5-GHz passively mode-locked quantum dot ring laser diode at 1.5 µm

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For the first time passive mode-locking in InAs/InP quantum-dot ring laser diodes operating at wavelengths around 1.5 µm is reported. Pulse generation at 5 GHz from an 18-mm long ring cavity, including a saturable absorber, is verified by a background-free 55-ps autocorrelation signal and RF-spectra with 50-dB peaks at 5 GHz having widths down to 0.30 MHz at -20 dB. The clockwise and counterclockwise propagating fields show complementary optical spectra. Due to the inhomogeneous broadening and depending on the operation conditions, different groups of dot-sizes appear to couple either with the clockwise or counterclockwise propagating fields.

Introduction

Active and passive mode-locking of laser diodes is a well-established technique for generating picosecond pulses at wavelengths around 1.55 µm. In telecommunications mode-locked laser diodes (MLLDs) can be used as high-speed sources in optical time-domain multiplexed (OTDM) systems and as multi-wavelength sources in wavelength-division multiplexed (WDM) systems. These MLLDs have also found their way to other fields of research, such as biomedical imaging and frequency comb generation, e.g. for metrology purposes.

Passively mode-locked quantum dot (QD) lasers operating at wavelengths around 1.3 µm have shown to be very promising with respect to operation stability and short-pulse generation [1]. However MLLDs based on InAs/InP QD or quantum dash material and operating in the 1.5-µm wavelength region show a different behavior [2-4]. In [3,4] we have shown that although these devices show a large operating regime for stable mode-locking and a large optical bandwidth of about 6 nm, the output pulses are heavily chirped and elongated. Also we have measured a relatively large timing jitter of about 35 ps for a 5-GHz device.

A well-known advantage of ring-configurations is that they typically operate in colliding-pulse mode-locking. This mechanism can in principle lead to decreased timing jitter and decreased pulse duration [5]. In this work we investigate a 5-GHz passively mode-locked QD ring laser diode and report on the results with respect to the stability of mode-locking. The degree to which these ring lasers show bi-directional operation and the relation with the passive mode-locking was also studied.

Design and fabrication

The QD laser structure is grown on n-type (100) InP substrates by metal-organic vapor-phase epitaxy, as presented in [6]. MLLDs with a ring configuration are realized using the same fabrication technology as presented in [3]. Some realized devices and a diagram of the device lay-out are shown in Fig. 1.

In this work we focus our attention on a device consisting of an 18-mm long ring cavity, corresponding to a 5-GHz roundtrip frequency. The results may then be compared to the results obtained with a 4.6-GHz linear laser [3,4]. The waveguide width is 2 µm. We have used bends with an adiabatically increasing and decreasing radius to eliminate offsets in the waveguide and to minimize internal reflections as a consequence. A separate waveguide section, used as a saturable absorber (SA), with a length of 300 µm is located in the ring cavity, opposite to a directional coupler which couples approximately 5% to 10% of the light to the output waveguides. The output waveguide is oriented at the Brewster angle for the fundamental mode with the facets which have also been antireflection coated.

The three-section device is operated by forward biasing the 18-mm ring cavity, creating a semiconductor optical amplifier (SOA) and by reversely biasing the shorter gain section, creating an SA. The output waveguide is biased separately and was used here to increase the optical output power. The devices are mounted on a copper chuck, p-side up, and kept at a fixed temperature of 10 °C during operation.

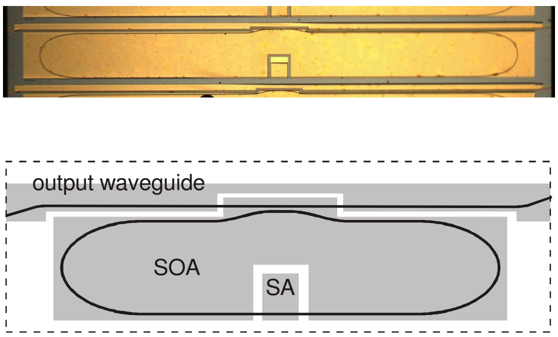

Fig. 1 (top) Picture of the realized devices. (bottom) Schematic overview of the QD ring MLLD, showing the separate contacts (grey) for the SOA, SA and output waveguide. The waveguides are indicated by the black line.

