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Low-Jitter and High-Power 40-GHz All-Active Mode-Locked Lasers

Kresten Yvind, David Larsson, Lotte J. Christiansen, Casper Angelo, Leif K. Oxenløwe, Jesper Mørk, Dan Birkedal, Jørn M. Hvam, and Jesper Hanberg

***Abstract*—A novel design strategy for the epitaxial structure of monolithic mode-locked semiconductor lasers is presented. Using an all-active design, we fabricate 40-GHz lasers generating 2.8-ps almost chirp-free pulses with record low high-frequency jitter and more than 7-mW fiber coupled output power.**

***Index Terms*—Laser noise, mode-locked lasers (MLLs), semiconductor lasers, semiconductor optical pulse amplifiers.**

I. Introduction

Monolithic semiconductor mode-locked lasers (MLLs) are attractive candidates for generating short optical pulses at high repetition rate due to their good performance, small size, inherent robustness, and the possibility of integration with other semiconductor elements [1], [2]. Applications include optical time-division-multiplexed communication systems and optical signal processing.

Important design goals are to achieve short and unchirped pulses with low pulse-to-pulse (high-frequency) jitter. We present novel design principles for realizing this in a monolithic structure, thereby enabling further integration.

II. Low-Jitter Design

The high-frequency jitter is the intrinsic jitter of the laser. It originates from spontaneous emission and carrier noise and can be reduced in a number of ways [3], among these, increasing the inversion of the gain medium, lowering the roundtrip loss, and increasing the pulse energy. For long all-active lasers, a large part of the loss is due to the pulseshaping dynamics [4]. The pulse is broadened in the gain section due to gain saturation and this broadening can be counteracted using strong pulse shaping in the absorber section such that the laser still emits short pulses. Besides excess chirping due to self-phase modulation in the gain section, such an approach also introduces extra loss compared to a cavity where less pulse shaping is done and the gain, therefore, also has to be increased. This leads to an increased spontaneous emission level that in turn results in more jitter. An important design criterion for the MLL is, therefore, to achieve a low loss during mode-locking. Also, the circulating pulse should be strong such that added spontaneous emission photons do not perturb the pulse significantly. External modulation of the absorber section will also improve the jitter due to the retiming action. However, this will not decrease the pulse-to-pulse jitter when the width of the pulses becomes significantly shorter than the envelope of the modulation. In addition, the modulation will introduce extra loss and, thereby, increase the spontaneous emission noise.

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K. Yvind, D. Larsson, L. J. Christiansen, C. Angelo, L. K. Oxenløwe, J. Mørk, D. Birkedal, and J. M. Hvam are with the COM Center, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark (e-mail: ky@com.dtu.dk).

J. Hanberg is with GiGA,-an Intel Company, 2720 Skovlunde, Denmark (e-mail: jesper.hanberg@intel.com).

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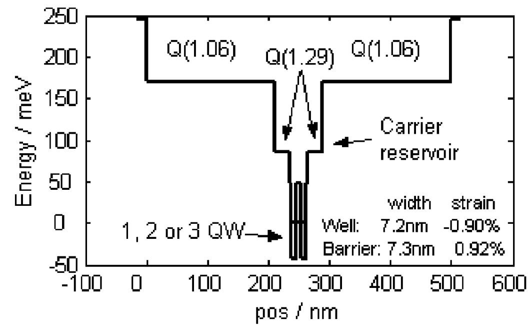

Fig. 1. Conduction band schematics of proposed structures. $Q(\lambda)$ is lattice-matched In–Ga–As–P with bandgap λ μm.

The devices presented in this letter are fabricated using a single epitaxial growth step and the synchronization to an external clock is achieved by modulating the absorber section. The function of the gain section is, therefore, simply to amplify the pulse with a minimum of pulse broadening. Since high optical power will help minimize the jitter, this corresponds to a requirement of large saturation energy of the gain section, i.e., low differential gain.

