MONOLITHICALLY INTEGRATED OPTICAL PULSE SOURCES FOR ULTRA-HIGH SPEED APPLICATIONS

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Abstract: Hybrid mode locked monolithic GaInAsP/InP wavelength tunable 40 GHz lasers have been developed for different high speed applications. Very short optical pulses (1.5 – 2 ps) with low amplitude noise (1 - 2 %) and low timing jitter (85 fs) are achieved by the presented pulse source modules.

Introduction

Mode locked lasers as optical pulse sources have been designed for a number of applications, such as: 1) ultra-high bit rate optical telecom systems (> 40 Gbit/s) utilizing Optical Time Division Multiplexing (OTDM) transmission techniques [e.g.1], 2) optical signal processing, 3) radio over fiber communication systems, and 4) ultrahigh speed measurement equipment.

Monolithically integrated mode-locked 40 GHz semiconductor lasers based on GaInAsP/InP are particularly competitive due to their compactness, easy handling, robustness, and cost [2-5]. Their compactness has already been demonstrated by fiber pigtailed modules (Fig. 1), which are suitable to be implemented into conventional line-cards of telecommunication or measurement systems.

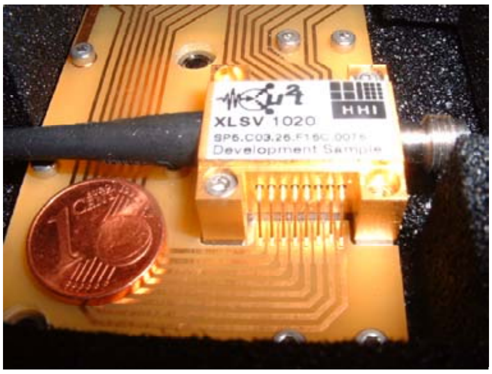

Fig. 1 Photograph of a fiber pigtailed 40 GHz pulse source module [6], containing a monolithic mode-locked laser. Left is shown the fiber pigtail and right the connector for radio frequency trigger.

However, a fundamental challenge for developing monolithically integrated semiconductor mode-locked lasers is to achieve both, low fabrication cost and performance characteristics, which meet all specifications given by system vendors, e.g. pulse widths below 2 ps, timing jitter lower than 300 fs, and amplitude noise below 3 % are required for the application in OTDM systems at bit rates up to 160 Gbit/s.

In this contribution, monolithically integrated 40 GHz mode-locked GaInAsP/InP Multi-Quantum Well (MQW) Distributed Bragg Reflector (DBR) lasers are presented which meet fundamental system specifications for OTDM application simultaneously.

Laser Design and Fabrication

The pulse source is a wavelength tunable multi-section mode locked laser, fabricated as a semi-insulating planar buried heterostructure in an extended cavity configuration. The integrated active and passive laser waveguide consist of a strained MQW and GaInAsP bulk material, respectively.

Both waveguides are butt coupled by utilizing selective area metal organic vapor phase epitaxy. The active MQW waveguide region integrates a gain section and saturable absorber (SA). The extended bulk cavity consists of three tunable phase sections for additional repetition rate fine tuning, and a DBR grating in order to meet predetermined wavelength allocations (cf. Fig. 2). The Bragg wavelength was chosen to be 1555 nm and it can be tuned about 5 nm by current injection. The total cavity length of the 40 GHz device is 1080 µm, resulting in repetition rates between 39.6 GHz and 39.9 GHz dependent on the applied bias.

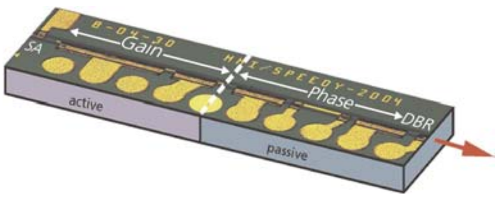

Fig. 2 Microphotograph of a monolithic mode-locked 40 GHz laser [5] with SA: Saturable absorber, Gain: gain section, Phase: two pn-junctions and one heater stripe, DBR: Distributed Bragg Reflector.

