# Measurements of integrated mode-locked laser for laser library development

V. Moskalenko, M. K. Smit, E. A. J. M. Bente

Technical University of Eindhoven, Eindhoven, Netherlands

*In this paper results of measurements on monolithic extended cavity ring passively mode-locked semiconductor lasers (PMMLs) are presented. We have designed PMMLs in various geometries in order to use them for theoretical model verification and subsequent development of a library of short-pulsed lasers within an active-passive integration platform. The different dynamic regimes depending on the voltage applied to the saturable absorber and current injected into the amplifier are characterized in both time and frequency domains. At the mode-locking operational conditions the output signal features an optical comb centered at 1.55 um and a 3dB bandwidth of 8.5 nm.*

## Introduction

A large number of applications in areas as high-speed communications [1], optical recovery [2], and high-speed gas spectroscopy [3] require short stable optical pulses or coherent optical frequencies which can be generated by mode-locked lasers (MMLs). However, such systems can be quite bulky, complex and vulnerable. In order to overcome these issues a photonic integration approach is used. In this technology passive MLLs (PMLLs) can be realized as a photonic integrated circuit (PIC) on which these lasers can be combined with other optical devices on the single monolithic chip. The aim of this work is to study PMLLs in the framework of active-passive integration technology, which enables the combination of passive and active waveguide devices. Through the use of the active-passive integration, the performance of a semiconductor mode-locked laser can be significantly improved due to several reasons. First, active-passive integration allows for a decoupling of amplifier lengths and the resonator length which determines the repetition rate. This helps to reduce the issue of amplitude modulations [4] and self-phase modulation as observed in all-active two-section devices. Another advantage of this technology is that the relative position of the SA and SOA and output coupler in cavity can be optimized. But also other optical devices can be included which can be freely located.

In integrated photonics, as in micro-electronics, the broad range of complex circuits can be realized using a set of small standard components, so called building blocks. Building blocks (BB) are organized in libraries. This approach enables one to design a large variety of complex optical devices relatively fast by combining building blocks from various libraries. Since there is large variety of complex optical devices which require short-pulsed laser as an optical source the library approach can be also applied to the PMLLs.

In this work we investigate PMLLs performance for various designs and operating conditions in order to use them in short-pulsed laser development in active-passive integration platform. The paper is organized as follow: in the first section we will introduce the concept of the library of short-pulsed lasers and main steps that have to be made. In the next two sections we present the PMLLs geometry and main experimental results that have been achieved. The conclusions are given in the last section.

## The idea of library of short-pulsed lasers

Depending on the circuit functionality and application the requirements on a PMML can vary over a wide range. For example, for high speed gas-spectroscopy applications the pulses repetition rate should not exceed 3 GHz and for a wavelength division multiplexing source it has to be in the order of tens of GHz. Thus, the BBs have to be developed in a way that designer in principle could change the characteristics of output signal without spending additional time on the BBs properties simulation. However, in order to link the characteristics of output signal and BB layout the performance of mode-locked lasers needs to be properly investigated using both experimental and simulation approaches. In spite of the fact that semiconductor mode-locked lasers have been studied for more than two decades theoretical prediction of their properties still remains challenging. A systematic study of theoretical predictions and experimental results under a range of operating conditions of a series of different devices is required to a) achieve high level of understanding of the non-linear processes taking place in the laser cavity and b) to determine which theoretical model is the most suitable to be used in laser library development. For this purpose several ring PMLLs of different geometry were fabricated. In the next section we will detail the device design used in this work.

## Symmetrical ring mode-locked laser

Passive mode-locking can be achieved by combining two elements a semiconductor optical amplifier (SOA) which provides gain that saturates at high intensities and a saturable absorber (SA) which introduces losses that are relatively large for low intensities but which become significantly smaller due to the saturation of absorption for a pulse with high intensity. In this work we present the ring symmetrical design of PMLL which includes not only SOA and SA sections but also passive waveguides (shallow and deep) and a 50% multi-interference coupler (MMI) output coupler. A schematic sketch of the laser cavity is presented on Fig. 1.

Fig. 1. Sketch of symmetrical ring PMML.

The use of passive waveguides in a PMLL allows to overcome or reduce issues in standard two–sections all active PMLLs, in particular self-phase modulations effects [4].

The symmetrical ring cavity enables operating in a self-colliding regime which provides more stable mode-locking and a more deeply saturated absorber. Due to the fact that in the ring cavity there is no need of cleaved facets the repetition rate can be controlled more accurately than that of a Fabry-Perot type structure with cleaved facets.

