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Optimum phase noise reduction and repetition rate tuning in quantum-dot mode-locked lasers

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Competing approaches exist, which allow control of phase noise and frequency tuning in mode-locked lasers, but no judgement of pros and cons based on a comparative analysis was presented yet. Here, we compare results of hybrid mode-locking, hybrid mode-locking with optical injection seeding, and sideband optical injection seeding performed on the same quantum dot laser under identical bias conditions. We achieved the lowest integrated jitter of 121 fs and a record large radio-frequency (RF) tuning range of 342 MHz with sideband injection seeding of the passively mode-locked laser. The combination of hybrid mode-locking together with optical injection-locking resulted in 240 fs integrated jitter and a RF tuning range of 167 MHz. Using conventional hybrid mode-locking, the integrated jitter and the RF tuning range were 620 fs and 10 MHz, respectively. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4861604]

Monolithic semiconductor mode-locked lasers (MLLs) emit series of narrow pulses of light at high repetition rates ranging from 5 to 80 GHz.[1,2] Optical frequency combs emitted by MLLs can be utilized in a variety of applications. Arbitrary waveform generation, orthogonal frequency-division multiplexing, and coherent wavelength division multiplexing techniques need stable frequency combs of narrow optical linewidth, while short periodic pulses with low level of pulse-to-pulse timing fluctuations are required in optical time-division multiplexing, optical sampling, and all-optical clock recovery.

MLLs based on InAs/GaAs quantum-dots (QDs) have demonstrated advantageous performance characteristics when compared to quantum well lasers, such as generation of ultrashort pulses,[3] thermal stability,[4,5] and low jitter below 10 fs per cycle,[6,7] which make them suitable candidates for use as optical sources in optical communication systems.[8] However, outside the optimal parameter range, frequency combs generated by passively MLLs (PMLLs) exhibit large phase noise and do not meet jitter requirements, which makes them ineffective in high-speed applications and optical sampling. Therefore, utilization of QD-PMLLs in these applications requires the introduction of noise stabilization techniques.

An important consideration for the production of deployable sources is the device cleaving error. A typical variation of 5 μm in the device length results in a 200 MHz pulse repetition rate shift for a 40 GHz laser which poses a difficulty for clocked systems. The mode-locking frequency can also vary significantly with bias conditions and temperature.[9] Therefore, universal techniques allowing the tuning of the device repetition rate become essential to compensate these variations and match device repetition rate to the predefined frequency of the system.

This Letter provides an overview and experimental comparison of several techniques, allowing noise reduction and tuning of the device fundamental frequency, F_{rep}, in MLLs.

For the relevant comparison of stabilization techniques, all experimental investigations were performed on the same device at a fixed temperature and similar bias conditions. We used a monolithic two-section QD laser of 1 mm length ($F_{rep} = 39.5$ GHz). The active zone of the device consisted of 15 layers of InAs QDs emitting at 1.3 μm embedded in InGaAs quantum wells. The saturable absorber of 100 μm length was separated from the gain section by an etched 20 μm gap, giving an electrical isolation of $\sim$10 kΩ between the sections. The facet next to the absorber was coated for high reflectivity of 95%, the facet next to the gain section was as cleaved (R $\sim$ 32%). The laser was integrated into a module comprising a thermo-electric cooler, a single-mode fiber pigtail, and an impedance matched microwave port. The temperature was set at 21 °C, the device absorber section was reverse biased at -8.0 V, and the gain current was around 60 mA in all measurements. The laser output was characterized by optical and electrical spectrum analyzers (OSA and ESA, respectively) and an autocorrelator (AC).

The PMLL emitted pulses of 2.8 ps duration with optical spectrum width of 10 nm at -10 dB level. Figure 1 shows an optical spectrum (a), an autocorrelation trace (b), and a radio-frequency (RF) spectrum (c) of the laser when passively mode-locked. The autocorrelation traces were fitted well to a Gaussian (Figure 1(a), red).

The QD-MLL demonstrated significant phase noise with optical modal linewidth values in the range of 100 MHz and large integrated jitter of $\sim$9 ps (retrieved from single- sideband noise and integrated from 10 kHz to 1 GHz) when operating in a passive mode-locked regime.

The reduction of jitter and RF frequency tuning can be achieved by the electrical modulation of the absorber reverse bias, "hybrid" mode-locking (HML). Since the first demonstration of hybrid mode-locking in a 10 GHz QD-MLL, (Ref. 10) a significant reduction of the pulse jitter[11] and a repetition rate control within a 30 MHz tuning range[12] have been achieved.

