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**Larsson, David; Yvind, Kresten; Hvam, Jørn Marcher**

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# Wide-Band Residual Phase-Noise Measurements on 40-GHz Monolithic Mode-Locked Lasers

David Larsson, Kresten Yvind, and Jørn M. Hvam

*Abstract*—**We have performed wide-band residual phase-noise measurements on semiconductor 40-GHz mode-locked lasers by employing electrical waveguide components for the radio-frequency circuit. The intrinsic timing jitters of lasers with one, two, and three quantum wells (QW) are compared and our design prediction, concerning noise versus number of QWs, is for the first time corroborated by experiments. A minimum jitter of 44 fs is found, by extrapolating to the Nyquist frequency, for the one-QW device, having nearly transform-limited pulses of 1.2 ps. This jitter is nearly three times lower than for a three-QW laser. There is good agreement between the measured results and existing theory.**

*Index Terms*—**Jitter, mode-locked laser diode, optical communications.**

## I. INTRODUCTION

**M**ODE-LOCKED lasers are attractive as pulse sources and as components for all-optical signal regeneration and demultiplexing, in high-speed optical time-division multiplexed systems [1] and for high-speed optical sampling systems, applications that require excellent timing stability. The further requirements on stability, compactness, and ease of integration favor monolithic semiconductor devices over other types [2]. We have recently reported design principles for all-active mode-locked lasers with ultralow amplitude and timing jitter [3], but were unable to measure anything but a rough upper estimate of the jitter of the lasers: 400 fs in the integration range 10 kHz–20 GHz. Important figures of merit such as phase-noise plateau level and knee position [4] were not measurable. No distinction between different designs was possible. In this letter, we present a wide-band residual phase-noise measurement setup working at 40 GHz, and use it to measure the intrinsic timing jitter of our lasers. This is, to our knowledge, the first such demonstration at this frequency.

While standard measurements of absolute phase-noise only measure the phase-noise close to the carrier, the phase-noise at large frequency 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. We base our measurement technique on the von der Linde method [5], but overcome the drawbacks of oscillator noise and

finite dynamic range of the spectrum analyzer, which limit the phase-noise levels that can be measured with absolute phase-noise measurements. Oscillator noise is typically much higher than the intrinsic mode-locked laser noise at low frequencies (<1 MHz [3]) and will as such hide all inherent differences in different laser designs at these frequencies. By combining the total laser noise with the synthesizer noise in a mixer we are able to reject the synthesizer part up to a frequency given by the delay between the two arms. Spectrum analyzers usually exhibit poor noise figures (NFs) of 30 dB or higher, bringing the noise floor up to −125 dBc/Hz in the case of an HP8565E. By removing the carrier in a mixer and preamplifying the noise in low-noise amplifiers (LNAs), it is possible to lower the noise floor several decades and to reach the shot-noise limit. Residual phase-noise measurements similar to what we present here have been performed by others at a repetition rate of 10 GHz or lower [4], [6]–[8]. However, increasing the repetition rate, the maximum frequency offset scales accordingly and requires a very high bandwidth of the electronics at 40 GHz. The present setup takes advantage of commercial waveguide components to cover the full $Q$-band (33 GHz–50 GHz) and allows practical measurement up 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.

