. Even, A. Bekiarski, M. Gioannini, and S. Loualiche, “Analysis of the double laser emission occurring in 1.55-µm InAs–InGaAsP quantum dots,” IEEE J. Sel. Top. Quantum Electron. 43(9), 810–816 (2007).

17. N. A. Naderi, F. Grillot, K. Yang, J. B. Wright, A. Gin, and L. F. Lester, “Two-color multi-section quantum dot distributed feedback laser,” Opt. Express 18(26), 27028–27035 (2010).

18. F. Grillot, N. A. Naderi, J. B. Wright, R. Raghunathan, M. T. Crowley, and L. F. Lester, “A dual-mode quantum dot laser operating in the excited state,” Appl. Phys. Lett. 99(23), 231110 (2011).

19. S. Breuer, M. Rossetti, W. Elsasser, L. Drzewietzki, P. Bardella, I. Montrosset, M. Krakowski, and M. Hopkinson, “Reverse ground-state excited-state transition dynamics in two-section quantum dot semiconductor lasers: mode-locking and state-switching,” Proc. SPIE 7720, 772011, 772011-10 (2010).

20. M. A. Cataluna, W. Sibbett, D. A. Livshits, J. Weinert, A. R. Kovsh, and E. U. Rafailov, “Stable mode locking via ground- or excited-state transitions in a two-section quantum-dot laser,” Appl. Phys. Lett. 89(8), 081124 (2006).

21. J. Liu, Z. Lu, S. Raymond, P. J. Poole, P. J. Barriés, and D. Poitras, “Dual-wavelength 92.5 GHz self-mode-locked InP-based quantum dot laser,” Opt. Lett. 33(15), 1702–1704 (2008).

22. C. Mesaritakis, C. Simos, H. Simos, I. Krestnikov, and D. Syvridis, “Dual ground-state pulse generation from a passively mode-locked InAs/InGaAs quantum dot laser,” Appl. Phys. Lett. 99(14), 141109 (2011).

23. M. J. R. Heck, E. J. Salumbides, A. Renault, E. A. J. M. Bente, Y. S. Oei, M. K. Smit, R. van Veldhoven, R. Nötzel, K. S. E. Eikema, and W. Ubachs, “Analysis of hybrid mode-locking of two-section quantum dot lasers operating at 1.5 microm,” Opt. Express 17(20), 18063–18075 (2009).

24. G. Fiol, D. Arsenijević, D. Bimberg, A. G. Vladimirov, M. Wolfrum, E. A. Viktorov, and P. Mandel, “Hybrid mode-locking in a 40 GHz monolithic quantum dot laser,” Appl. Phys. Lett. 96(1), 011104 (2010).

25. K. Sato, “Optical pulse generation using Fabry–Pérot lasers under continuous-wave operation,” IEEE J. Sel. Top. Quantum Electron. 9(5), 1288–1293 (2003).

26. W. Yang, N. J. Sauer, P. G. Bernasconi, and L. Zhang, “Self-mode-locked single-section Fabry-Perot semiconductor lasers at 1.56 microm,” Appl. Opt. 46(1), 113–116 (2007).

27. Z. G. Lu, J. R. Liu, P. J. Poole, S. Raymond, P. J. Barriés, D. Poitras, G. Pakulski, P. Grant, and D. Roy-Guy, “An L-band monolithic InAs/InP quantum dot mode-locked laser with femtosecond pulses,” Opt. Express 17(16), 13609–13614 (2009).

28. L. F. Tiemeyer, P. I. Kuijindersma, P. J. A. Thijs, and G. L. J. Rikken, “Passive FM locking in InGaAsP semiconductor lasers,” IEEE J. Quantum Electron. 25(6), 1385–1392 (1989).

29. Y. Barbutin, E. A. J. M. Bente, M. J. R. Heck, Y. S. Oei, R. Nötzel, and M. K. Smit, “Characterization of a 15 GHz integrated bulk InGaAsP passively modelocked ring laser at 1.53microm,” Opt. Express 14(21), 9716–9727 (2006).

30. M. S. Tahvili, Y. Barbarin, X. J. M. Leijtens, T. de Vries, E. Smalbrugge, J. Bolk, H. P. M. M. Ambrosius, M. K. Smit, and E. A. J. M. Bente, “Directional control of optical power in extended InP/InGaAsP cavity mode-locked ring lasers,” Opt. Lett. 36(13), 2462–2464 (2011).

31. C. Y. Wang, L. Diehl, A. Gordon, C. Jirauschek, F. X. Kärntner, A. Belyanin, D. Bour, S. Corzine, G. Höfler, M. Troccoli, J. Faist, and F. Capasso, “Coherent instabilities in a semiconductor laser with fast gain recovery,” Phys. Rev. A 75(3), 031802 (2007).
1. Introduction

More than 15 years of research on semiconductor quantum dots (QDs) has revealed distinctive properties of such material for incorporation as active medium in semiconductor optical amplifiers (SOAs) and lasers. So far, a major part of the research on QDs has been dedicated to InGaAs/GaAs material systems which emit in the wavelength range of 1.0-1.3µm. Progress in growth of InAs self assembled QDs [1] and quantum dashes [2] on InP substrate has allowed research on features of such quantum structures in the 1.5µm telecommunication window. At the COBRA Research Institute, optically active materials based on InAs QDs on n-type (100) InP substrate have been developed which provide peak gain in the wavelength range of 1.5µm to 1.8µm [3]. This brings the interesting properties of QDs to the wavelength region which is attractive not only for fiber optic communications but also for novel applications such as integrated tunable lasers for gas sensing and optical coherence tomography [4].

