IEEE Photonics Journal
An IEEE Photonics Society Publication

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Invited Paper

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Volume 6, Number 2, April 2014

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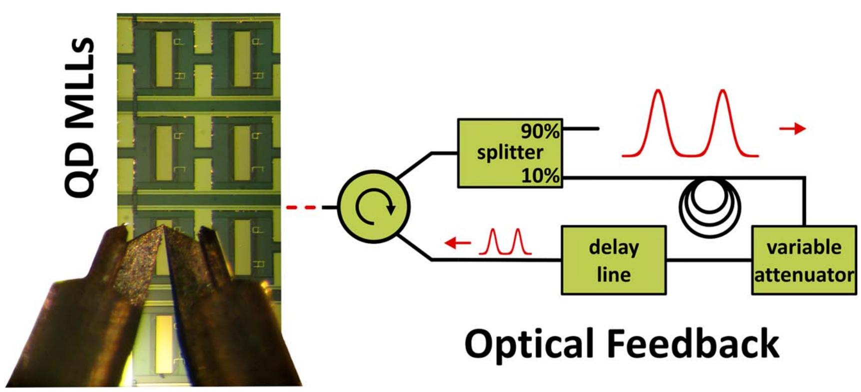

DOI: 10.1109/JPHOT.2014.2308195
1943-0655

Breakthroughs in Photonics 2013: Passive Mode-Locking of Quantum-Dot Lasers

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(Invited Paper)

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DOI: 10.1109/JPHOT.2014.2308195

Manuscript received February 10, 2014; accepted February 19, 2014. Date of publication February 25, 2014; date of current version April 30, 2014. This work was supported by the German Science Foundation (DFG) through the framework of the Collaborative Research Centre (SFB) 787.
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Abstract: Most recent achievements in passive mode-locking of quantum-dot lasers, with the main focus on jitter reduction and frequency tuning, are described. Different techniques, leading to record values for integrated jitter of 121 fs and a locking range of 342 MHz, are presented for a 40-GHz laser. Optical feedback is observed to be the method of choice in this field. For the first time, five different optical-feedback regimes are discovered, including the resonant one yielding a radio-frequency linewidth reduction by 99%.

Index Terms: Mode-locked lasers, quantum dots, phase noise, optical feedback.

1. Mode-Locking

Mode-locked lasers (MLLs) generating optical pulse combs at repetition rates ranging from single digit up to several tens of Gigahertz [1], [2] are of great interest for a variety of applications, such as photonic switching, optical interconnects [3], electro-optic sampling [4], but also for domains like material machining and optical coherence tomography [5]. Solid-state lasers, still having record values in terms of pulse width and peak power [6], have been used for some of these applications, but they suffer from their cost and complexity. Because of the small footprint, low production costs, absence of extensive cooling and direct electrical-to-optical conversion semiconductor lasers have become ideal candidates for such applications [7]. Especially in optical communication networks [8] semiconductor MLLs, enabling pulse generation at frequencies far beyond the intrinsic direct modulation limit, can be utilized as optical clocks or, in combination with modulators, as transmitters for optical time division multiplexing (OTDM).

Quantum-dots (QD) as gain media for MLLs feature decisive advantages compared to conventional gain media [e.g., quantum wells (QW)] [9]. The inhomogeneous broadening, typically for self-assembled Stranski-Krastanov growth, leads to a broad gain spectrum. Assisted by the fast recovery of QD absorbers in the order of 700 fs under large reverse bias conditions narrow pulses are generated [10]. The ultra-low threshold current and superior temperature stability of QD lasers represent a major breakthrough towards green photonics [11]. Low jitter is crucial for MLLs operating at high frequencies. Jitter originates mainly from random fluctuations of the photon density, the gain and the refractive index caused by amplified spontaneous emission (ASE). Therefore, a reduced ASE is directly improving the jitter. QD devices exhibit lower levels of ASE compared to QW based devices [12].

Mode-locking implies that the phase of individual longitudinal modes in a laser resonator is locked and pulsed emission, instead of continuous wave lasing, occurs [13]. The temporal delay between two consecutive pulses, termed the repetition rate or frequency of the MLL, is directly linked to the spacing of the longitudinal modes given by the resonator length. Therefore, the frequency, defined by the cavity length and the refractive index, is in principle not tunable.

Mode-locking in semiconductor lasers [14] can be realized by two different approaches: active and passive mode-locking. Active mode-locking is based on direct current modulation by an external electrical signal, whose frequency corresponds to the cavity length. At large frequencies external sources providing required frequencies and currents are not available. Furthermore, the modulation of carriers inside the laser diodes becomes inefficient due to parasitics. Passive mode-locking [15] overcomes the need for external sources and only direct current bias is used. In monolithic semiconductor lasers passive mode-locking is realized by utilizing a saturable absorber, e.g., a second electrically isolated section. The nonlinear absorption characteristic induces a pile-up of the photon density inside the cavity. However, the pulse combs of passively MLLs exhibit a jitter in the order of a few picoseconds, which does not meet requirements of high-speed applications or optical sampling. Therefore, the implementation of phase-noise and jitter reduction techniques is crucial. As mentioned above, the frequency of a passively MLL is given by the device length, which varies due to cleaving tolerances. Consideration of techniques allowing additionally the tuning of the repetition rate within a certain range is important as well.

