

## Operating regime and stability of mode-locking in 10GHz quantum dot laser diodes around 1.5 $\mu$ m

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## Operating regime and stability of mode-locking in 10GHz quantum dot laser diodes around 1.5 $\mu$ m

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*In this paper we investigate and explore the stability and operating regime of mode-locking (ML) in 4mm long Fabry-Perot type lasers, corresponding to a roundtrip frequency of 10GHz. The devices are fabricated on InAs/InP quantum dot material, operating at wavelengths around 1.5 $\mu$ m, and are HR-coated at the absorber side. In order to find the stable ML region of operation in these devices, we have performed sweep-scans on the injection current of the gain section, and the reverse bias voltage on the absorber section. We will present the optical and electrical spectrum of devices with different absorber length. These results will be compared with the performance of earlier devices without HR coating.*

### Introduction

Mode-locked laser diodes (MLLDs) are already in use as high-speed sources [1] and gaining much attention in different fields of research such as frequency comb generation [2], and biomedical imaging [3]. Utilizing quantum dot (QD) gain material in MLLDs offers many advantages including broad gain spectrum and low spontaneous emission levels compared to quantum well material. Most of the results on mode-locking (ML) in QD lasers concern InGaAs/GaAs material which operates in the 1.2-1.3 $\mu$ m region. Recently, we have been much focusing on ML behavior in lasers incorporating InAs/InP(100) QD gain material, operating around 1.55 $\mu$ m.

The first observation of ML in two-section QD MLLDs operating around 1.55 $\mu$ m demonstrated large and stable ML operating regime, however, with strikingly different behavior than what is commonly observed in MLLDs [4]. The output pulses from the 5GHz MLLD were shown to be very elongated with a chirp of around 20ps/nm. There have been experiments on the 10GHz MLLDs as well [5]; observations on these devices show that such short MLLDs require higher current densities to generate enough gain in the SOA section. As a result of the increased amount of current, the emission from excited state of QDs will start to take place. The ML operating regime in these devices appears to be limited by the emergence of a second group of modes at shorter wavelengths.

In order to try to operate the SOA at a lower gain and thus avoid the excited state lasing, it is necessary to decrease the cavity losses. We have applied high-reflection (HR) coatings at the SA-side facet of 4mm long MLLDs, to study the effect of decreased required  $I_{SOA}$  on ML. We will present the measurement results for 10GHz MLLDs, and compare them with the observations published previously in [5].

## Experimental Results

In this section, measurement results obtained from a 4mm long MLLD, having a 120 $\mu$ m absorber section which is equal to 3% of the total device length, are presented. A single-section 4mm long FP laser, fabricated on the same chip, is also tested for comparison and reference. All measurements are done at 12°C, unless otherwise stated. The output light from the devices is collected by a lensed fiber, and an optical isolator is used to prevent possible back-reflection to the lasers.

The MLLD has a threshold current of 173mA to 190mA for SA reverse bias voltages of 0V to 1V. The threshold current for the FP laser is 115mA. The threshold current values reported previously for similar devices without the HR coating is 160mA for the FP laser and 330mA to 410mA for the 3% SA section MLLD for bias voltages of 0V to 8V, measured at 10°C [5].

Passive mode locking is studied by recording the electrical power spectrum. The recorded traces of RF spectra show well-defined peaks at the cavity round-trip frequency, 9.89GHz corresponding to 4mm long cavity, and its higher order harmonics. A typical trace recorded by the RF spectrum analyzer at  $I_{SOA}=275$ mA and  $V_{SA}=-0.5$ V, is shown in Fig.1. The height of the peak at the fundamental frequency is more than 45dB over the noise floor, and the full width of the peak at 20dB below the top of the peak is 0.7MHz. Moreover, the RF signal intensity around the DC-component in the spectrum is at the noise floor, which indicates clear and stable mode-locking.