QDs show low spontaneous emission levels and a broad gain spectrum. The wide gain bandwidth is in principle an ideal feature for optical pulse generation. In case of InGaAs/GaAs QD-based mode-locked (ML) lasers, there has been much progress since the first demonstration of a 7.4GHz passively mode-locked QD laser in 2001 [5]. Several research groups in recent years have studied and achieved sub-ps pulse generation [6], high peak power and Fourier limited pulse generation (see for example [7] and references therein). QDs and Q-dash material offer the widest available bandwidth from ML devices in comparison with bulk or quantum well material. Recently, we have investigated ML operation in lasers incorporating InAs/InP(100) QD gain material. We have previously reported on highly chirped ML operation in Fabry-Perot (FP) type InAs/InP(100) QD lasers over a wide range of operating parameters. Such devices generate elongated pulses with a relatively wide, i.e. 8nm, optical bandwidth [8, 9]. Our observations have demonstrated operating regimes that have outputs which look similar to FM locking [10] and our devices show different ML properties in comparison with InGaAs/GaAs QD-based lasers. On the other hand, the ML behavior in our devices has similar properties as observed in single-section InAs/InP Q-dash ML lasers [11].

The aim of this paper is to compare the performance of devices with different repetition rates and roundtrip losses and point out the relationship between the results. This will help with work aimed at understanding the origin of the observed dynamics in the lasers. In this paper, we consider an aspect of mode-locking in InAs/InP QD lasers which is the occurrence of stable dual-wavelength ML operation. The dual-wavelength short pulse operation is in itself interesting for applications such as optical generation of THz signals or coherent anti-Stokes Raman spectroscopy (CARS) experiments on rotational states in molecules. We will present detailed characterization of a 4mm-long two-section laser which has 10GHz repetition frequency and investigate the region of ML in terms of operating parameters in section 2. In section 3, we show that over the whole range of ML, the optical spectrum consists of two spectral lobes. We confirm the fact that both spectral lobes contribute to pulsed operation and are synchronized. In section 4, we report on regimes of hybrid ML in the 10GHz QD laser. Under hybrid ML, a clean electrical signal from an external source is available and thus application of a broader range of measurement equipment is possible. We present the evaluation of spectral chirp based on recorded time traces from a fast sampling oscilloscope.

In order to better understand the physical mechanism behind ML in our QD devices, we have fabricated devices with three different repetition rates. In section 5, we investigate a 3GHz laser and follow similar characterization steps as mentioned in the preceding lines to highlight key features of ML in InAs/InP(100) QD lasers. The 3GHz laser is 13mm long and has, to the extent of our knowledge, the lowest repetition rate reported for a monolithic InAs/InP(100) QD laser. In section 6, we present the mode-locked operation of a single-section laser which is 9mm long and operates at 4.5GHz repetition frequency. This is the first...
observation of self-induced ML in devices which incorporate our QD material. Discussions and conclusions are summarized in section 7, where an overview of the experimental results is given and a comparison is made with our previously reported devices. We will discuss the observed spectral splitting which is linked to the ML operation in the devices presented. We show that the power balance in the spectral lobes is affected by the cavity losses and equivalently the lasing threshold current density. Furthermore, we investigate the systematic generation of chirped pulses in our InAs/InP(100) QD ML lasers and confirm the fact that even under hybrid ML, duration of generated pulses is almost half the roundtrip time, independent of the cavity length.

2. Passively mode-locked 10GHz laser

In this section, we present results of characterization measurements which have been carried out on two-section Fabry-Pérot type devices. The gain medium incorporates five layers of InAs (on ultrathin GaAs interlayers) QDs. QD layers are stacked in the center of the 500nm-thick InGaAsP waveguiding layer and separated by 40nm. Details of material growth, layer stack and device fabrication are given in [8, 12].

Two-section devices are operated by current injection to the SOA-section (\(I_{\text{SOA}}\)) to create the gain section. A saturable absorber (SA) section is achieved by applying reverse bias voltage (\(V_{\text{SA}}\)) on the shorter section. The two sections are electrically isolated by an isolation segment which is a 30um-long 45°-tilted etched section. Fabricated devices are mounted on specially designed RF submounts which provide contact pads in ground-signal-ground (GSG) configuration for wire-bonding and applying RF signals on SA-sections. The RF submount is realized on 280µm-thick AlN polished substrate. The chip is first fixed and wire-bonded on the RF submount; the submount is then glued on a copper chuck. During measurements, the copper chuck is water cooled and the chip is temperature stabilized at 12°C using a thermistor and Peltier element. In order to decrease the cavity losses and operate the SOA-section at a lower injection current/gain level, we have applied a highly-reflective (HR, reflectivity>96%) coating on the absorber side of the devices. A lensed fiber which has an anti-reflection coated tip is used at the SOA-section side to collect the output light from the devices. We use an optical isolator to prevent possible back-reflection to the lasers.

Figure 1 shows top view of an array of 12 realized MLLDs. Their cavity length determines the round-trip frequency. The devices have different lengths of absorber section and are tested for the best ML performance. The device on which we focus in this section is 4mm long and has a 120µm-long absorber section, equal to 3% of the total cavity length. The device has a threshold current of 173mA to 190mA for SA reverse bias voltages of \(V_{\text{SA}} = 0V\) to \(V_{\text{SA}} = –1V\). A single-section 4mm-long FP laser is also on the same chip. Its threshold current is 115mA. The higher threshold currents for the two-section devices are due to the loss introduced by the absorber section.