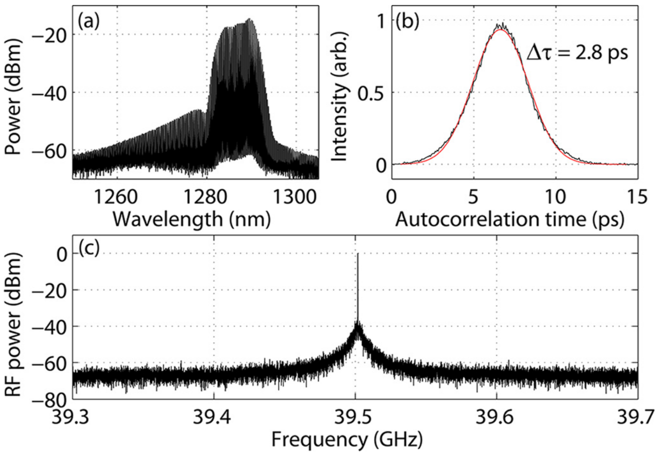

FIG. 1. (a) Optical spectrum, (b) autocorrelation trace (black) with Gaussian fit (red), (c) RF spectrum of the PMLL.

For hybrid mode-locking, the voltage applied to the device absorber section combined a DC component V and a 40 GHz low noise signal in the form of $V + A\mathrm{Cos}(\Omega t)$, where A and Ω are the amplitude and frequency of modulation of the reverse bias, respectively.

Hybrid mode-locking allowed tuning of the device repetition rate by changing Ω. The locking boundaries measured versus the modulation power for the chosen bias conditions are shown in Figure 2(a); the laser repetition rate followed the modulation frequency in the range shown in grey. We considered the laser as locked to the external modulation when the fundamental frequency of mode-locking followed the modulation frequency Ω with sideband suppression ratio of >30 dB. Similarly to the previously published results,[12] the laser exhibited an asymmetrical locking range, wider at frequencies lower than the passive mode-locking frequency. The maximum tuning range of ∼10 MHz was achieved at maximum applied modulation power of 14 dBm (3.2 V_{pp}). Synchronization to the external clock resulted in the RF linewidth narrowing to the values below resolution bandwidth of the ESA (1 kHz). The device integrated timing jitter decreased with V_{pp} down to a minimum value of 620 fs (Figure 2(b)).

Hybrid mode-locking did not significantly affect the optical spectrum and autocorrelation traces; they were close to those of the passive mode-locked regime and practically unchanged for all studied modulation amplitudes and frequencies with spectral widths of 10 nm at −10 dB level, and pulse width of 3.1 ps. The modal optical linewidths were also similar to the PMLL.

External optical injection has been shown to be an effective method for noise reduction in semiconductor MLLs. The combination of single-tone CW injection and active/hybrid mode-locking resulted in optical linewidth reduction below 20 kHz (Ref. 13) and phase locking of all slave modes to the master laser in QW devices.[14,15] Excited state pulse injection into a QD-PMLL oscillating in the ground state band demonstrated phase and amplitude noise reduction of the slave laser.[16] Stable injection-locking with no instabilities observed at zero detuning frequency has been demonstrated in QD single section and PMLLs.[17–19] These observations suggest that the noise characteristics of QD hybrid mode-locked lasers (HMLLs) could be further improved by optical injection seeding.

For CW injection, the light from a tunable laser (master laser) was injected through an optical fiber circulator into the gain section of the QD-HMLL (slave laser). A polarization controller was used to match the polarization of the injection seed and the slave. The master laser had a narrow optical linewidth of ∼200 kHz.

As shown in Figure 3(a), when the slave laser was locked to the master its optical spectrum was narrowed with the majority of the power red shifted from the injection wavelength, here 1288.44 nm. Optical spectrum narrowing led to pulse broadening: the autocorrelation traces in Figure 3(b) show Gaussian shape with deconvolved pulse width of 4.8 ps. The pulse train had a higher DC level than for the PMLL due to large injection power, but still well distinguished pulses.

We measured the common-mode optical linewidth of the slave using a self-heterodyne technique: the slave output was split in a 50/50 fiber coupler, one part of the signal was shifted by 80 MHz via an acousto-optic modulator and then recombined with the other part. A 10 km fiber spool was included to break the coherence between the laser outputs. We added a variable delay to adjust the pulse arrival time and a polarization controller to match polarization in both

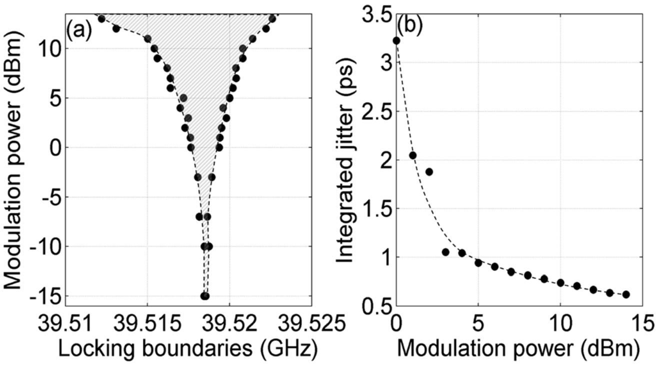

FIG. 2. (a) Measured boundaries of the F_{rep} tuning range versus modulation power. (b) Integrated timing jitter versus modulation power.

