Dual Wavelength Passive and Hybrid Mode-Locking of a 10GHz Quantum Dot Laser Diode at 1.5μm

M.S. Tahvili, M.J.R. Heck*, R. Nötzel, M.K. Smit, E.A.J.M. Bente
COBRA Research Institute, Eindhoven University of Technology
Eindhoven, the Netherlands
s.tahvili@tue.nl

Abstract— **We report on stable dual-wavelength operation in passive and hybrid mode-locking of a 10GHz two-section InAs/InP(100) quantum dot laser diode operating at 1.5μm. The range of stable passive mode-locking, the locking range of hybrid mode-locking and detailed measurements of the phase modulation in the output pulses will be presented.**

Keywords- mode-locked laser diode; quantum dot; hybrid mode-locking; dual-wavelength;

I. INTRODUCTION

Quantum dot (QD) material has been shown to be a promising gain medium for mode-locked laser diodes (MLLDs). The inhomogeneous broadening leads to a broad gain spectrum, which can in principle bring about ultra-short pulse generation. The QDs show reduced amplified spontaneous emission levels compared to bulk or quantum well material which can lead to a lower phase noise. Recently, we have been investigating mode-locking (ML) behavior in lasers incorporating InAs/InP(100) QD gain material, operating around 1.55μm [1]-[2]. The QD laser structure is grown on n-type (100) InP substrates by metal–organic vapor phase epitaxy [3]. The laser structure has five layers of InAs QDs stacked and located at the centre of a 500nm thick InGaAsP optical waveguiding core. Fabry–Perot type (FP) laser devices with two electrically isolated sections have been realized. The structures are cleaved to create the mirrors of the FP cavity. A high reflection (HR) coating is applied to the relatively short absorber-side facet of the lasers to decrease the cavity losses and reduce the pump current density. We intend to develop a short pulse laser light source based on the quantum dot gain material operating at 1.55um wavelength region. Combining the operation of such a laser source with an integrated pulse shaper will enable us to employ the miniature pulsed laser systems into a variety of applications including metrology and biomedical imaging.

In this paper, experimental results including verification of dual-wavelength operation, locking range of hybrid ML and evaluation of chirp profile of generated pulses, obtained from a 4mm (10GHz) MLLD with 120μm absorber section are presented. The output light from the device is collected by a lensed fiber and all measurements are performed at 12°C.

II. PASSIVE MODE-LOCKING

The two-section devices are operated by forward biasing the longer section, creating a semiconductor optical amplifier (SOA) and by reversely biasing the shorter section, creating a saturable absorber (SA). An operating range can be defined where stable ML is achieved in terms of the values of injected current of the SOA-section and bias voltage of the SA, I_{SOA} and V_{SA} respectively. To determine the stable ML operating range of the MLLD, I_{SOA} is sweep-scanned and the RF spectra traces are recorded. The measurement is repeated for a range of values of V_{SA}. The height of RF peak at the fundamental frequency over the noise floor, is mapped as a function of operating parameters and a plot is presented in Fig.1.

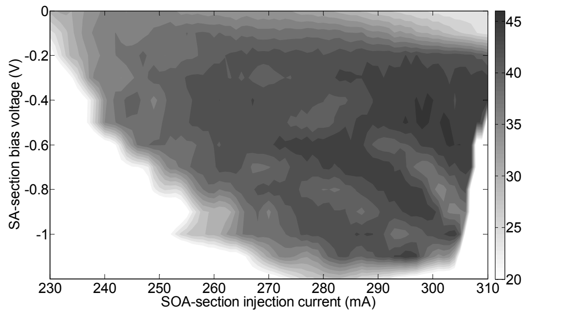

Fig.1. Height of the peak (grey scaled in dB) at the fundamental frequency over noise floor, recorded by the electrical spectrum analyzer. The electrical bandwidth used to obtain the spectra is 50kHz.

A. Dual wavelength operation

The optical spectrum shows that over the whole range of stable ML two separated groups of modes exist together. E.g. at I_{SOA}=270mA and V_{SA}=−0.5V the two groups are separated by 13nm. The longer wavelength group of modes has a FWHM of 5nm and shows relatively higher optical power as compared to the other lobe which has a FWHM of 3nm.

The output in the two groups of modes was studied in more detail. A tunable 1.2nm bandpass filter (BF) is tuned over the whole optical spectrum to filter the MLLD output signal. The filtered signal is then amplified using a booster SOA. 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. Fig.2 shows the RF spectra of the optical signals with the filter tuned at the centre of the two mode groups (light and dark grey) and an RF spectrum from the total long wavelength mode group (LWMG) (black). It appears that both mode groups generate pulses. The total output from the LWMG shows little or no amplitude noise at low frequencies, while the 1.2nm filtered output, which contains only a fraction of the output of a group, does show increased amplitude noise. This observation is similar to [1]. The changes in relative height of peaks at harmonic frequencies in the RF spectrum

This work is supported by the IOP Photonic Devices program managed by the Technology Foundation STW and SenterNovem.

*M.J.R. Heck is currently with the Department of Electrical and Computer Engineering, University of California Santa Barbara, Santa Barbara, USA.