The facet at the DBR section (= laser output port) is anti-reflection coated while the absorber facet remains as cleaved.

The devices have been packaged into robust fiber pigtailed modules (cf. Fig. 1). The modules have been equipped with impedance matching circuits [4, 6] in order to keep the driving power of the external trigger as low as possible (12 dBm).

Laser Characteristics

The performance of the lasers has been investigated under hybrid mode locking conditions. For that the reverse voltage onto the SA section was modulated with an external radio frequency (RF). The RF was matched to the internal laser round trip frequency of the laser (39.813 GHz).

Mode locking could typically be achieved for gain currents in the range from 50 mA to 200 mA and reverse

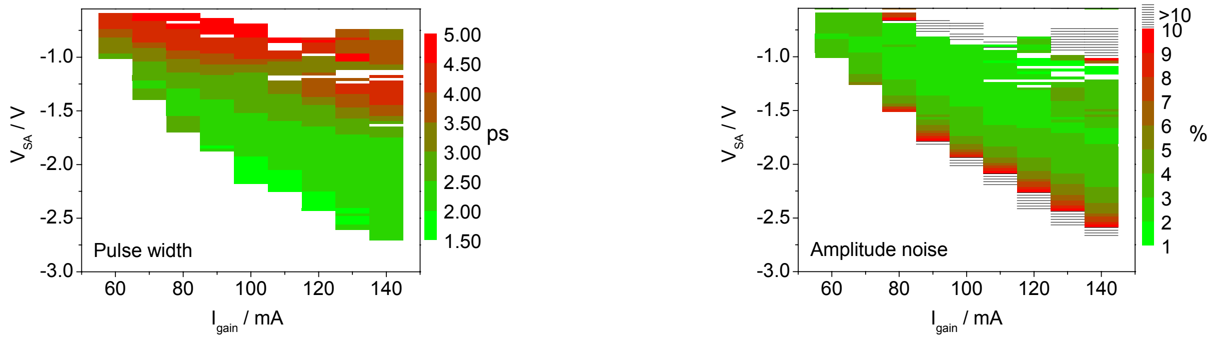

Fig. 3: Pulse width (left) and amplitude noise (right) vs. tuning of gain current (I_{gain}) and absorber voltage (V_{SA}) representing mode-locking operation area.

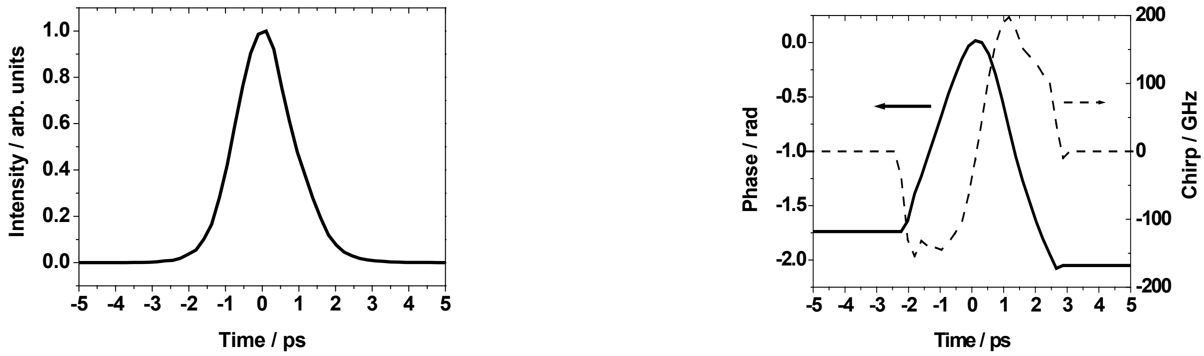

Fig. 4: Retrieved pulse shape (left), with a pulse width of 1.8 ps and the responsible optical phase and chirp (right).

