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Measurements of record-low residual jitter in 40-GHz monolithic mode-locked lasers

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Abstract: We have performed residual phase-noise measurements on 40-GHz mode-locked lasers. The intrinsic jitter of lasers with 1, 2 and 3 QWs is compared and a minimum of 39 fs is found for the 1-QW device.

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Mode-locked lasers are attractive components for pulse generation and all-optical clock-recovery in high-speed optical time-division multiplexed systems and for high-speed optical sampling systems; applications that put high demands on the timing stability. The requirements on stability, compactness and ease of integration, favour monolithic semiconductor devices over other types [1]. We have recently demonstrated all-active mode-locked lasers with ultra-low amplitude and timing jitter [2], but unfortunately our jitter measurement was limited by driving oscillator noise and the spectrum analyzer dynamic range. In this paper we describe how we have constructed a wideband residual phase-noise measurement set-up working at 40 GHz, which to our knowledge is the first of its kind at this frequency, and used it to measure the intrinsic timing jitter of our lasers.

While standard absolute phase noise measurements only measures the phase noise close to the carrier, the phase noise at large offsets, i.e. on a short timescale is in fact the most important for most optical signal processing. The slow part of the jitter can be tracked by a clock recovery circuit (CR), but the high-frequency jitter will always be present and may give detrimental performance in optical signal processing systems. Our measurement technique is based on the von der Linde method [3], but overcomes the drawbacks of oscillator noise and spectrum analyzer thermal noise, which reduces the important high frequency dynamic-range. Similar residual phase-noise measurements have been performed at lower repetition rates [4-7] such as 10 GHz or lower. However, when increasing the repetition rate the upper limit of integration scales with this rate and requires a very high bandwidth of the electronics. The present set-up uses waveguide components to cover the full Q-band (33 GHz – 50 GHz) and allows practical measurement to 10 GHz offset, which is enough to observe all the characteristic features of the spectrum and to extrapolate to the Nyquist frequency of 20 GHz. The distinction between slow and fast jitter, equivalent to the choice of lower integration limit, will depend on the bandwidth of the CR circuit and possibly also the path length difference between the CR signal and data stream, if optical signal processing is used.

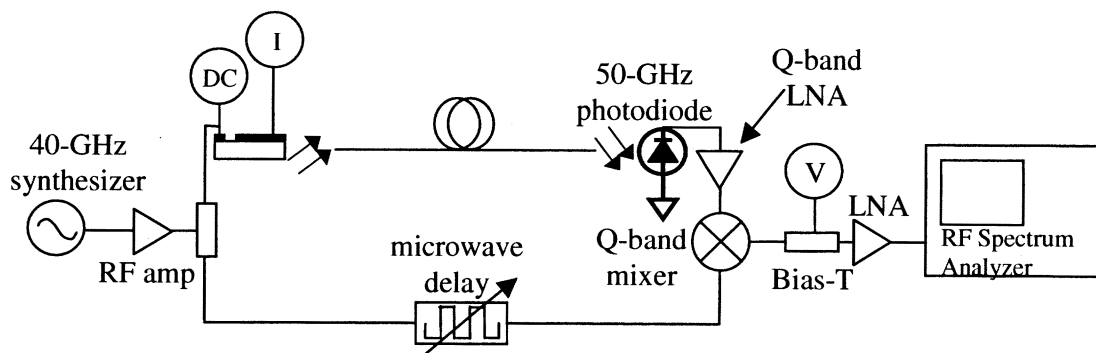


Fig. 1. Residual phase-noise measurement set-up operating at 40 GHz.

The device under test (DUT) is our laser, the optical fibre and the photo diode. The measurement system, figure 1, consists of an electrical delay line, a mixer and two low-noise amplifiers. The delay line is tuned so that the RF- and LO-signal to the mixer are in quadrature. Since the measurement only rejects oscillator phase-noise for frequencies $f \leq 1/4\Delta t$, where Δt is the path difference between the two

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arms, it is important to have both a quiet oscillator and a short fibre between laser and detector [8]. As a consequence, we make use of an Agilent E8247C synthesizer with “ultra-low phase-noise” option and a fibre length of 2 m. The RF-spectrum is measured with an Agilent LWA-system. The system was calibrated using 2 synthesizers and a calibration curve is added to all data points to correct for the transfer function of the system. The noise floor is measured with the DUT replaced with an equivalent microwave attenuator.

The design considerations for achieving ultra-low jitter performance in monolithic mode-locked lasers have been discussed in [2] and [9]. The measured devices are low loss ridge waveguide all-active FP-lasers, with 1, 2 or 3 QWs in the active layer, grown in one epitaxial step. The epitaxial material is InGaAsP on InP emitting at 1550 nm, see [2] for details. The synchronisation to an external clock is achieved by modulating the absorber section. All measurements have been performed at 20°C.