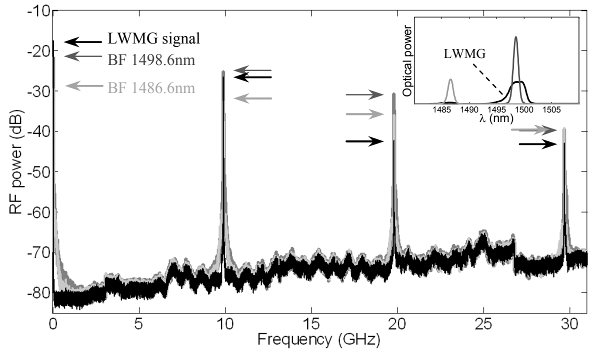

Fig.2. RF spectra obtained at I_{SOA}=260mA, V_{SA}=−0.5V, recorded with resolution bandwidth of 3MHz. The arrows on the plot point to the top of RF peaks. The inset shows optical spectra of the signals.

reveal not only that there is a difference in total optical power of the signals, but also a difference in the shape and modulation depth of the pulses in the two mode groups.

The pulsed operation of the QD laser at both wavelength mode groups is confirmed by autocorrelator traces which show FWHM of 16.2ps and 8.8ps for the 1.2nm filtered signal from long and short wavelength mode groups respectively. The total LWMG signal shows a FWHM of 45ps indicating a large chirp in the pulse, similar to earlier observations [1].

III. 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 on 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. 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.

A. Locking range

To define a locking range in terms of frequency and power of the modulating signal and evaluate the stability of optical pulses, the value of timing jitter is used. Such a value has been determined by integration of the single sideband phase noise signal over 20kHz-80MHz offset around the fundamental RF peak.

A good operating point for the free running QD MLLD is at I_{SOA}=280mA and V_{SA}=−0.5V with f_{rep}=9.904GHz where the laser shows a timing jitter of 14.5ps. Fig.3 shows the timing jitter results obtained with hybrid ML over a range of RF power levels and frequencies where the jitter remains below 5.5ps. At P_{RF}=15dBm, a maximum locking range of ~22MHz is achieved. The minimum jitter in this range is about 1ps.

B. Chirp evaluation

The RF signal can be used to trigger a 50GHz sampling oscilloscope with optical input and record traces of optical pulses. As an example, a recorded trace of the LWMG signal is shown in the inset of Fig.4. The figure shows that the output pulse expands over 40ps (FWHM) in one period. The autocorrelator shows a FWHM of 43ps for the optical pulse.

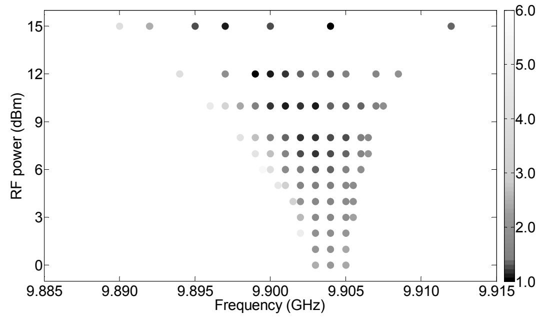

Fig.3. Time jitter (grey scaled in ps) for hybridly mode-locked QD MLLD over a range of applied RF power levels and frequencies.

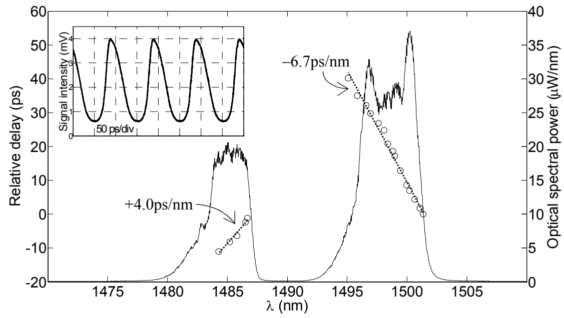

Fig.4. Relative time delay of pulses with different spectral components superimposed on a plot of the optical spectrum. The inset shows an oscilloscope trace for the LNW signal at I_{SOA}=290mA, V_{SA}=−0.5V, and P_{RF}=3dB.

A similar approach as reported in [2] is employed to evaluate the value of chirp. In this method, the BF is tuned over the spectrum, and oscilloscope traces are recorded and then analyzed to determine the relative time delay of the different spectral components. The result is shown in Fig.4 for the QD MLLD operating at P_{RF}=3dB. The overall output pulse from all different spectral components is around 50ps which is half the period of the repetition rate. The value of the linear chirp is determined to be –6.7ps/nm and +4.0ps/nm over the long- and short-wavelength lobes of optical spectrum respectively.

IV. Conclusions

We have demonstrated the dual-wavelength operation of a 10GHz QD MLLD. The laser can operate in a mode where two groups of wavelength modes are locked. The spectral components at different wavelengths are synchronized in pulsed operation. While the phenomenon which drives ML in 1.55µm QD material seems to be effective, the mechanism causing the chirp and giving rise to elongated optical pulses appears to be robust. These observations are consistent with our earlier work on 5GHz lasers.

References

[1] M. J. R. Heck, et.al., “Passively mode-locked 4.6 GHz and 10.5 GHz quantum dot laser diodes around 1.55 µm with large operating regime,” IEEE J. Sel. Top. Quant. Electron., vol. 15, pp. 634–643, 2009.

[2] M.J.R. Heck, et.al., "Analysis of hybrid mode-locking of two-section quantum dot lasers operating at 1.5 µm," Opt. Exp., vol. 17, pp. 18063-18075, 2009.

[3] R. Nötzel, et.al., “Self assembled InAs/InP quantum dots for telecom applications in the 1.55 um wavelength range: wavelength tuning, stacking, polarization control, and lasing,” Jap. J. of Appl. Physics, 45(8B), pp. 6544-6549, 2006.