## II. EXPERIMENTAL SETUP

The device under test (DUT) is our laser and the optical fiber (the photodiode response (bandwidth > 50 GHz) has a slope of 0.08 dB/GHz and is considered flat). The measurement system (Fig. 1) consists of a tuneable electrical delay line, a double-balanced mixer, a bias-$T$, two LNAs, and a radio-frequency (RF) spectrum analyzer. The NF of the total system is dominated by the first amplifier, which has an NF of 5 dB and a gain of 24 dB, giving a theoretical thermal noise floor of −169 dBm/Hz. The phase-noise contribution from shot-noise in the photodiode is −168 dBm/Hz at an optical average input power of 4.5 dBm (2-mA dc-current). The photodiode, the first LNA, and the mixer have all been measured with respect to power saturation to define the linear regime and care is taken not to saturate the system by monitoring the dc-current of the photodiode. The delay line is tuned such that the signals from the photodetector and the local oscillator (LO) are in quadrature at the mixer, making the mixer an effective phase detector. The mixer diodes are highly balanced with respect to positive and negative voltages, with a peak difference of less than 10 mV, suggesting an optimal rejection of amplitude modulation noise at less than +5-mV intermediate-frequency dc output. Since the measurement only rejects oscillator phase-noise for frequencies $f \leq 1/4\Delta t$, where
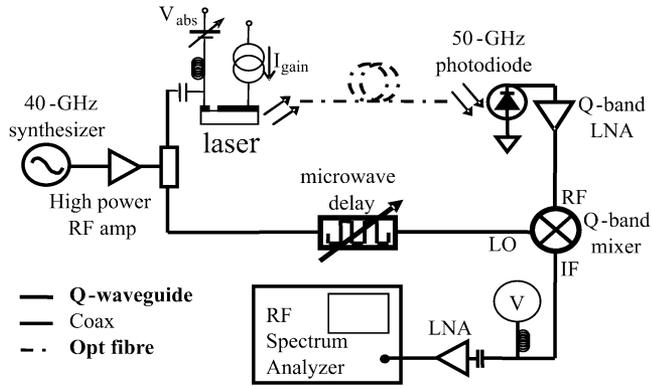
Fig. 1. Residual phase-noise measurement setup operating at 40 GHz. $V_{abs}$: absorber dc voltage. $I_{gain}$: gain current. RF: radio frequency (signal). IF: intermediate frequency. $V$: voltage meter. Only the mixer, first LNA, and the delay are waveguides ($<$10 cm in each arm).

$\Delta t$ is the path difference between the two arms, it is important to have both a quiet oscillator and a short fiber between laser and detector [9]. As a consequence, we make use of an Agilent E8247C synthesizer with "ultralow phase-noise" option and a fiber length of 2 m. To further reduce the electrical delay, we insert an electrical cable in the LO branch that matches the electrical cable to the laser. The RF-spectrum is measured with an HP71000 Spectrum Analyzer. The whole system was calibrated using two synthesizers (Beat Note Method [8]), and a calibration curve versus frequency 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. Each decade is measured with a resolution bandwidth of 1%–0.3% (depending on decade) of the span, and this effectively masks any coherent spikes that might be picked up in the measurement.

## III. LOW NOISE RESULTS

Theoretical and practical design considerations to achieve ultralow noise performance in monolithic mode-locked lasers have been discussed in [3] and [6] and reviewed in [10]. The measured devices are low-loss ridge-waveguide all-active Fabry–Pérot lasers, with one, two, or three quantum wells (QWs) in the active layer, grown in one epitaxial step [3]. The synchronization to an external clock is achieved by modulating the absorber section, the facet of which is high-reflection coated. The measurements on one- and two-QW lasers have been performed at 20 °C, while the measurements on the three-QW laser were performed at 18 °C to keep the wavelength inside the erbium-doped fiber amplifier range. Just before the noise measurement, part of the signal is split off to measure the optical power, optical spectrum and autocorrelation, (Table I).

The operating points, also in Table I, are chosen from an optimization of the relative intensity noise (RIN) (Fig. 2) and are similar to the operating conditions in the earlier publication [3]. The most sensitive parameter is the repetition rate (cavity detuning), which can be tuned approximately 200 MHz away from the optimum point without loosing the mode-locking. However, far from the optimum repetition frequency (but still within 200 MHz), the peak of the RIN can be as much as 20 dB