Just before the noise measurement, part of the signal is split off to measure the optical power, optical spectra and auto-correlation, see table 1. The operating points, also in table 1, are chosen from an optimisation of the RIN spectra and are not the same as in the earlier publication [2], but similar.

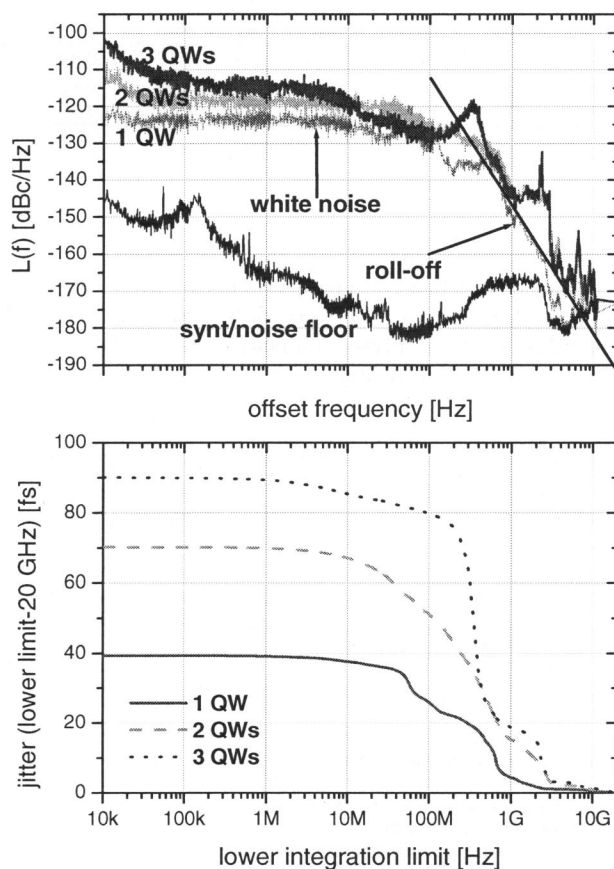


Fig. 2. Top: Residual phase-noise spectra of 1, 2 and 3 QW devices and Agilent E8257C synthesizer. Bottom: Integrated rms jitter from “the lower integration limit” to 20 GHz. All the devices have received the same RF-power, 26 dBm. The operating conditions are given in table 1.

The single-side-band phase-noise spectrum (SSB) in the top part of figure 2 is found from the measured double-side-band spectrum by subtracting 3 dB. The noise spectra have a characteristic white noise plateau, which is as low as -123dBc/Hz for the 1-QW device, showing good qualitative

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agreement with the theoretical predictions in [10], and quantitative agreement with the absolute phase noise measurements on the same devices in [2]. The “white” spontaneous emission noise is filtered by the cavity with a characteristic corner frequency and a 30-35 dB roll-off, which again qualitatively agree well with the theoretical results of [10] and with the experimental results in [4] and [6]. The lower graph of figure 2 shows the intrinsic laser jitter integrated from a variable lower limit to the Nyquist frequency of 20 GHz. The 1-QW device has a record low timing jitter of only 39 fs, measured in the full band from 10 kHz to 20 GHz offset. Since we are not able to measure the noise correctly after 10 GHz, we calculate an upper estimate of the jitter between 20 GHz and 10 GHz from the noise floor, which already have been reached. This can be safely done since the laser is fundamentally mode-locked and therefore no supermode noise is present. The extrapolated part of the noise-spectra has a minor impact on the overall jitter, contributing with less than 1.2 fs. In fact the two decades of the noise spectra around the corner frequency – approximately 100 MHz here – are the most important contributors to the overall jitter. The white noise plateau is reduced with a lower number of quantum wells. This agrees well with the prediction in [2]: the higher inversion and gain saturation energy of the gain medium results in less pulseshaping dynamics, which reduces the total loss and thus the amplified spontaneous emission noise level.

Table 1. Operating conditions and pulse properties of the devices investigated.

#QW	I_{gain} mA	V_{abs} V	P_{rf} dBm	f_{rep} GHz	λ μm	$\Delta\tau$ ps	$\Delta\lambda$ nm	$\Delta\tau\Delta\nu$	P_{out} mW
1	180	-3.3	26	39.62	1529	2.3	1.55	0.49	6.2
2	200	-3.8	26	39.53	1546	1.35	2.33	0.42	6.8
3	240	-3.7	26	39.50	1571	2.1	1.42	0.39	5.8

Summary

We have presented the first results of wideband residual phase-noise measurements on 40-GHz mode-locked lasers. The data show good agreement with theoretical predictions, and with similar earlier measurements at lower frequencies. We have measured a phase-noise plateau of -123 dBc/Hz and an intrinsic total integrated jitter of 39 fs for a 1-QW laser.

Acknowledgements

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