To observe and monitor the operation parameters for which the device is in ML regime, the injection current of the SOA section is sweep-scanned, and the RF spectra traces are recorded. The measurement is repeated for a range of values of the SA bias voltage. The height of RF peak (over the noise floor) and the RF peak width are mapped as a function of operating parameters and a plot is presented in Fig.2. The figure shows that ML occurs at SA reverse voltages from 0V to 1V, and SOA injection currents which depend on the bias voltage, starting from 230mA to 250mA, and up to 280mA; peaks can be up to more than 45dB in height over the noise floor, and very narrow with a width (at  $-20$ dB) ranging from less than 0.5MHz to around 2.5MHz in this region. The variation of roundtrip frequency over the stable ML operating regime is about 10MHz.

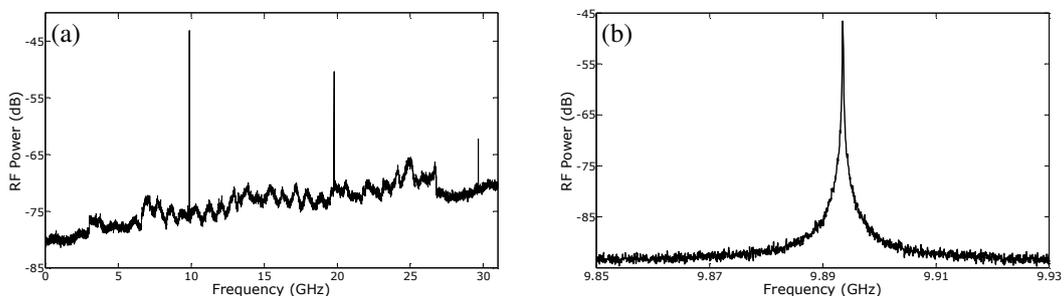


Fig.1. (a) Electrical RF power spectrum obtained at  $I_{SOA}=275$ mA, and  $V_{SA}=-0.5$ V. The electrical bandwidth used is 3MHz. The RF spectrum shows clear peaks at harmonic frequencies of 9.89GHz with signal at noise level around the DC component. (b) Detailed view of the RF power spectrum around the cavity roundtrip frequency recorded with 50kHz electrical bandwidth.

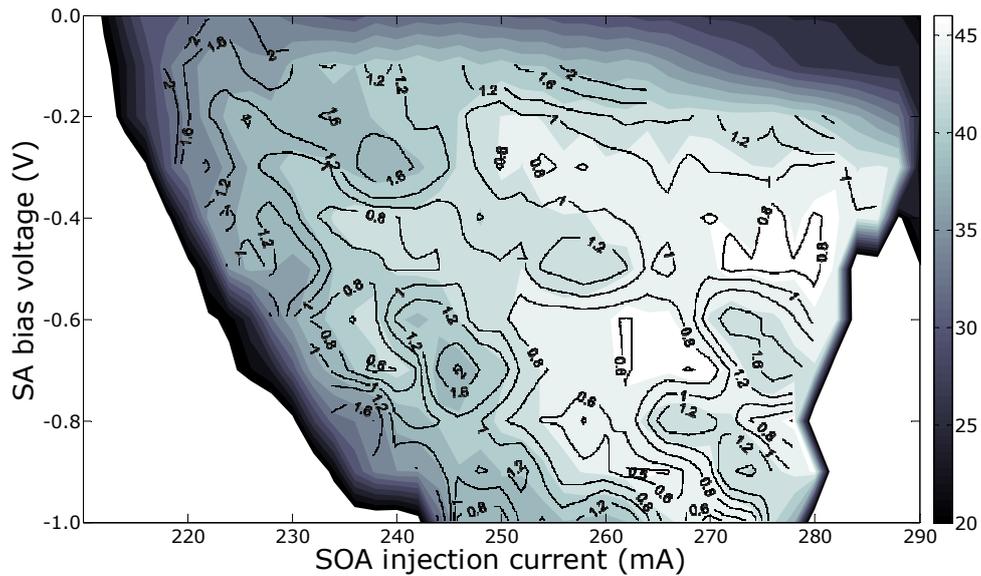


Fig2. Height of the peak at the fundamental frequency over noise floor, recorded by the electrical spectrum analyzer. The electrical band-width used to obtain the spectra is 50kHz, and RF power is gray scaled in dB. The value of full width of peak (in MHz), at 20dB lower than the top of peak, is superimposed on the RF power mapping.