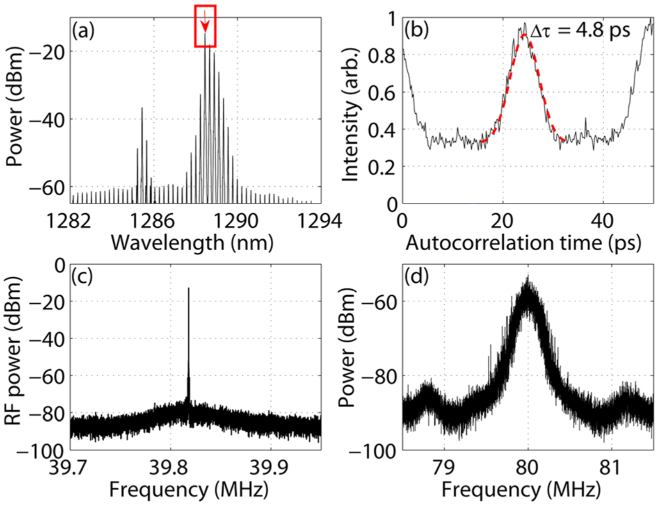

FIG. 3. (a) Optical spectrum of the injection-locked HMLL. Injection seed is shown with an arrow. (b) Autocorrelation trace. (c) RF spectrum. (d) Self-heterodyne beating signal. Injection power $P_{inj} = 770\,\mu W$; injection wavelength of 1288.44 nm, absorber bias modulation power of 14 dBm.

branches. For 14 dBm modulation amplitude, and injection power and wavelength of 770 μW and 1288.44 nm, the beating signal linewidth found from the Lorentzian fit was ~200 kHz, demonstrating complete optical linewidth reduction for the slave (Figure 3(d)). With injection seed, the integrated jitter was reduced by a factor of ~3, down to 240 fs. The example of the RF spectrum within the locking range boundaries is shown in Figure 3(c).

Due to the reduction of the slave spectral width, injection locking resulted in the increase of the F_{rep} tuning range when compared to the free-running HMLL, which is consistent with previously published theoretical results.[12]

Figure 4 shows RF spectra of the injected HMLL for a range of modulation frequencies, demonstrating the largest F_{rep} tuning range of 167 MHz. In the case of reduced modulation amplitude of 9 dBm while the injection settings are unchanged, the locking range decreased down to 40 MHz and the integrated jitter increased to a value of 365 fs. This shows that both the optical injection and HML have an influence on the laser emission (unlike the sidebands injection-locking of the PMLL discussed in the next paragraph, where the injection dominates within the locking range).

Injection-locking via two coherent lines, generated by modulation of a CW master source,[20] has been shown to be a successful technique to improve noise properties in 10 GHz QD-MLLs, resulting in improved control of the pulse repetition rate, wavelength tuning, all-modal linewidth reduction, and decrease of timing jitter, along with pulse stabilization and chirp reduction.[21,22] In this section, we discuss the outcomes of the sideband injection locking for the QD-PMLL under test and compare them with stabilization techniques discussed above.

For dual-tone injection, the light from a tunable laser was modulated by a Mach-Zehnder amplitude modulator biased at the transmission minimum and driven via a low-noise signal generator at $F_{rep}/2$, giving two coherent sidebands separated by F_{rep} with a suppressed carrier frequency. As before, the master emission was coupled to the gain section of the laser through a fibre-optic circulator.

Similar to the CW injection seeding, dual-tone injection resulted in the optical spectrum narrowing and red shifting and the pulse width broadening. Self-heterodyne measurements demonstrated narrow beating signal with ~135 kHz full width at half maximum, thus showing all-modal optical linewidth reduction for the slave. The injection power, P_{inj}, had a major influence on the slave characteristics. Two locking regimes were found, with wider and narrower spectral widths. Examples of optical spectra and corresponding autocorrelation traces for the two observed regimes are shown in Figure 5.

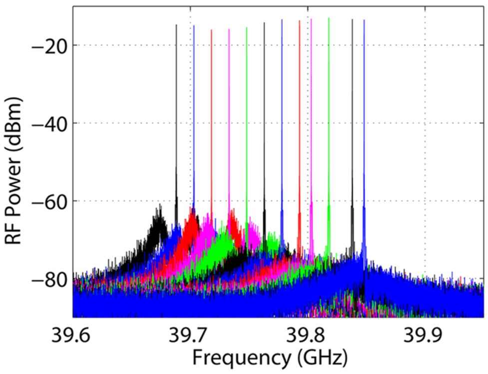

FIG. 4. RF spectra of the injection-locked QD-HMLL for a range of modulation frequencies.