Jitter reduction and frequency tuning are in the focus of this paper. After having summarized the major results achieved in 2013, we give some details on the achievements in QD MLLs under optical feedback made by us. Besides these two topics, accomplishments in the field of pulse characteristics, namely optical output power and pulse width, are reported in [16]–[18]. Injection-locking properties of passively MLLs operating as microwave sources are studied in [19].

2. Jitter Reduction and Frequency Tuning

A standard technique to reduce the jitter and define precisely the MLL frequency is hybrid mode-locking. In contrast to active mode-locking, the hybrid regime is based on the modulation of the absorber voltage at the desired frequency, which is much more efficient. For a 40 GHz QD MLL integrated jitter values down to 190 fs [20] (determined from single-sideband phase-noise measurements in the range from 10 kHz to 1 GHz) and frequency tuning up to 30 MHz are reported [21]. Nevertheless, an electrical signal source is still required, which is costly at high frequencies. The proof of concept of a promising approach, where the external electrical signal is operating at sub-harmonics of the repetition rate of the MLL, is reported by Ahripov *et al.* [22], but the grade of improvement strongly depends on the power of the electrical signal.

An opto-electronic feedback technique was introduced by Drzewietzki *et al.* to stabilize the pulse emission of a passively MLL [23]. The time-delayed MLL light was converted into an electrical signal by means of a photo diode, amplified to a power level of 32 dBm and then used to modulate the reverse bias of the absorber section. Thus, the MLL is operating in quasi self-hybrid configuration without an external oscillator. Compared to the free-running case the phase noise was reduced by 5 dB for all values up to a carrier offset frequency of 3 MHz.

Wide frequency tuning was reported by Cheng *et al.* for a 2 GHz passive QD MLL [24]. With a grating-coupled external cavity arrangement a repetition rate tuning from the fundamental frequency of 2 GHz down to a record low value of 79.3 MHz, having a radio-frequency (RF) linewidth of 25 Hz, was achieved.

Another possibility for phase-noise reduction and frequency tuning is optical injection. A RF-linewidth reduction below 1 kHz by injection of an external narrow-linewidth laser light was shown for a 10 GHz passively MLL [25]. Recently, this technique is employed with a 40 GHz hybrid MLL resulting in a jitter of 240 fs and a tuning range of 167 MHz [26]. For the same laser, but operating in passive regime, a dual-tone injection was performed. The light from an external narrow-linewidth laser is modulated by a Mach–Zehnder modulator at half the MLL repetition rate producing two coherent sidebands with suppressed carrier. Indeed, high power levels of the injected dual-tone signal led to a certain pulse width broadening. However, a record value for the frequency tuning range of 342 MHz and a strongly suppressed phase noise resulting in a decisively reduced jitter of 121 fs were observed [26].

3. Optical Feedback

As in the case of hybrid mode-locking, self-hybrid and optical injection techniques suffer from the same disadvantage since expensive and power consuming external devices are necessary. Optical self-feedback (OFB), where a part of the MLL light is injected back into the device, is used as a simple and effective way to reduce the jitter and to tune the repetition rate. Similar to what has been demonstrated decades ago for distributed-feedback lasers [27], OFB has been revisited, theoretically [28] and by measurements [29], as a powerful technique for phase-noise suppression in MLLs. For a 5.25 GHz QD MLL the RF-linewidth in the electrical spectrum was reduced from 46 kHz to 1.1 kHz [30], while for a 10 GHz single-section InP-based quantum-dash laser a reduction from 30 kHz to 200 Hz was achieved [31]. But OFB was also reported to degrade MLL pulses [32]. Thus, detailed experimental investigations of the impact of OFB parameters on the MLL emission are required. For the first time, five different regimes of the OFB were discovered, including a resonant one, where significant jitter reduction occurs [33]. Numerical modeling led to an understanding of this complex behavior.

The measurements were performed with a two-section QD MLLs emitting at a wavelength of 1.3 μm. The p-doped active region consists of 10 layers of InAs/GaAs QDs [34]. The overall length of the laser is 1 mm corresponding to a fundamental repetition rate of around 40 GHz. For the experimental setup 10% of the optical laser output are fed into the fiber based OFB loop which comprises an optical circulator, a variable attenuator, an optical delay line and a polarization controller. Thus, the OFB is completely defined by control of three parameters. The number of pulses or their round-trip time inside the loop is given by the overall length of the optical fiber. By tuning the optical delay line within an interval of 27.5 ps (the effects of OFB are periodic with the repetition period of the MLL) the relative position between originally emitted and injected pulses is adjusted. The feedback strength, with respect to the laser output power, was between 16 dB and 52 dB and is controlled by means of the attenuation. An electrical spectrum analyzer was used to determine the RF, the RF-peak power and phase-noise performance of the laser emission. Optical properties were derived from autocorrelation, frequency-resolved optical gating and optical spectrum measurements.