absorber voltages between 0.5 V and 4 V. Within so-called mode locking areas the average fiber-coupled power was found to be 0.5 to 1 mW. Typical mode locking areas are shown in Fig. 3, and the graphics present pulse width (left) and amplitude noise (right), respectively vs. gain current and absorber voltage. As shown in Fig. 3 (left), the shortest pulses can be achieved for bias conditions along the lower borderline of the colored mode locking area. Under these conditions pulse lengths in the range from 1.5 to 2.5 ps are emitted. The pulse widths were detected using the frequency resolved optical gating (FROG) technique, allowing also the determination of the chirp and the pulse shape after data retrieval from autocorrelation intensity and wavelength vs. time [7]. A typical pulse with a length of 1.8 ps is shown in Fig. 4 (left). The retrieved pulse is almost symmetric and has nearly a $sech^2$ shape. On the right hand side of Fig. 4 the retrieved phase and chirp of the same pulse are shown. The pulses are characterized by a nearly linear up chirp (around 200 GHz within the FWHM of the pulse) which could be completely compensated by implementing an adapted length of single mode fiber (SMF). Without compensation, the time bandwidth product was found to be 0.45.

The control of amplitude noise is a challenge for designing semiconductor mode locked lasers with short cavities. As depicted in Fig. 3 (right) amplitude noise is rather high. It was determined to be in the range from 1 % to more than 10 %. Moreover, Fig. 3 points out, that there is a trade-off between pulse width and amplitude noise: if bias conditions are chosen in order to achieve short pulses, the amplitude noise increases to high levels, and vice versa. This trade-off gets clear in Fig. 5, showing the amplitude noise versus pulse width for lasers containing 3 or 6 QW.

High amplitude noise is due the so called Q-switched mode locking (QML) [e.g. 8-10]. The SA section, which is needed for passive or hybrid mode locking, induces QML. Substantial suppression of QML has been achieved in hybrid solid-state lasers by separately optimizing the saturation behavior of the SA, the so-called semiconductor saturable

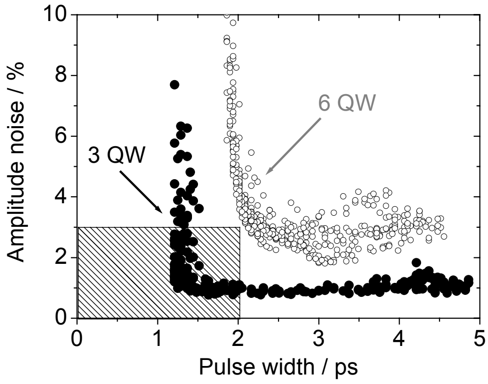

Fig. 5: Amplitude noise (AN) vs. pulse width for 3-QW- and 6-QW mode locked laser.

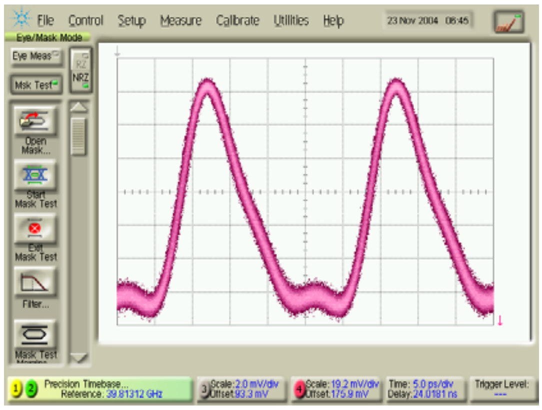

Fig. 6: Pulse trace of a 3-QW laser with low amplitude noise of 1.2 % and low pulse with of 1.5 ps.

absorber mirrors (SESAM) [8, 9]. This solution can not properly transferred to monolithic lasers, because the layers of the gain and the SA are identical. For suppressing the QML in monolithic lasers, the saturation energy of the gain sections has to be controlled to become maximum. This can be achieved by using low QW numbers in the active material [5].