![Fig. 1. Top view of an array of 12 mode-locked lasers with different lengths of absorber section and total cavity length of 13mm. Devices are mounted and wire-bonded on an RF submount. Two single-section FP structures (top and bottom) are included as reference lasers.](image)

Passive mode-locking is studied by recording the electrical power spectrum. In the ML state, the recorded traces from the electrical spectrum analyzer (ESA) show well-defined peaks at the cavity round-trip frequency, i.e. 10GHz corresponding to a 4mm-long cavity, and its higher order harmonics. The height of RF peak is related to the pulsed power and hence is an indication of stable mode-locking. Our first step to characterize the QD laser is to define an
operating range in terms of the values of injected current to the SOA-section and bias voltage on the SA-section to indicate where stable ML is achieved. To determine the stable ML operating range of the MLLD, $I_{SOA}$ is sweep-scanned and the RF spectra traces are recorded with a 50GHz ESA which is connected to a 50GHz photo diode (PD). The measurement is repeated for a range of values of bias voltage $V_{SA}$. The height of RF peak at the fundamental frequency over the noise floor (and lower frequency components) is then mapped as function of operating parameters. A plot is presented in Fig. 2. The 10GHz laser operates in a stable passive ML regime from $V_{SA} = -0.1V$ (for $I_{SOA} = 240-310mA$) to $V_{SA} = -1.0V$ (for $I_{SOA} = 260mA-300mA$). Recorded RF peaks are up to more than 45dB in height over the noise floor of the electrical spectrum analyzer.

In the range of stable mode-locking, the 3dB width of fundamental RF peaks is in order of 110kHz to 300kHz (electrical bandwidth=50kHz). The width of peaks at ~20dB below top of the peak ranges from less than 0.5MHz to around 2.5MHz in the ML region. Contour plots of the width of RF peaks are superimposed on the map plot of Fig. 2. Figure 2 shows that the decrease in peak height is accompanied by an increase of width of the peak at the fundamental frequency. This effect is expected and means that the amount of pulsed power remains relatively constant over the optimum range of stable ML.

The variation of roundtrip frequency over the operating region of stable ML is about 10MHz. The repetition frequency of a passively ML laser diode is influenced by the bias conditions due to the gain/absorption saturation effects [13]. Increasing the injection current to the gain section, as well as reducing the reverse bias on the absorber corresponds to an increase in pulse energy and vice versa. Therefore, the repetition frequency of a passively ML semiconductor laser varies with pulse energy. Figure 3 shows the changes in the repetition frequency (open squares) of the 10GHz passively mode-locked QD laser as the injection current to the SOA-section is increased at $V_{SA} = -0.5V$. The filled black squares in Fig. 3 show the repetition frequency at $I_{SOA} = 280mA$ for different values of absorber reverse bias.
3. Dual-wavelength operation at 10GHz

Dual-wavelength synchronous ML is very attractive for application such as THz generation and nonlinear microscopy for bio-imaging, where a two-color pulse train is required. In case of Ti:sapphire ML lasers, various techniques are being studied and implemented (see for example [14] and references in [15]) to achieve dual-wavelength mode-locking. In QD lasers, simultaneous emission from ground state (GS) and excited state (ES) is a well known origin of two color emission [16, 17]. Dual-mode emission from the ES with the possibility to tune the frequency difference between the modes is reported in [18]. In the ML state, the GS-ES emission may give rise to synchronously mode-locked dual-wavelength ML. GS-ES emission state in two-section InGaAs/GaAs laser diodes is reported in [19, 20]. Apart from the conventional multi state emission in QD lasers, dual wavelength emission from a single energy state, i.e. GS, is also reported for 92.5GHz ML operation in a single-section InAs/InP QD structure [21]. Recently, similar performance was observed in a multi-section InAs/InGaAs QD laser grown on a GaAs(100) substrate [22].

3.1 Optical spectra

In this section, we report on optical spectra of our MLLDs in the state of passive ML. Figure 4 shows the evolution of optical spectra of the output light of the 10GHz laser while the SOA-section injection current is increased from above threshold over the ML region. Above threshold, the laser emits in the wavelength range of 1.49µm to 1.50µm. Near the onset of ML, the optical spectrum splits in two parts. The two lobes get spectrally separated gradually as the injection current increases. Nevertheless, at a certain operating point, the two groups of modes suddenly jump together and form a wide spectrum. At this point the laser starts Q-switching and enters a weak Q-switched ML state.

As indicated in Fig. 4, the double-lobe spectrum evolves slowly from a single mode group as the injection current increases and then changes suddenly back to a structure more similar to the one at lower currents. There are two reasons that the two spectral lobes belong to the same transition rather than separate emission from GS and ES. Firstly, simultaneous emission from GS and ES at higher current densities is most likely to lead to emergence of a separate spectral lobe as the injection current is increased. However one also expects then that such a structure would always be separate and stay separate. Another fact is that the measurement of
optical gain of similar QD material [3] indicates that separation of GS and ES in our material is around 60nm, which is more than the 10-15nm wavelength distance observed in Fig. 4.

Figure 4 presents the optical spectra (linear scale) as a function of $I_{SOA}$ and $V_{SA}$ obtained with the 10GHz laser. The region of ML is indicated in each plot. The laser is mode-locked for all current values except those outside the range of the dashed-dotted lines. It is clear that over the whole region of ML, the optical spectrum consists of two groups of modes. For all the five values of the bias voltage shown in Fig. 5, the short-$\lambda$ side of the spectrum significantly shifts to blue as the current is increased. However, the long-$\lambda$ side undergoes a minor red-shift. On the other hand, the qualitative shape of optical spectra remains similar for different values of bias voltage. Figure 5 will be discussed in more detail in section 7.

**3.2 Verification of ML in both mode groups**

An instance of a dual-wavelength optical spectrum recorded at $I_{SOA} = 280mA (~1.5I_{th})$ and $V_{SA} = -0.5V$ is presented in Fig. 6(a). The two groups of modes are similar in shape and are separated by ~12nm; the width of long-wavelength group of modes is around 5nm and shows higher optical power as compared to the other lobe which has a FWHM of 3nm. The output signal in the two groups of modes is studied in more detail in order to verify pulsed operation at both spectral lobes. A tunable band-pass filter (BPF) with 1.2nm FWHM bandwidth that
can be tuned over the whole optical spectrum is used to filter the MLLD output signal. The filtered signal is then amplified using a booster SOA and measured at the characterization setup. If only the SOA is used at the output of the laser, the short wavelength group is effectively filtered out due to the gain properties of the booster amplifier.