The active region of the lasers is shown in Fig. 1. In order to aid the discussion of the design principles, simple gain calculations (assuming parabolic bands and no homogeneous broadening) for one, two, and three quantum wells (QWs) are shown in Fig. 2.

The gain curves of Fig. 2 illustrate that the differential gain increases if the gain coefficient is lowered. Given that the gain in a laser to a first approximation is given by the total cavity loss, this means that if the gain section is made longer the saturation energy of the medium will be lowered and additional pulse broadening and self-phase modulation will arise. On the other hand, if the gain section is made very short, the required gain coefficient will be large and the gain is saturated due to bandfilling of the QWs such that the differential gain is lowered. For monolithic lasers, the length of the laser is fixed by the required repetition rate, implying that regrowth or other processing technology must be used to make a short gain section [1], [2].

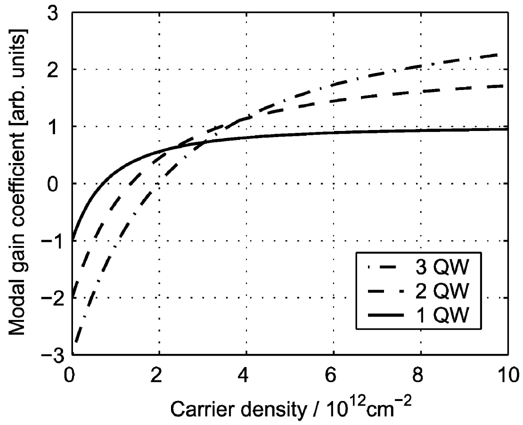

Fig. 2. "Modal gain coefficient" as function of carrier density for the structures in Fig. 1.

We have chosen to increase the gain saturation energy by simply using fewer QWs. This lowers the differential modal gain by lowering the confinement factor and, equally important, the inversion of the QWs is increased since fewer wells have to deliver the same gain (cf. Fig. 2).

The waveguide loss is kept low by using thick undoped quaternary layers and graded p-doping. However, this also tends to inhibit fast carrier transport from the contacts and a "carrier reservoir" is, therefore, used to ensure that a sufficient number of carriers are available for the amplification in the gain section. The steps in the band structure also aid carrier escape in the absorber.

The laser chips are ridge waveguide structures with a 2-μm -wide ridge formed by combined dry and wet etching, using Cyclotene (TM) 3022-35 planarization, thinning to 100 μm and standard Ti–Pt–Au p-contact and Ni–Ge–Au n-contact metallization. The contacts are separated with a wet etch through the highly doped contact layer, giving an isolation of >1 kΩ. The epitaxial material is metal–organic chemical vapor deposition-grown InGaAsP on InP (cf. Fig. 1).

The chips are cleaved to a length of $\sim$1070 μm, soldered junction side up to an AlN microwave substrate and the absorber section is bonded to a coplanar transmission line that is contacted with a high-frequency probe for hybrid mode-locking. No 50-Ω termination was employed and all measurements are performed at 20 °C. After mounting, a three-period SiO_2–Si high-reflection coating was applied to the absorber facet.

Fig. 3 shows the light–current (L–I) characteristics under uniform injection into both absorber and gain section. A high output power of more than 20 mW and thresholds of 7, 8, and 10 mA for one, two, and three QWs, respectively, are achieved.

III. Mode-Locking Results

When passively mode-locked by applying 3–4-V reverse bias to the absorber section, the lasers generate 3–4-ps pulses. The threshold gain current is only increased by a few milliamperes, compared to the case of a forward biased absorber section, showing the gentle reshaping and low roundtrip loss in the device, resulting in a low amplified spontaneous emission level.

