Phosphorus-free mode-locked semiconductor laser with emission wavelength 1550 nm

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Abstract. We have fabricated passive mode-locked laser diodes based on strained InGaAlAs/InGaAs/InP heterostructures with crystal lattice mismatch parameter of +1.0 % between quantum well and barrier. The laser with temperature stabilization at 18 °C was demonstrated 10.027 GHz optical pulse repetition rate with 6 ps pulse duration time. Timing jitter of optical pulses in mode-locked regime was 0.145 ps.

1. Introduction
Development of high-speed internet, entry of optical interconnects in supercomputers and data centers, ubiquity of cloud technologies accelerates substitution of electronic components by photonic in communication technologies [1]. Optoelectronic semiconductor devices based on A3B5 compounds are widely used in the field of communication due to the demonstrated reliability, low cost, energy efficiency and integration capabilities [2]. Development of optical analog-to-digital (ADC) converters can be distinguished among the basic trends of progress in the photonic components. Conversion of analog signals with a frequency greater than 10 GHz and sampling time less than 10 fs cannot be done without optical components [3]. Role of clock-pulse generator in the optical ADC can play an edge-emitting semiconductor laser with passive mode-locking [4–6]. Active region of the laser emitting at telecommunication wavelength of 1550 nm can be made on the basis of elastically strained heterostructure InGaAs/InAlGaAs on InP substrate. It is known that the using the strained InGaAs quantum wells (QWs) reduce threshold current density and increase differential gain [7–9].

2. Experiment
The laser heterostructures were grown on the InP substrate (100) by molecular-beam epitaxy using Riber MBE49 system. Our first attempts to fabricate laser heterostructure with misfit stresses between QW and barriers started from determination of necessary lattice mismatch parameter. In the works [10,11] we experimentally determined the critical thickness of QW and lattice mismatch parameter showing best interface morphology and lasing characteristics, i.e. 31 Å and 1%, and the results agreed with the theory [9,12]. In the work [13] we studied threshold and gain characteristics of laser heterostructures with different number of QWs in active region, the investigated lasers showed a high modal gain of
11 cm\(^{-1}\) and a low transparency current density of 46 A/cm\(^2\) per QW, the maximum threshold gain in the laser with 8 QWs of 175 cm\(^{-1}\) was obtained. To improve threshold characteristics and to reduce optical losses we developed second generation of laser heterostructures with optimized number and thickness of QWs, doping level and thickness of emitter and doping level of waveguide. Active region of the second generation contained 3 In\(_{0.67}\)Ga\(_{0.33}\)As QWs separated by In\(_{0.53}\)Al\(_{0.20}\)Ga\(_{0.27}\)As barriers with crystal lattice mismatch parameter of +1.0\% between QW and barrier. The In\(_{0.53}\)Ga\(_{0.47}\)As waveguide layer had 0.3 um width without doping. The In\(_{0.53}\)Al\(_{0.47}\)As emitters were lattice-matched with the lattice parameter of InP substrate and thickness of p-emitter was 1.5 um while thickness of n-emitter was 1 um. Detailed information about first and second generations of laser heterostructures is shown on the figure 1. Comparison of threshold current and optical losses of first and second generation is represented on the figure 2 and 3. One can see that threshold current density \(J_{th}\) was reduced twofold and optical losses \(\alpha_i\) were reduced from 103 cm\(^{-1}\) to 33 cm\(^{-1}\).

We utilized the second generation laser heterostructures to evaluate a passive mode-locking regime in two sections laser configuration [14]. The fabricated edge-emitting mode-locked laser had a cavity length of 4 mm, stripe width of 5 um and etching depth of 250 nm. Passive mode-locking regime was obtained by utilizing of saturable absorber i.e. negatively biased part of gain section with 120 um length electrically separated from the gain section. Schematics of the fabricated laser is represented on the figure 1.

**Figure 1.** Optimization of the laser heterostructure and schematics of the mode-locked semiconductor laser with two-section configuration.

**Figure 2.** Threshold characteristics of the fabricated laser generations.

**Figure 3.** Reciprocal differential losses of the fabricated laser generations.
3. Experimental results and discussion

The fabricated mode-locked lasers were mounted on copper heatsink. Measurements carried out at stabilized temperature 18 °C. The lasers were pumped by direct current \( I = 340 \text{ mA} \), and saturable absorber was biased at \( V_{\text{SA}} = 2.8 \text{ V} \), the laser had optical power of 6 mW at that bias point. Optical spectrum had the centre at 1539 nm.

The pulse duration was measured using a photodetector whose response to a \( \delta \)-pulse is 18 ps and an oscilloscope with a bandwidth of 50 GHz at -3 dB. The laser radiation was carried into a multimode 50/125 optical fiber, part of the radiation was removed by a fiber splitter to the synchronization channel of the oscilloscope and a monochromator. In multimode fiber the optical pulse is tightened by 2 ps due to the fiber length of 20 m as well as the spectral width and wavelength of radiation, the bending radius of the fiber and the eccentricity of the optical connectors.

Using equation (1) the reconstructed pulse duration at half-height \( \tau \) is equal to 6 ps:

\[
\tau = \sqrt{\tau_{\text{pulse}}^2 - \tau_{\text{ph}}^2 - \tau_{\text{osc}}^2 - 2},
\]

where \( \tau_{\text{ph}} = 18 \text{ ps} \) is the response time of the photodetector (18.5-picosecond detector 1454-50 from NewFocus), \( \tau_{\text{osc}} = 7 \text{ ps} \) is the response time of the oscilloscope and \( \tau_{\text{pulse}} = 20.9 \text{ ps} \) is the half-amplitude duration of optical pulse from the fabricated laser measured by oscilloscope (insert to the figure 4). Losses on the connectors were not considered. Optical pulse repetition rate was equal to 10.027 GHz and given from radio-frequency spectrum of optical pulse train (see figure 4) from the fabricated mode-locked laser.

An indirect method can be used to calculate the jitter of the fabricated mode-locked laser. One way is based on the fact that with large delay relative to synchronization pulse, the jitter is proportional to the following equation:

\[
\tau_{\text{osc}} = \sqrt{\tau_0^2 + N \cdot \tau_{\text{ML}}^2},
\]

where \( \tau_{\text{osc}} \) is the measured oscilloscope jitter, \( \tau_0 \) is the internal oscilloscope jitter, \( N \) is the number of pulses, \( \tau_{\text{ML}} \) is the jitter of mode-locked laser. The estimation gave the value of \( \tau_{\text{ML}} \) about 0.145 ps. Figure 5 is shown dependence of measured oscilloscope jitter on number of pulses and approximation by formula (2).

![Figure 4](image1.png)  
**Figure 4.** Radio frequency spectrum of optical pulse train. Oscillograph trace of the generated pulses is on the insert to the figure.  

![Figure 5](image2.png)  
**Figure 5.** Oscilloscope jitter as a function of number of optical pulses and fitting curve determinates jitter of the mode-locked laser.
4. Conclusions
Threshold current density of tested mode-locked lasers based on strained InGaAlAs/InGaAs/InP heterostructures with crystal lattice mismatch parameter of +1.0% between quantum well and barrier was lower 600 A/cm², optical losses were ≈ 33 cm⁻¹. At stabilized temperature 18 °C in passive mode-locking regime the laser with the cavity length of 4 mm and the saturable absorber length of 120 μm demonstrated generation of optical pulses with pulse duration time 6 ps and repetition rate 10.027 GHz. Estimation gave the value of timing jitter 0.145 ps.

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