Figure 6(b) shows the RF spectra of the optical signals with the filter tuned at the centre of each of the two mode groups, i.e. green and red when the filter is tuned at 1486.5nm and 1498.5nm respectively. The RF spectrum from the total long wavelength mode group (LWMG) is shown in black. Clear RF peaks at the repetition frequency and higher harmonics confirm that both mode groups contribute to the pulsed operation. The recorded RF spectra with 50kHz resolution bandwidth show that the optical signals generated at the two lobes have within 0.003% similar repetition frequencies.

Another important conclusion follows by comparison of the pedestal around RF components for the three signals. In particular, the pedestal around the DC component is of importance because it corresponds to the amplitude noise. In Fig. 6(b), the low frequency components in the RF spectrum corresponding to the total output from the LWMG are very low and in the order of the ESA noise level. However, the filtered signals, which contain only a fraction of the laser output, show significantly increased DC pedestal. This shows that the filtered signals exhibit a higher amplitude noise and that the two spectral lobes are coupled. The coupling is attributed to spectral energy exchange between optical modes. The observations are consistent with the results presented in [9].

![Fig. 6. (a) Dual-wavelength optical spectrum (linear scale, µW/nm) of the 10GHz QD laser operating at $I_{SOA} = 280mA, V_{SA} = -0.5V$. (b) RF spectra of full bandwidth and filtered optical signals when BPF is tuned at the center of short-wavelength (green) and the long-wavelength (red) lobes. RF resolution bandwidth is 3MHz. The arrows on the figure show top of RF peaks.](image)

We verify the pulsed operation of both mode groups further in the next section by investigation of time traces. For this we had to use a sampling oscilloscope system. In order to apply the sampling oscilloscope, the device is operated with the SA under an external modulation, i.e. apply hybrid ML. The results are presented in the following section 4.

**4. Hybrid mode-locking**

In hybrid ML of a two-section MLLD, a stable electrical modulating signal at a frequency close to the free spectral range of the laser cavity is applied to the absorber section. The RF signal can be applied to slightly tune the repetition rate of the pulsed laser, but more importantly it reduces the timing jitter. We have previously investigated hybrid mode-locking in a 4.6GHz QD MLLD and shown that by applying an external modulating signal, it is...
possible to achieve timing jitter as low as 0.6ps, while the measured value of timing jitter for the passively mode-locked laser was 35-40ps [23]. Furthermore, hybrid ML enables broader range of measurement and characterization possibilities, e.g. with high-speed electrical sampling oscilloscopes, due to the availability of a clean electrical trigger. The RF source used is an Anritsu MG3691B low phase noise synthesized signal generator.

4.1 RF locking range

In order to define an RF locking range in terms of frequency and power of the modulating signal, we use the value of timing jitter. Timing jitter is an important parameter for practical applications and is usually referred to when evaluating the stability of optical pulses. In this paper, jitter values are determined by integration of the single sideband phase noise signal over 10kHz-80MHz offset around the fundamental RF peak.

A good operating point for the passively mode-locked (free running) 4mm-long QD MLLD is at $I_{\text{SOA}} = 280\text{mA}$ and $V_{\text{SA}} = -0.5\text{V}$ with $f_{\text{rep}} = 9.904\text{GHz}$. At this point, we measure a timing jitter of 14.5ps. Figure 7 shows a map in which the values of timing jitter are indicated. Jitter values are measured under hybrid ML for a range of RF power levels and frequencies. Over the whole range of operating parameters, the jitter remains below 5.5ps. The value of minimum jitter measured in this range is about 1ps. At $P_{\text{RF}} = 15\text{dBm}$, a maximum locking range of ~22MHz is achieved.

![Figure 7](image)

**Fig. 7.** Measured values of timing jitter (color-coded in ps) determine the RF locking range vs. RF power and frequency. Jitter values are calculated by integration of single side-band phase noise signal (10kHz-80MHz) around the fundamental harmonic. The transitions on the higher-frequency side of the locking range are too abrupt to visualize. The device is operated at $I_{\text{SOA}} = 280\text{mA}$ and $V_{\text{SA}} = -0.5\text{V}$.

At any power level of the external RF signal, a certain frequency tuning range exists where the ML is stable. Detuning the modulating signal from the free-running frequency, outside the locking range (shown in Fig. 7), results in a state of passive ML which is perturbed by the RF signal. The tuning range broadens as the modulating power is increased; however, the locking range is not symmetric around the free-running frequency. In slow saturable absorber mode-locking the pulse repetition rate and the pulse amplitude are correlated; in other words, the repetition frequency depends nonlinearly on the laser pulse energy. In [13], the detuning parameter (difference between the repetition frequency of the passively mode-locked laser and the cavity roundtrip frequency) is expressed as a function of
pulse energy and the repetition frequency tuning characteristics of a passively mode-locked laser is discussed.

The origin of the asymmetry observed in Fig. 7 becomes clear by considering the change in repetition frequency around the operating point $I_{SOA} = 280\text{mA}$ and $V_{SA} = -0.5\text{V}$ which is depicted in Fig. 3. At this point, the repetition frequency increases by either increasing the injection current to the gain section or by decreasing the absorber bias voltage, i.e. increasing the pulse energy. On the other hand, if the injection current is reduced or the bias voltage on the absorber is increased (pulse energy decreased), the repetition frequency decreases until certain bias parameters are reached, and then starts to increase. This behavior is in good agreement with the model presented in [13].

It follows from the observations of Fig. 3 that at the operating point of $I_{SOA} = 280\text{mA}$ and $V_{SA} = -0.5\text{V}$, the required change in the pulse energy is smaller for tuning the repetition frequency of the MLLD towards lower frequencies than towards higher frequencies. At this bias condition, frequency tuning range around the free-running frequency is asymmetrical and is skewed towards lower frequencies. The RF locking range which is presented in Fig. 7 accords very well with the preceding statement. This observation is consistent with arguments given in [24] where hybrid ML is studied theoretically using a set of delay-differential equations and compared with experiments on GaAs-based QD lasers.