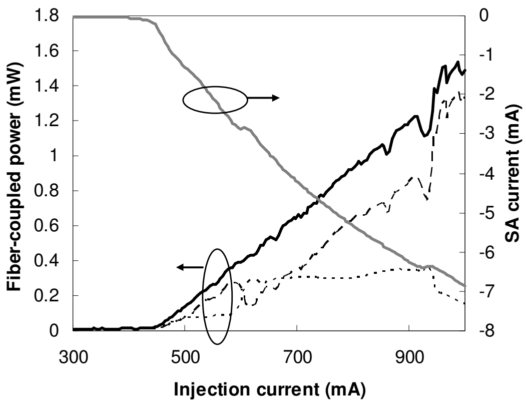

Fig. 2 Measured fiber-coupled output power for the LHS-output ($\times 10^3$, dashed) and RHS-output (dotted) and the calculated summation of both (solid black). The reverse bias current generated in the SA is also given (solid grey). V_{SA} = -1 V.

Experimental results

In a ring MLLD the optical field can propagate in clockwise (CW) and counter-clockwise (CCW) direction. This distinct feature sets these lasers apart from the FP-type MLLDs. Both outputs, i.e. the right-hand-side (RHS) output where the CW field exits and the left-hand-side (LHS) for the CCW field have been characterized. Lensed fibertips are used for collecting the light. The RHS could be aligned with minimum coupling losses of about 5 dB. However due to an issue with access of a fiber-tip to the output, the LHS coupling losses are higher.

The measured power at both outputs of the ring laser is shown in Fig. 2. The threshold current is 450 mA. With the output waveguide biased at 150 mA, the fiber-coupled power at the RHS is between 0.3 mW and 0.4 mW for injection currents over 600 mA. The power at the RHS is not linearly increasing as might be expected from a laser diode. The same is observed in the LHS fiber-coupled power. However the shapes of both

power-current (PI) curves are complementary and power exchange between the CW and CCW fields seems to take place when the injection current is changed.
Since the measured SA bias current increases monotonously with increasing injection current, the total field inside the ring cavity, i.e. the sum of the CW and CCW fields, should also increase monotonously. This fact can be used to scale the power level of the LHS output. A monotonously increasing (~linear above threshold) PI curve for the total power of the laser is found when the LHS power is scaled by a factor of 1000. This is mainly due to the poor LHS fiber coupling. But other factors may also contribute such as an unequal gain and/or loss in the two halves of the output waveguide.
To verify passive mode-locking in this ring MLLD a 50-GHz photodiode connected to a 50-GHz bandwidth electrical spectrum analyzer (ESA) is used to obtain the RF-spectra at the RHS output. In Fig. 3 the RF-spectrum at an injection current of 820 mA and an SA bias voltage of -1 V is shown. The first RF-peak at the fundamental frequency is 50 dB over the noise floor. The width of this peak is narrow, i.e. 0.30 MHz at -20 dB, as can be seen in Fig. 3. This is almost twice as narrow as the width of 0.57 MHz found for FP-type lasers [4]. It can be said that this RF-spectrum indicates clear and stable mode-locking. In Fig. 4 the RF-peak height is given for a large range of operation parameters, i.e. the injection current and the SA bias voltage. A large regime of stable mode-locking is found for injection currents between 700 mA and 900 mA and for bias voltages between 0 V and -2 V. Over this range, the variation in the RF-peak position is less than 2.3 MHz. Also over this current range ($V_{SA} = -1$ V) the position of the RF-peaks obtained at the LHS and RHS outputs are identical within the measurement accuracy. Mode-locking is further confirmed by an autocorrelator trace, showing a clear second-harmonic generated signal with a width of about 55 ps. The total timing jitter is determined by integrating the single-sideband phase noise spectrum over the range 10 kHz – 80 MHz. This timing jitter has a value of (25±5) ps.

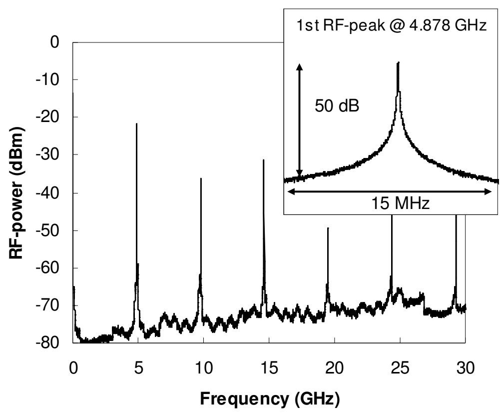

Fig. 3 RHS output RF-spectrum obtained with a ring injection current of 820 mA and an SA bias voltage of -1 V. The output waveguide current is 150 mA. Inset: Detailed view of the spectrum around the first RF-peak.