In Fig. 1(a) the RF-peak power as a function of feedback attenuation and delay for a 16.6 m fiber loop length is presented. Five different OFB-regimes are discovered. For each regime, Fig. 1(b) and (c) show representative single-sideband phase-noise and electrical spectrum traces, respectively. Regime 1, which is located below 20 dB, exhibits low peak power in the RF spectrum. The corresponding phase-noise trace is similar to the one without OFB and in consequence the width of the central line of the RF spectrum remains constant. Beyond the carrier offset frequency of 5 MHz regime 1 shows strong peaks. Their frequencies are multiples of 12.4 MHz, which corresponds to the round-trip time inside the feedback loop. Autocorrelation measurements of pulses in regime 1 yield a strong cw-background confirming disturbed mode-locking by the OFB. In regime 2 the MLL exhibits chaotic behavior and phase-noise traces could not be measured. In regime 3 the cw-background of the pulses and the sidebands in the RF spectrum are smaller than in regime 1, but the phase noise is still larger due to wider central line. The mode-locking is disturbed by the OFB as well. In regime 4 resonant optical feedback occurs. The peak power in the RF spectrum is increased by 10 dB, while the white noise plateau shifts from 80 kHz to 10 kHz and the thermal noise level is reached at 1 MHz. Compared to all other regimes, the sidebands and the phase noise are strongly suppressed as shown in Fig. 1(b) and (c), respectively. At the same time the pulses are not affected. In regime 5 weak influences of the OFB on pluses can be observed and the RF linewidth switches between one without OFB and larger widths. Thus for all practical purposes the MLL under OFB should operate in the regime 4. Additionally, in this regime a linear

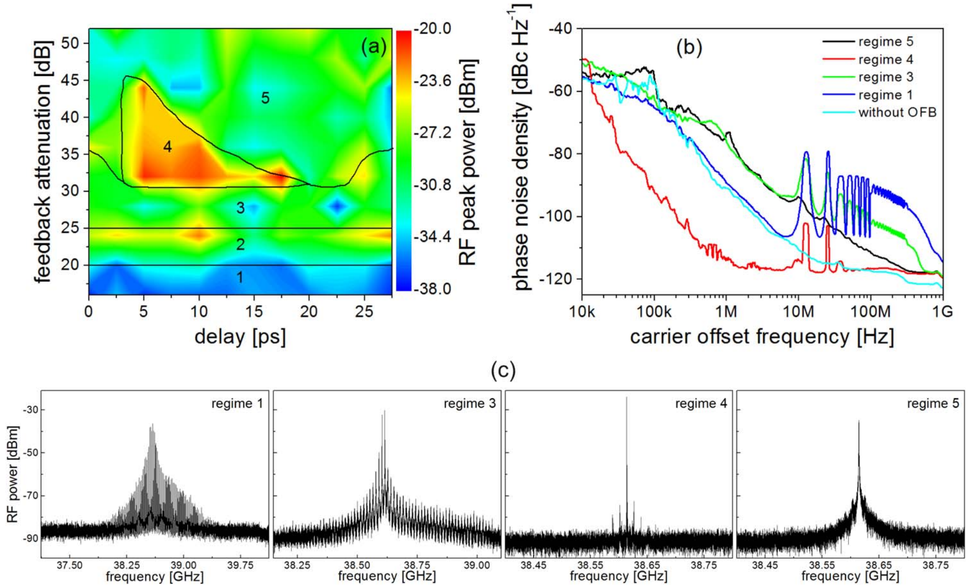

Fig. 1. (a) Color coded map of the RF-peak power as a function of OFB parameters: delay and feedback attenuation. For different OFB-regimes, (b) representative single-sideband phase-noise diagrams and (c) electrical spectrum traces are shown. The overall fiber length is 16.6 m.

dependence of the mode-locking frequency on the delay was observed, since only an integer number of pulses can propagate through the feedback loop. A frequency tuning within 7 MHz was achieved.

With the aim to extend the range of the resonant feedback the third OFB parameter, the overall fiber length, was changed. The optimal length is found to be 31.7 m. The regime 3 vanishes and the resonant regime stretches out over all delay values. At a feedback attenuation of 29 dB and a relative delay of 19 ps the 3-dB-linewidth and the integrated jitter are reduced from 187 kHz for the free-running MLL down to 1.9 kHz and from 3.8 ps down to 219 fs, respectively. The corresponding pulse-to-pulse jitter is found to be 23 fs.

We believe that OFB will be the method of choice for jitter reduction and frequency tuning, since the results are not restricted to the particular wavelength or frequency of the laser. Inexpensive low-noise multi-ten GHz laser modules can now find their way into systems.

4. Conclusion

In 2013, novel techniques for phase-noise reduction and frequency tuning of passively mode-locked quantum-dot lasers were studied as well as generation of microwave signals using such lasers. Record integrated jitter of 121 fs and locking range of 342 MHz are presented for a 40 GHz laser.

The influence of optical feedback on passive mode-locking is investigated in detail and five different regimes depending on three optical self-feedback parameters are discovered. The resonant regime is of practical interest and offers a cost-effective way to crucially reduce the jitter and to enable frequency tuning.

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