4.2 Evaluation of chirp

To evaluate the value of chirp in devices under test, a similar approach as reported in [9] is adopted. A schematic of the measurement setup is shown in Fig. 8(a). In this method, the output of the hybridly mode-locked device is passed through a BPF which is tuned over the spectrum and then the oscilloscope traces are recorded. The traces are analyzed to determine the relative time delay of the different spectral components. A 50GHz sampling oscilloscope is used to record time traces. In case of hybrid ML, the RF signal can be used as the trigger for the sampling oscilloscope.

The recorded time traces for the 10GHz QD MLLD operating at $P_{RF} = 3\text{dB}$ are presented in Fig. 8(b). It is clear that as the BPF is tuned over the spectrum, the signals in the time traces move in time accordingly. These signals also confirm that both mode groups contribute to the pulsed operation. The pulse train period for each of the signals is ~100ps (10GHz repetition rate). The value of the linear chirp is determined to be $-6.7\text{ps/\text{nm}}$ over the long-wavelength spectral lobe. On the short-wavelength side of the spectrum, we measure a $+4.0\text{ps/\text{nm}}$ chirp. The overall time delay from all different spectral components is around 50ps which is half the roundtrip time. The autocorrelator shows approximately 43ps FWHM for the optical pulse which is consistent with the data in Fig. 8(c). The optical path from the QD laser to the sampling oscilloscope (Fig. 8(a)), includes a total length of 6m single mode fiber, the tunable Fabry-Pérot BPF and the booster SOA. Standard single mode fiber has a dispersion of 13-15ps/\text{nm-km} at $\lambda = 1480-1505\text{nm}$, which corresponds to a maximum 2ps time delay difference over the spectrum. The BPF does not have a significant effect on the signal dispersion. The booster SOA is operated in a linear gain regime. In absence of self phase modulation and pulse reshaping mechanisms, the waveguide chromatic dispersion of a short SOA (less than 1mm) is negligible. Therefore the contribution of the optical components outside the laser cavity to the measured chirp profile is estimated to be $+0.08\text{ps/\text{nm}}$.

It is interesting that the spectral chirp has opposite signs over the two groups of modes. The measured chirp profile in Fig. 8(c) indicates that the leading edge of pulses in time domain consists of the short-wavelength lobe, i.e. from 1480nm to 1487nm. The spectral components to follow are from the long-wavelength side, from 1502nm to 1495nm.
Fig. 8. (a) Schematic of the setup used to measure relative timing difference of spectrally filtered optical pulses. (b) Typical time traces recorded with the 50GHz sampling oscilloscope. (c) Measured values of timing differences (ps, left axis) on a plot of optical spectrum (µW/nm, right axis) indicate an almost linear spectral chirp over each mode group.

5. 3GHz mode-locked laser

5.1 Passive mode-locking

In order to have an overview of ML properties in QD MLLDs with different repetition rates, we have also fabricated a series of 13mm-long lasers. In this section, we present results obtained with the 3GHz laser. To the extent of our knowledge, the 3GHz mode-locked laser has the lowest repetition rate reported for a monolithic InAs/InP(100) QD laser. The MLLD under test in this section has a 650µm absorber section which is 3% of the total cavity length.

We follow similar measurement steps, as described in section 2, to map the region of ML in terms of operating parameters, i.e. $I_{SOA}$ and $V_{SA}$. To assure a uniform current distribution to the relatively long gain section, we used two probe tips for current injection. The device operates in stable ML regime for a range of injection current $I_{SOA} = 600-870$mA at $V_{SA} = -0.2$V and $I_{SOA} = 650-900$mA at $V_{SA} = -1.2$V. In the ML operating range, recorded ESA traces show clear RF peaks at 3GHz and higher harmonics; fundamental RF peaks are up to 55dB in height over the noise floor. The width of RF peaks at –20dB below the top of peak range from less than 200kHz to around 2MHz in this region. Variation of roundtrip frequency over the entire stable ML operating regime is about 10MHz. Figure 9 shows the changes in the repetition frequency (open squares) as the injection current to the SOA-section is increased at $V_{SA} = -0.8$V. The filled black squares in Fig. 9 show the repetition frequency of the 3GHz passively mode-locked laser at $I_{SOA} = 800$mA for different values of absorber reverse bias.

Observations on the optical spectra show that the 3GHz laser generates a dual-wavelength spectrum, similar to the 10GHz laser. The optical spectrum spreads over approximately 20nm optical bandwidth which is larger than widths observed from the 10GHz MLLD. However, the power balance between the two spectral lobes is different, i.e. the short-wavelength group of modes contains a relatively large portion of spectral power. The spectral components between the two main lobes are not fully suppressed as well.
Fig. 9. Repetition frequency tuning characteristics of the 3GHz passively mode-locked QD laser at $V_{SA} = -0.8\text{V}$ as the injection current to the SOA-section is increased (open squares). The filled black squares show the repetition frequency at $I_{SOA} = 800\text{mA}$ for different values of absorber reverse bias.

To verify the opposite sign of chirp over the optical spectrum in passively mode-locked regime, we have used the setup which is schematically shown in Fig. 10(a). We take a similar approach as mentioned in previous sections to filter the spectrum and record corresponding time traces. In case of the 3GHz laser, we can apply a 6GHz real-time oscilloscope. This allows for a study of the purely passively mode-locked state similar to the way presented in [9]. This will also allow us a comparison with (more accurate) results from hybrid mode-locking in the next section 5.2. In the passive ML regime the oscilloscope needs to be triggered on the optical pulses themselves. Therefore, the output light of the MLLD is first split using a 3dB power splitter. Each branch of the power splitter includes a tunable BPF which are connected to input channels of the real-time oscilloscope through fast PDs. The trigger signal is provided through a BPF with 2.0nm bandwidth and the central wavelength fixed at ~1494nm. The other BPF (1.2nm bandwidth) is tuned and the output is recorded by the oscilloscope. We monitor the triggering optical signal during the measurement to make sure trigger signal is stable enough and that recorded time traces are not affected by the amplitude noise of the trigger signal, as much as possible.