The laser output was collected using a lensed isolator with $\sim$3-dB coupling loss. An HP8565E electrical spectrum

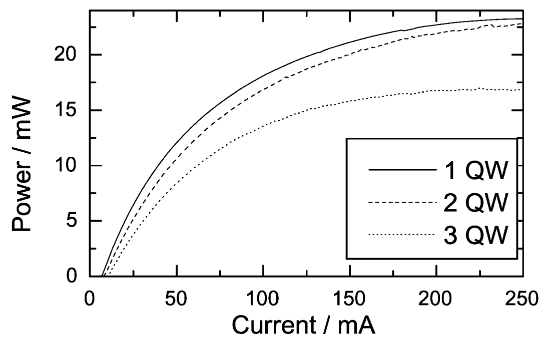

Fig. 3. Measured L–I characteristics for devices with one, two, and three QWs, showing high output power and low thresholds.

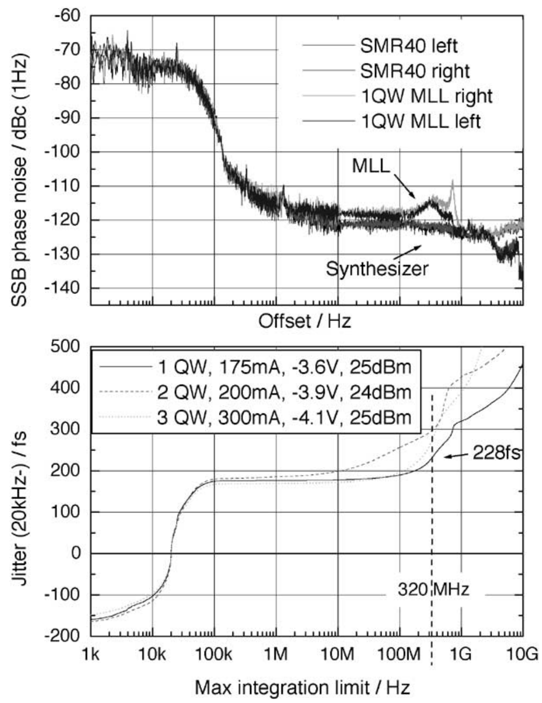

Fig. 4. Top: SSB phase noise spectra of one-QW 39.63-GHz MLL and Rohde&Schwarts SMR40 synthesizer. Bottom: Integrated jitter from 20 kHz to the displayed upper integration limit. Jitter values obtained for upper integration limits lower than 20 kHz are indicated as negative, and jitter from different integration ranges should be added as squares.

analyzer with a 50-GHz photodiode was used to measure the single-sideband (SSB) phase noise on the 40-GHz carrier (see Fig. 4) and integration of the noise power was used to extract the timing jitter. When the laser is to be used as a transmitter in a communication system, where clock recovery is performed in the receiver, the timing jitter on a very long timescale will not matter as this will be trivially tracked by the clock-recovery circuit. ITU-T specifies the measurement filters to be 20 kHz to 320 MHz for 40-GHz sources with special emphasis on the high frequency part [5]. Ideally, one should evaluate the phase noise all the way to the Nyquist frequency, but for the present measurement, we are limited in dynamic range. While it is possible to trade low-frequency jitter for high-frequency jitter and amplitude noise using harmonic mode-locking [6], the present lasers are fundamentally mode-locked and we, therefore, expect the noise to fall off at large offsets [7].

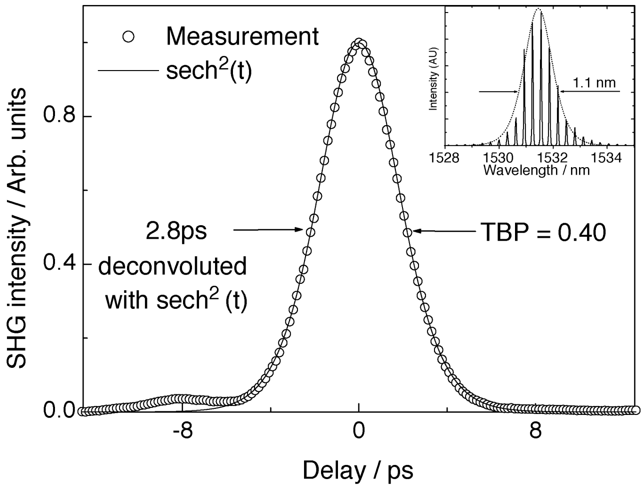

Fig. 5. Pulse autocorrelation and spectrum for one-QW device corresponding to the conditions shown in Fig. 4.