TABLE I
OPERATING CONDITIONS AND PULSE PROPERTIES OF THE
INVESTIGATED DEVICES

| #QW | $I_{gain}$ [mA] | $V_{abs}$ [V] | $P_{rf}$ [dBm] | $f_{rep}$ [GHz] | $\lambda$ [nm] | $\Delta\tau$ [ps] | $\Delta\lambda$ [nm] | $\Delta\tau\Delta\nu$ | $P_{fibre}$ [mW] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 191 | -2.7 | 26 | 39.78 | 1531 | 1.2 | 2.22 | 0.38 | 9.2 |
| 2 | 190 | -3.8 | 26 | 39.58 | 1547 | 1.1 | 3.62 | 0.51 | 8.7 |
| 3 | 240 | -4.0 | 26 | 39.53 | 1562 | 1.4 | 3.55 | 0.61 | 9.0 |

$P_{rf}$: modulation power (No 50-$\Omega$ matching, $\sim$28% is absorbed). Both temporal and spectral widths are given by fits to a hyperbolic secant. The one-QW spectrum exhibits an extended tail on the short-wavelength side of the peak.
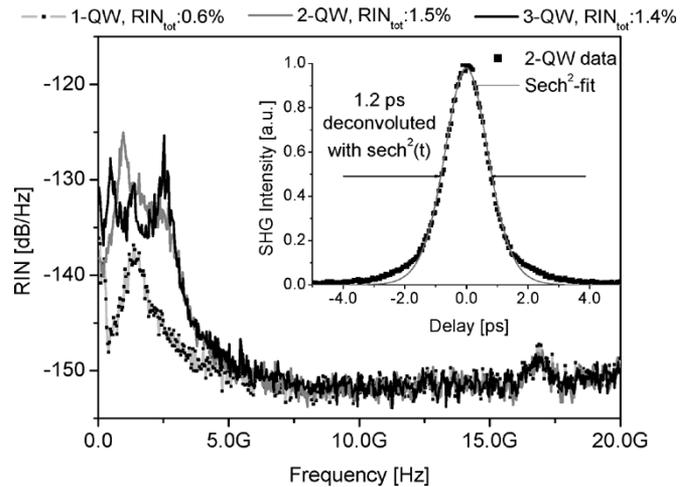


Fig. 2. RIN spectra for one-, two-, and three-QW lasers. RIN is limited to $-153$ dB/Hz by shot noise. Inset: Autocorrelation trace from a two-QW laser after a dispersion of 0.63 ps/nm and its Sech$^2$-fit. The small broadening of the pulse foot is typical for the compressed pulses and is believed to originate from small nonlinear chirp in the wings of the pulse.

higher than at the optimum. The pulsewidths $\Delta\tau$ in Table I have been measured with a fiber span and a fiber amplifier equivalent to a total dispersion of 0.63 ps/nm. The inset of Fig. 2 presents an example of the obtained autocorrelation traces for a two-QW laser.