Figure 10(b) shows the relative time delays measured for the QD MLLD operating at $I_{SOA} = 750\text{mA}$ and $V_{SA} = -0.6\text{V}$. A different sign of chirp value over the two spectral lobes, i.e. positive chirp over shorter wavelength and negative chirp over longer wavelength group is observed. The measurement is repeated for four operating points at different values of injection current ($I_{SOA} = 750\text{mA}, 800\text{mA}$) and bias voltage ($V_{SA} = -0.6\text{V}, -0.8\text{V}$) and in all cases we observed opposite sign of chirp on the spectral lobes, where the short-wavelength spectral lobe shows a positive chirp.
5.2 Hybrid mode-locking

In case of the 13mm long QD MLLD, a good operating point for the free running laser is at $I_{\text{SOA}} = 800\text{mA}$ and $V_{\text{SA}} = -0.8\text{V}$ with $f_{\text{rep}} = 3.105\text{GHz}$. At this point the value of timing jitter for the optical pulses is measured to be 8-16ps. Figure 11 shows the timing jitter values measured for the hybridly mode-locked laser, over a range of RF power levels and frequencies. The range is chosen such that the jitter remains below 3ps. The minimum jitter value achieved in this range is about 0.7ps.

At $P_{\text{RF}} = 15\text{dB}$, the tuning range is around 27MHz and is comparable to the case of 10GHz laser where we measure approximately 22MHz of locking range (see Fig. 7). At $P_{\text{RF}} = 20\text{dBm}$ a maximum locking range of ~70MHz is achieved, which is a significant tuning range around the 3.105GHz repetition frequency of the laser. The tolerable detuning to the lower frequencies is $\Delta f = 5\text{MHz}$, while a detuning of $\Delta f = 65\text{MHz}$ to higher frequencies is allowed. It is clear from Fig. 11 that the locking range is strongly asymmetrical around the free running frequency. However, unlike the case of the 10GHz laser, the locking range is skewed towards higher frequencies. This difference in shape of the RF locking range is to be expected given the data in Fig. 9 and the operating point of the passively ML 3GHz laser in comparison with the data of the 10GHz laser in Fig. 3. In case of the 3GHz laser, a larger tuning range is achieved towards the higher frequencies since the (passive ML) operating point lies relatively close to, and on the left side of the bias condition where the minimum repetition frequency occurs.

Figure 10. (a) Schematic of the setup used to measure relative timing difference of spectrally filtered optical pulses in passive ML regime. (b) Measured values of timing differences (ps, left axis) on a plot of optical spectrum ($\mu\text{W/nm}$, right axis).
Fig. 11. RF locking range: measured values of timing jitter at several values of RF power and frequencies for the 3GHZ QD MLLD. The device is operated at $I_{SOA} = 800\text{mA}$ and $V_{SA} = −0.8\text{V}$. Timing jitter in case of passively mode-locked laser is 8-16ps.

In order to evaluate the effect of the RF signal on the optical spectra, a number of optical spectra obtained from the 13mm-long MLLD are recorded in the regime of hybrid ML at $P_{RF} = 15\text{dBm}$ and shown in Fig. 12. Modulating the absorber voltage at frequencies lower than the free-running frequency, i.e. 3.105GHz, mostly affects the longer wavelength spectral lobe. As the modulating frequency decreases, the long-wavelength lobe shifts to the blue side (~1.2nm for 3MHz frequency change) and the spectral power in this lobe increases. This results in an overall reduction of the total optical bandwidth. However, if the modulating frequency is increased above the free-running frequency, the short-wavelength group undergoes a blue shift of around 6nm. Meanwhile, the long-wavelength group broadens and shifts towards the short-wavelength group (~3nm for 24MHz). Therefore, the total optical bandwidth is increased by approximately 3nm.

Fig. 12. Recorded optical spectra (linear scale) obtained with the 13mm-long MLLD under hybrid ML at several RF frequencies. Modulation RF power is $P_{RF} = 15\text{dBm}$. Free running frequency is $f_{rep} = 3.105\text{GHz}$. 
5.3 Chirp evaluation under hybrid mode-locking

Evaluating the chirp profile for the 3GHz QD MLLD confirms opposite sign of chirp over the spectral lobes under hybrid mode-locking. The observation is consistent with the results on the dual-wavelength 10GHz MLLD. To determine the chirp, we used the same technique. Results are shown in Fig. 13. Figure 13(a) shows time traces of spectrally filtered pulses, recorded with a 30GHz sampling oscilloscope. Timing difference between different pulses is clear from the figure. The measured timing differences are shown in Fig. 13(b) over a plot of the optical spectrum at $I_{SOA} = 800mA$, $V_{SA} = -0.8V$ and $P_{RF} = 19dBm$. Available RF power on the absorber is approximately 6dBm which is the maximum power available in this setup due to losses introduced by the 3dB power splitter and RF cables.

6. Self mode-locked 4.5GHz QD laser

Self induced ML is already demonstrated in quantum well [25, 26] as well as InP-based quantum dot and dash material [27]. Passive mode-locking in FP lasers was first reported in [28] for an InGaAsP laser with cavity length of 250µm. The effect was explained through power dependent self- and cross gain saturation. The analysis presented in [10, 28] shows that four-wave mixing accompanied by nonlinear gain saturation leads to passive mode-locking.