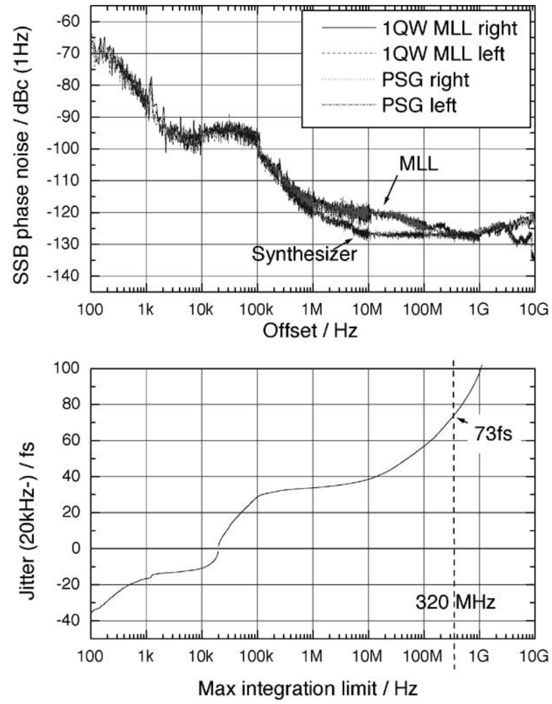

Fig. 6. Jitter for one-QW device using low-noise synthesizer. $I_{\rm gain} = 175$ mA, $V_{\rm abs} = -2.77$ V, $P_{\rm RF} = 25$ dBm, $f_{\rm rep} = 39.77$ GHz. No (additional) correction has been applied to SSB data close to the noise floor of the spectrum analyzer.

TABLE I
SUMMARY OF THREE DEVICES ($L_{\rm ABS}$= LENGTH OF ABSORBER)

# QW	L_{abs} μm	f, GHz	Δτ, ps	Δτ Δν	λ nm	P_{out} mW
1	60	39.63	2.8	0.40	1531	7.2
2	55	39.46	4.5	0.39	1556	9.0
3	50	39.49	4.9	0.66	1574	

The operating conditions for the lasers are given in the legend of the lower graph in Fig. 4 and were chosen to give an optimum suppression of the relaxation oscillation peak while keeping short pulses. The curves detail the influence of the upper integration limit for the jitter and it is seen that the jitter for all of the devices is very low, mainly determined by the synthesizer. The $\mathrm{RIN}_{\rm system}$ (100 kHz–3 GHz), measured on an HP70000 system, was about -154 dB/Hz, i.e., at the measurement limit for a 3-dBm input.

The autocorrelation and optical spectrum, depicted in Fig. 5 for the one-QW device, demonstrate that a short, almost transform-limited pulse, is obtained. Results for the other lasers are summarized in Table I and it is apparent that lowering the number of QWs results in shorter and less chirped pulses, in agreement with the predictions. The fiber-coupled output power is record high for all the lasers.

While the phase noise values of Fig. 4 are record low, there is still a large contribution from the driver noise at low offsets and persisting even up to about 1 GHz, as can be seen in Fig. 6, where an Agilent PSG8247C synthesizer with "ultralow phase noise" option is used to drive a one-QW laser.

The jitter in Fig. 6 is as low as 73 fs and this includes a large contribution from the synthesizer at low offsets and from the measurement noise floor at high offsets. The pulsewidth for this measurement was 2.5 ps but the time-bandwidth product was 0.6 and a large amount of excess spectral components on the short wavelength side was present in the optical spectrum. Intracavity spectral filtering can be used to further lower the jitter [3], [7] and decrease the time-bandwidth product toward the transform limit, and improved jitter measurement methods are also expected to lower the measured values [6], [7].

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