The ML operating range is not as wide in comparison to the 9mm (corresponding to 5GHz roundtrip frequency) uncoated MLLDs, but the performance shows improvements as compared with the 4mm uncoated devices [5].

The evolution of optical spectrum for the 4mm HR-coated device with 120 $\mu$ m SA section as a function of SOA injection current and at  $V_{SA} = -0.5V$  is given in Fig.3(a). A typical optical spectrum for the same device at  $I_{SOA} = 275mA$  is presented in Fig.3(b). The width of long-wavelength group of modes is around 5nm which is comparable to the width of the spectra previously observed in 9mm two-section MLLDs [4]. Such spectrum is also observed from the single-section reference device. It is obvious from Fig.2 and Fig.3 that over the whole range of stable ML, two groups of modes exist together. These groups of modes are quite similar in shape, and can be associated to the emission from QDs ground- and excited-states (GS and ES), since they are observed in the optical spectrum of the single-section reference device as well [5]-[6].

Nevertheless, at a certain operating point, the two groups of modes suddenly jump together and form a wide and complex spectrum. The sudden change in the spectrum is immediate at the onset of complicated dynamics which eventually destabilizes ML. The emergence of a second group of modes at shorter wavelengths (emission from ES) is observed for the 4mm uncoated devices previously [5]. However, the behavior is different, as the short-wavelength group seems to come to, and eventually merge into the GS emission gradually as the SOA injection current is increased, while for the coated device, studied in this paper, the change in the spectrum happens suddenly. A comparison of the recorded optical spectra at temperatures  $T = 10^{\circ}C$  and  $T = 12^{\circ}C$  indicates differences in the shape, evolution, and the value of injection current at which the sudden change takes place.

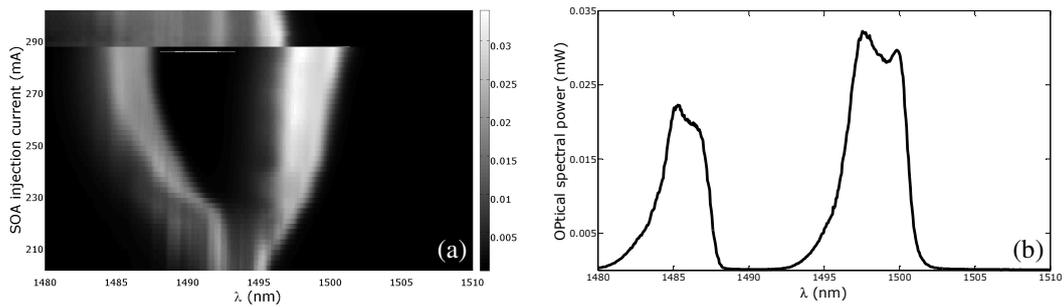


Fig.3. (a) Evolution of optical spectrum (linear scale in mW) for the 4mm HR-coated QD MLLD with 120 $\mu$ m SA section ( $V_{SA} = -0.5V$ ), obtained as a function of SOA injection current. Emergence of a second group of modes at shorter wavelengths is visible. (b) Optical spectrum for the same device at  $I_{SOA} = 275mA$ . The optical bandwidth used is 1nm.

## Conclusions

The 4mm HR-coated two-section MLL's are studied for mode-locking behavior, and the region at which stable ML takes place is explored in terms of operation parameters, i.e.  $I_{SOA}$  and  $V_{SA}$ . The RF spectra recorded by the electrical spectrum analyzer show clear peaks at harmonic frequencies of 9.9GHz. The peaks can be up to more than 45dB in height over the noise floor, and have the full width at -20dB ranging from less than 0.5MHz to around 2.5MHz in the operating region. The roundtrip frequency is stable with a variation of about 10MHz in this region. The application of an HR coating has not suppressed the appearance of ES lasing; however, the two groups of modes exist together and the ML is stable. We will study the role each group of modes plays in more details.

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