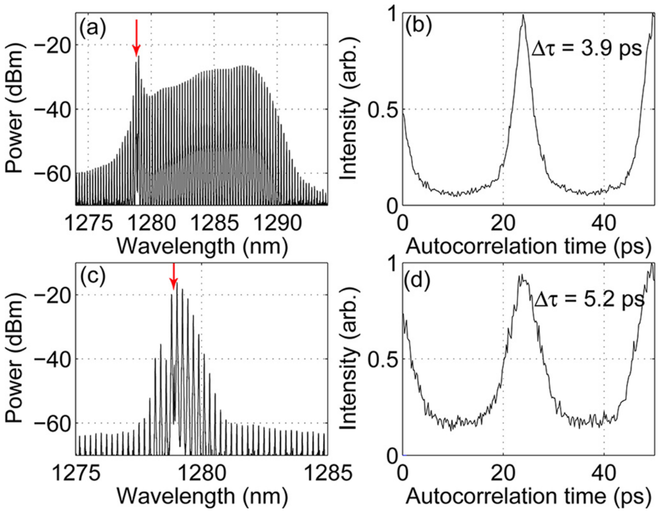

FIG. 5. (a) Optical spectrum and (b) autocorrelation trace of the PMLL with sidebands injection-locking; injection power $P_{inj} = 240\,\mu$W. (c) Optical spectrum and (d) autocorrelation trace of the PMLL with sidebands injection-locking; injection power $P_{inj} = 570\,\mu$W.

As expected, the regime with fewer modes allowed F_{rep} tuning in a larger range and resulted in a lower jitter.[12] For comparison, single sideband phase noise measurements in the range from 10 kHz to 1 GHz for the HMLL (black solid line), HMLL with injection seeding (red dashed line), and PMLL with dual-tone injection (blue dotted line) at their respective optimal operating point are shown in Figure 6(a). For dual-tone injection seeding, a strongly suppressed phase noise is observed over the entire frequency range of the carrier offset, resulting in a decisively reduced jitter of 121 fs. Figure 6(b) shows F_{rep} tuning range (red triangles) and timing jitter (black circles) of the sidebands injection-locked PMLL as a function of sideband injection power. For 570 μW, an integrated jitter of 121 fs along with a record F_{rep} tuning range of 342 MHz has been achieved. However, the spectral width reduction led to the pulse width broadening to a value of 5.2 ps (Figure 5(d)).

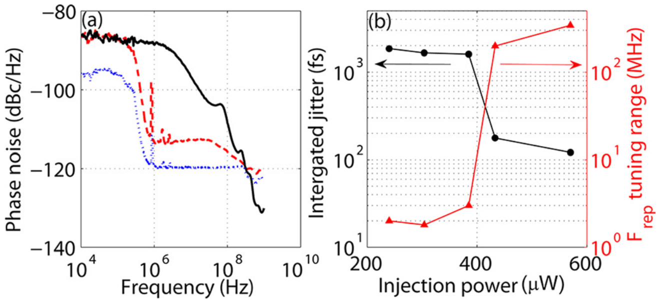

FIG. 6. (a) Single sideband phase noise in the range from 10 kHz to 1 GHz for the HMLL (black solid line), HMLL with injection seeding (red dashed line), and PMLL with dual-tone injection (blue dotted line). (b) F_{rep} tuning range (red triangles) and integrated jitter (black circles) of the PMLL with sidebands injection-locking.

Several techniques allowing repetition rate tuning and noise reduction in MLLs has been studied on the same device. Hybrid mode-locking resulted in jitter reduction to 620 fs and F_{rep} tuning range of 10 MHz for the chosen bias conditions. Hybrid mode-locking had no significant impact on the device optical spectrum and modal linewidth; autocorrelation traces were slightly broader (3.1 ps) when compared to the PMLL (2.8 ps).

Hybrid modulation with CW injection and dual-tone injection seeding of the PMLL had similar outcomes, resulting in linewidth narrowing for all laser modes, RF linewidth reduction below the resolution bandwidth of the ESA, and the optical spectrum narrowing and red shifting. An increase of the injection power resulted in a wider F_{rep} tuning range and lower jitter values due to reduction in the number of lasing modes. Hybrid modulation with injection resulted in the jitter of 240 fs and 167 MHz tuning range. The lowest integrated jitter of 121 fs and the widest F_{rep} tuning range of 342 MHz were achieved with dual-tone injection seeding.

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