In this section, we present experimental results obtained from a 9mm-long, single-section FP laser. The laser has cleaved facets and lasing threshold at $I = 430mA$. Figure 14(a) shows the evolution of the optical spectrum as the injection current is increased. The optical spectrum splits in two (almost) separate lobes at approximately $I = 600mA$. This coincides with the onset of mode-locking at a repetition frequency of $f_{rep}$~4.5GHz. The ESA trace in Fig. 14(b) is recorded at $I = 650mA$ and shows clear RF peaks at harmonics of the repetition frequency. This is an indication of mode-locking.

As the current is increased above $I = 650mA$, a third lobe at around $\lambda = 1500nm$ appears in the optical spectrum. The ML is affected by appearance of the third spectral lobe. The ESA trace in Fig. 14(c) is recorded at $I = 700mA$ and contains RF peaks at harmonics of $f_{rep} = 4.5GHz$ accompanied by additional frequency components. The extra frequency components have relatively low spectral power and indicate increased amplitude modulation at 388MHz.

Following similar measurement steps as mentioned in previous sections, we confirm the synchronized pulsed operation of both spectral lobes. A BPF is tuned over the spectrum and time traces are recorded using a 6GHz real-time oscilloscope. Results are shown in Fig. 15(a). Relative time delay between traces are then measured and mapped on a plot of spectrum in
Fig. 15(b). The measured spectral phase relation indicates different sign of chirp over the two spectral lobes, which is consistent with observations presented in the preceding sections.

![Graph](image)

**Fig. 14.** (a) Evolution of optical spectrum (mW/nm) obtained with the single-section QD laser, as the injection current is increased. Region of ML is indicated. (b) Electrical spectrum recorded at $I = 650\text{mA}$, and (c) $I = 700\text{mA}$.

**Fig. 15.** (a) Time traces of spectrally filtered optical pulses recorded with a 6GHz real time oscilloscope. (b) Measured values of timing delays on a plot of optical spectrum at $I = 650\text{mA}$.

A point to mention is that we have observed the self-induced mode-locking in a single-section 10GHz (4mm-long cavity) QD laser as well. The 10GHz single-section laser operates in a dual-wavelength ML state. However, the electrical bandwidth of our real-time oscilloscope does not allow us to observe the 10GHz optical signal, thus we have not been able to evaluate the spectral chirp.

**7. Summary and discussion**

We have fabricated and characterized InAs/InP QD-based mode-locked lasers with different repetition frequencies. The devices under test provide a larger optical bandwidth than the bulk and quantum well ML devices that we have fabricated (see for instance [29, 30]). Wide coherent bandwidth which is desirable for generation of short optical pulses, together with the
potential for full photonic integration are the main motivations to use InAs/InP QD mode-locked lasers as sources of optical pulses in combination with optical pulse shapers.

We have presented stabilization of the timing jitter of optical pulses in the regime of hybrid mode-locking. Furthermore, we have mapped regions of RF locking in terms of modulating power and frequency. A map of RF locking range is defined by measuring the timing jitter and is in itself of importance for practical purposes, such as in specifying the RF tuning range.

7.1 Spectral splitting: dual-wavelength ML

The main feature of mode-locking in the devices presented in this paper is the dual-wavelength pulsed operation. We have confirmed the synchronized pulsed operation of both spectral lobes by electrical spectra and recorded time traces of filtered spectral components. Furthermore, we have shown that spectral chirp has different sign over the two lobes.

In order to investigate the origin of dual-wavelength ML operation, we have recorded optical spectra at different values of operating parameters, i.e. $I_{SOA}$ and $V_{SA}$. The optical spectra obtained with the 10GHz two-section laser and the 4.5GHz single-section FP lasers are similar. In case of the 3GHz laser, the power balance between the spectral lobes is different; however, dual-wavelength operation is observed and confirmed. From the results in the previous sections, a number of conclusions can be made that are presented below.

(a) In QD lasers, simultaneous emission from GS and ES is a well known origin of two color emission. This phenomenon is more likely to give rise to a distinct spectral lobe at higher pump levels. In the devices presented here, we observe a splitting of the output spectrum from a single lobe as the current density is increased. This means that both spectral lobes are generated from a single state.

(b) In case of the single-section QD laser (Fig. 14), the emission above threshold starts at GS. Optical spectrum then splits into two lobes at the onset of mode-locking. Regarding the observed similarities in case of two-section devices, we believe that our devices operate at GS.

(c) It is clear from Fig. 5 that as the reverse bias on the absorber is increased, the spectral splitting occurs at a higher value of current injection. While an increased absorber voltage causes a relatively higher roundtrip loss, a higher current injection brings about a higher optical gain. This suggests that the onset of spectral splitting is mostly dependent on the internal optical power.

(d) Observation of mode-locking in the single-section QD laser reveals that processes in the gain section make our QD laser devices go into mode-locked operation. While the absorber section affects the laser behavior, it is not essential for mode-locking. The advantage of self mode-locked single-section MLLDs is that they require a single bias source and hence are operated more easily. On the other hand, for practical purposes two-section MLLDs offer several benefits such as timing jitter stabilization and tuning the repetition frequency which were mentioned in case of hybrid ML.

The physical reason for the splitting is not exactly obvious. The waveguides have been designed to operate in a single transverse mode. The first order mode can in principle be supported but it experiences a much higher loss. Multiple transverse modes would show up in the high resolution spectra and we did not observe them. Other explanations are speculative and indeed need to be explored which falls outside the scope of this paper. As mentioned before, our observations show that the spectral splitting is related to the internal optical power. AC Stark effects such as Rabi splitting (see for example [31]) could possibly play a role since the transition dipole moments in QDs are very large. Another option for the
dynamics might be optical pumping effects of carriers from one dot size group to other dot
groups.