The single-sideband phase-noise spectra in Fig. 3(a) are found from the measured double-sideband spectra by subtracting 3 dB. The noise below 30 kHz is dominated by Flicker noise, arising from noise in the dc-current supply. The noise spectra have a characteristic white noise plateau, which is as low as $-122$ dBc/Hz for the one-QW device, showing good agreement with theoretical predictions [11], and with the absolute phase-noise measurements on the same devices [3]. The "white" spontaneous emission noise is filtered by the cavity with a characteristic corner frequency ($f_c \sim 100$ MHz) and a 25-dB/decade rolloff, which again agree well with theoretical results for a slightly detuned cavity [11], and with experimental results at lower pulse repetition rates [4], [6]. The white noise plateau is reduced with a lower number of QWs. This corroborates our earlier prediction [3]: The higher inversion and gain saturation energy of the gain medium results in less pulse-shaping dynamics, which reduces the total loss and, thus, the amplified spontaneous emission noise level. The effect is
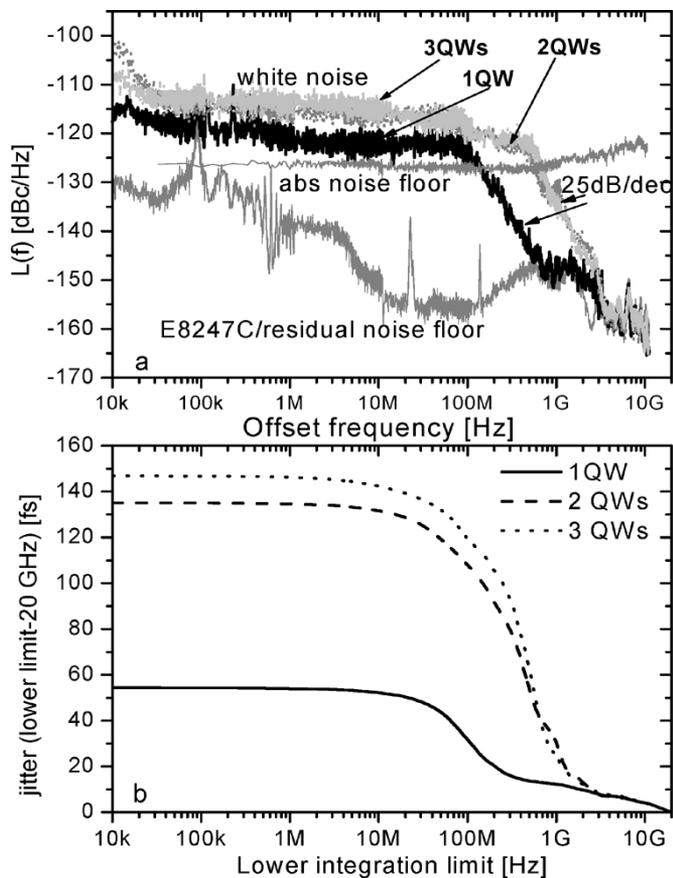
Fig. 3. (a)Residual phase-noise spectra of one-, two-, and three-QW devices and Agilent E8247C synthesizer. The noise floor of an absolute phase-noise measurement [3] is added as reference. The estimated accuracy is ±1.5 dB. (b) Integrated root-mean-square jitter from "the lower integration limit" to 20 GHz, using the noise floor to 20 GHz. The operating conditions are given in Table I.

especially pronounced between the one- and two-QW designs, reflecting the fact that the calculated saturation energy is much higher for the former. The high-frequency noise of the two- and three-QW lasers are significantly higher than that for the one-QW laser due to the presence of relaxation-oscillation type peaks present in the range 700 MHz–2.5 GHz, which are not possible to suppress further by optimising the operating conditions. These peaks are also present in the RIN spectra, indicating a coupling between amplitude noise and phase-noise in the laser due to a finite alpha-factor and finite recovery times of the gain medium.

The lower graph of Fig. 3 shows the intrinsic laser jitter integrated from a variable lower limit to the Nyquist frequency of 20 GHz. This is a measure of the effective jitter the way it would appear if it were compared to a perfect clock on a short timescale equivalent to the frequency offset. As an example, if a wide-band clock-recovery circuit, say 100 MHz, is used in the detection of a signal based on the one-QW laser, the effective

jitter of the laser is approximately 30 fs. Since we are not able to measure the noise correctly after we meet the noise-floor, we can either calculate an upper estimate of the jitter between 20 and 10 GHz from the noise floor (which already has been reached), or assume that the rolloff continues as predicted from theory [11]. The latter can be safely done since the laser is fundamentally mode-locked and, therefore, no supermode noise is present. Measured in the full band from 10-kHz to 20-GHz offset, the one-QW device has a record low timing jitter of only 54 fs if integrating the noise-floor [Fig. 3(b)] and as low as 44 fs if assuming a continuing rolloff.

In conclusion, we have presented the first wide-band residual phase-noise measurements on 40-GHz mode-locked lasers. We have experimentally corroborated the coupling between gain saturation energy (number of QWs) and low noise. We have measured a phase-noise plateau of −122 dBc/Hz and an upper limit for the total integrated jitter of 54 fs for a one-QW laser.

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