Fig. 5 represents the correlation of QW number and amplitude noise. Whereas the 6-QW laser fails to meet the specifications for 160 Gb/s application due to high noise, the 3-QW laser generates pulses having widths below 2 ps and amplitude noise lower than 3 % simultaneously (shown by the shadowed box in Fig. 5). The low noise pulse emission was proven also in time domain. In Fig. 6 is shown a pulse trace with pulse length of 1.5 ps and an amplitude noise of only 1.2 %.

The timing jitter of the pulses was derived from single side-band (SSB) phase noise measurements. A typical SSB phase noise spectrum of the laser emission is plotted in Fig. 7 together with the phase noise curve for the 40 GHz RF source which drove the monolithic mode locked laser. The SSB phase noise of the laser followed the RF source up to a frequency offset of 2 MHz from the carrier. The calculated timing jitter (integration from 100 Hz to 10 MHz) was found to be 85 fs, which was slightly higher than the timing jitter of the RF source (76 fs).

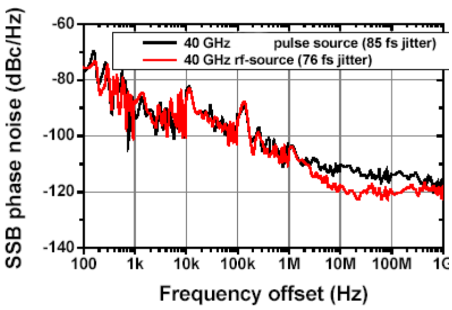

Fig. 7: Single side-band phase noise of the mode locked laser and the RF source.

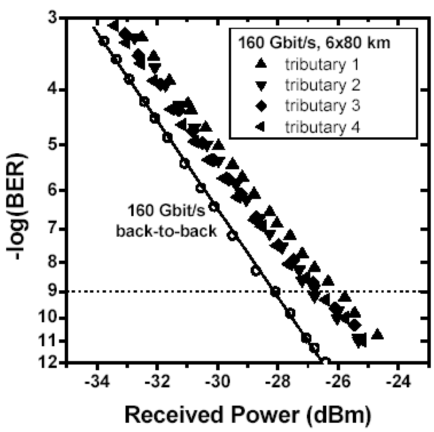

Fig. 8: Bit error measurements back-to-back and after the 480 km transmission.

160 Gbit/s RZ-DPSK Transmission Experiments

The modules were tested as pulse source in a 160 Gbit/s RZ-DPSK transmission experiment [11]. The RZ-DPSK transmitter comprised the mode locked laser pulse source module, a $LiNbO_3$ dual-drive Mach-Zehnder type phase modulator and a passive fiber delay-line multiplexer to generate a single polarization 160 Gbit/s data signal. The bit-error rate of the 160 Gbit/s RZ-DPSK data signal was measured after transmission over a 480 km fiber link. The results are shown in Fig. 8, together with a 160 Gbit/s back-to-back measurement without transmission. Error-free performance was achieved for all four 40 Gbit/s

OTDM tributaries after 480 km transmission with power penalties between 1.2 and 2.1 dB compared to back-to-back.

Summary

Wavelength tunable monolithic mode locked lasers on GaInAsP/InP have been fabricated and characterized for hybrid mode locking operation. Low timing jitter of 85 fs, minimum pulse widths of 1.5 ps and amplitude noise of 1.2 % for a repetition frequency of 39.813 GHz have been simultaneously achieved. The pulses exhibit typical time-bandwidth products in the range of 0.35 to 0.55 depending on different driving conditions. However, the time-bandwidth product could be reduced close to the transform limit by implementing adapted lengths of SMF fiber due to only linear chirp of the laser. An average fiber-coupled power of around 1 mW was obtained. The lasers have been packaged into modules for easy handling in transmission experiments. The suitability of the laser modules was demonstrated for high-speed RZ-DPSK transmission in a 160 Gbit/s transmission experiment. These good results demonstrate the high quality and stable performance of the 40 GHz monolithic mode locked lasers.

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