7.2 Chirped pulse generation

In [8] we have reported on a unique feature of ML operation in a 9mm-long FP-type QD MLLD. The MLLD had a repetition rate of 4.6GHz and generated very elongated pulses in spite of a relatively wide optical bandwidth. In passively ML state, the time variation of the output power was only approximately ten percent of the total power, meaning that the duration of pulses was close to the roundtrip time and pulses overlapped. We measured a nearly linear chirp of \(-20\text{ps/nm}\) over the spectrum. In hybrid ML regime [23], time duration of pulses was reduced to less than half the roundtrip time. The negative chirp was verified when the chirp was (almost) compensated for by using length sections of single mode fibers with normal dispersion.

The results presented in this paper complement and extend the previously reported results on the 4.6GHz laser [9, 23]. Comparing the chirp results of the different devices gives some insight into the dynamics when the operating current density and roundtrip losses are considered. The injection current density in the ML region for the 10GHz and 3GHz lasers is in the range of 3.1–3.9kA/cm\(^2\) and 2.4–3.6kA/cm\(^2\) respectively. The value of current density for the 4.6GHz two-section laser, which is reported in [9], is in the range of 4.3–5.7kA/cm\(^2\). The facets of the 10GHz and the 3GHz lasers which are presented in this paper are HR coated at the absorber side, while the 4.6GHz laser had uncoated facets. Thus, the reduction in operating current density in the devices presented in this paper is attributed to application of HR coating. The operating range in terms of absorber voltage seems to be less wide as compared with the ML region of the 4.6GHz laser. A 9mm-long single section FP laser is also presented in this paper which operates in stable mode-locked regime for current densities in the range of 3.4–3.7kA/cm\(^2\). The single-section device has non-coated facets. Its operating current densities are therefore lower than that of the two-section 4.6GHz laser which also has no coating applied but does have an absorber.

Figure 16 shows instances of optical spectra and spectral chirp which are obtained from the different QD MLLDs presented at an operating point of strong ML. Figure 16(a) and 16(b) correspond to the 13mm-long and 4mm-long two-section lasers respectively. The device in Fig. 16(c) is the 9mm-long single-section laser which has un-coated facets. The device in Fig. 16(d) is the one presented in [8] and is a 9mm-long two-section laser with un-coated facets. In Fig. 16, the devices are arranged in order of the threshold current density from left to right. The threshold current density in the 3GHz laser is \(J_{\text{th}} = 1.82\text{kA/cm}^2\); this is the lowest value due to the longest gain section among the four lasers. The 4mm-long laser with HR-coating comes next with \(J_{\text{th}} = 2.28\text{kA/cm}^2\). The single-section 9mm-long laser has a slightly higher threshold current density. The two-section 9mm-long with the highest cavity losses has \(J_{\text{th}} = 3.78\text{kA/cm}^2\).

The device with the lowest operating current density, i.e. the 3GHz laser at \(J_{\text{SOA}} = 3.27\text{kA/cm}^2\), shows a dual-lobe spectrum. The longer-wavelength side has a narrow lobe and the shorter wavelength side has around 80% of the spectral power. It is clear that this laser tends to operate on the shorter-wavelength side of the spectrum. In terms of the operating current densities, the 10GHz laser with an HR-coated facet and the 4.5GHz single-section laser come next in the order with \(J_{\text{SOA}} = 3.61\text{kA/cm}^2\). The optical spectra for these devices consist of two clear spectral lobes with comparable amount of power. In case of the next device, i.e. the 9mm-long two-section laser with uncoated facets, the operating current density is \(J_{\text{SOA}} = 5.15\text{kA/cm}^2\). This laser operates with only a single spectral lobe in the ML region, which we believe is the long-wavelength side of the spectrum. This is consistent with the observation presented in Fig. 4 which shows that at higher current densities, the two spectral lobes jump together to form a single-lobe spectrum.
The chirp in our devices is high and leads to elongated optical pulses. The total time differences between spectral components are 50ps, 70ps and 150ps for the 4mm, 9mm and 13mm cavity lengths. From Fig. 16 one can clearly see that the long wavelength spectral lobe is always up-chirped and the short wavelength lobe is always down-chirped. Our results show the chirp is driven by a robust mechanism which prevents the formation of a short pulse, i.e. locking of the phases of all spectral components to the same value. Even under hybrid ML, the pulse duration is almost half the roundtrip time, independent of the cavity length. We stress the fact that the intracavity dispersion in our devices is similar to that of a normal FP laser and the origin of the very large chirps is not directly linked to the dispersion.

![Optical spectra](image)

Fig. 16. Optical spectra (linear scale, a.u.) and spectral chirp (ps/nm) obtained with (a) 3GHz laser at \( J = 3.27kA/cm^2 \), (b) 10GHz laser at \( J = 3.61kA/cm^2 \), (c) 4.5GHz single-section at \( J = 3.61kA/cm^2 \), and (d) 4.6GHz two-section at \( J = 5.15kA/cm^2 \).

The question remains on the exact origin of the dynamics. We have shown that mode-locked operation in InAs/InP(100) QD MLLDs has similar properties to the state of FM locking. Theoretical discussion on details of FM locking in these devices is out of the scope this paper. However, the generation of highly chirped pulses, the presence of correlated amplitude noise in our devices and the observation of self-induced mode-locking in a single section laser stress the fact that the processes in the gain section play a critical role in these devices. The inhomogeneous broadening and size distribution of quantum dots provide the wide and smooth gain spectrum in InAs/InP QD-based devices. The gain in QD material is localized in the dots which are spatially separated. The carriers providing the gain are held at the position of the dots and their mobility is significantly reduced compared to the carrier mobility in bulk or quantum well material. The low side-wall surface recombination rate observed in deeply-etched ridge waveguide QD lasers confirms this effect. Therefore, dynamic gain gratings are stronger in QD materials than in quantum well systems and as a result the four-wave mixing process [2] is more efficient, which is the process that we assume to be at the basis of the laser dynamics observed.

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