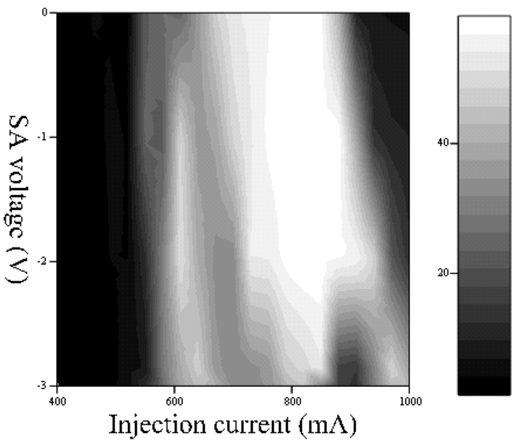

Fig. 4 RHS output RF-peak heights (dB-scale) as a function of SA bias voltage and ring injection current. The same settings as in Fig. 3 are used.

The optical spectra of both laser outputs, i.e. from CW and CCW propagation, are given in Fig. 5. As can be seen the CW-spectrum has three groups of laser modes for injection currents of 720 mA to 890 mA, located around 1490 nm, 1505 nm and 1520 nm. The width of these individual groups is approximately 3 nm FWHM. We ascribe these spectral features to lasing transitions from the electron ground and excited dot states. When the CW and CCW spectra are compared it can be seen that they are complementary, i.e. the CCW spectrum fills in the holes of the CW spectrum (Fig. 5). This means that the CW and CCW signals lase at different wavelengths, which indicates that they make use of different sets of quantum dots, with different sizes.

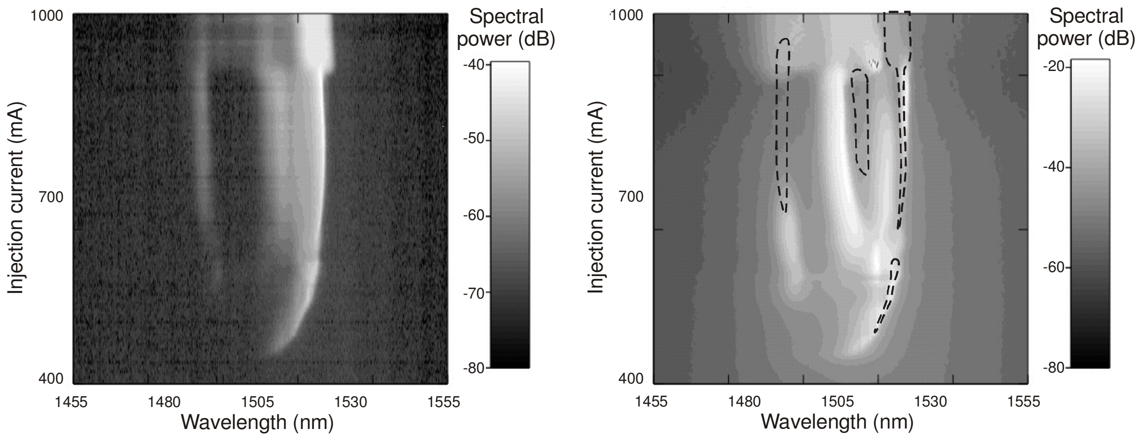

Fig. 5 Optical spectra (dB, greyscale coded) of (left) the LHS output (CCW) and (right) the RHS output (CW). The dashed line in (right) shows the position of selected maxima in (left). V_{SA} = -1 V. The optical bandwidth used to obtain the spectra is 0.2 nm.

Conclusion

Passive mode-locking at 1.5-µm wavelengths has been observed in a 5-GHz QD ring MLLD over a large operating regime. As compared to 5-GHz FP-type QD-MLLDs previously fabricated and studied by us [3,4], we observe a decrease in RF-linewidth at -20 dB from 0.57 MHz to 0.30 MHz and a decrease in timing jitter from (35±5) ps to (25±5) ps. Also the variation of the RF-peak position is more stable in the ring-type MLLD. The reason for this increased performance can be the relatively low coupling ratio of the directional coupler in the ring laser, where only 5% to 10% of the power is coupled out each roundtrip. Another reason can be the effect of colliding pulse mode-locking. The CW and CCW propagating fields lase at different wavelengths, which is a unique and interesting feature of QD ring MLLDs.

The authors gratefully acknowledge the support of the Smart Mix Program of the Netherlands Ministry of Economic Affairs and the Netherlands Ministry of Education, Culture and Science and of the NRC Photonics Grant.

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