In order to minimize back reflections into the device the output waveguides are tilted under an angle of 7 degrees. The SOA and SA section contain a layer structure with four InGaAs quantum wells. The SOA and SA sections were electrically independent by introducing electrical isolation sections. The device results presented here are on a PIC fabricated within a multiproject wafer run available through an Oclaro foundry service. Three 16 GHz ring mode-locked lasers with different lengths of SOAs (1300 µm, 1500 µm and 1700 µm) and 50 µm long SAs were fabricated. In the next section the experimental results of the laser with a 1700 µm SOA are presented.

## Measurements results

The device was mounted on a copper chuck and the temperature was stabilized at 12° C. The output light was collected using lensed fibers with antireflection coating. Optical isolators were used to prevent back reflections into the cavity. The PMLL laser was operated with a total injection current ($I_{soa}$) to the SOA sections and a reverse voltage ($V_{sa}$) applied to the SA. The mode-locking was confirmed by observation of RF spectra, optical spectra and autocorrelation trace. The RF spectra were recorded using a 50 GHz electrical spectrum analyser connected to the fast photodiode. The optical spectra were characterized using an optical spectrum analyser (OSA) with a resolution of 0.16 pm. In order to obtain autocorrelation traces the optical signal from PMML went through the polarization controller and was amplified by the erbium doped fiber amplifier (EDFA) with a 10 m long fiber.

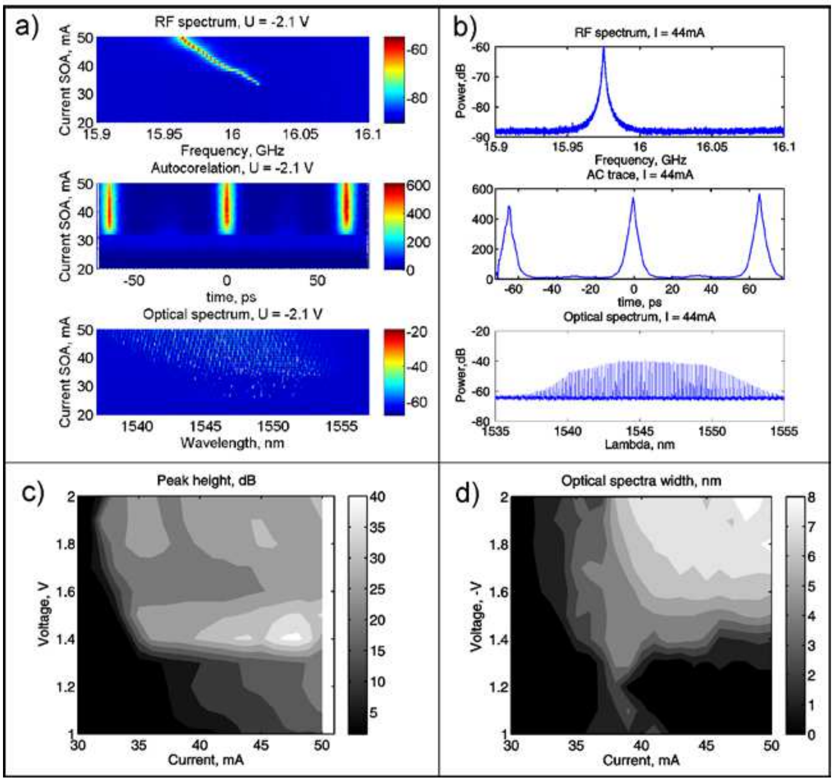

Fig. 2. a) Evolution of RF spectra, autocorrelation trace and optical spectra with injected current at Usa = -2.1 V. b) RF spectrum, autocorrelation trace and optical spectrum at U = -2.1 V and Isoa = 44 mA, c) A map of the RF peak height as a function biasing conditions applied to the SOA and SA d) A map of the spectral bandwidth (FWHM) measured at the same set of operating conditions as in (c)

The device has been measured under various operating conditions. The Fig. 2 (a) shows RF spectra, AC traces and optical spectra at the range of injected currents ($I_{soa}$ = 10-50 mA). The maximum injected current was determined by the maximal power of the optical signal which can be absorbed by the SA without causing damage. The lasing threshold of the PMLL at 2.1V applied reverse voltage was $I_{soa}$ = 27 mA. The signal recorded by the OSA shows continuous wave lasing at the currents above threshold until $I_{soa}$ = 33 mA. At the injected currents above $I_{soa}$ = 33 mA the device operates in a mode-locking regime. At these conditions the electrical spectrum shows a clear peak at 16.02 GHz which corresponds to the roundtrip time. Analysis of autocorrelation shows pulse duration of 3.8 ps.

By further increasing the injected current, the beat tone between modes shifts to lower values. As described in [5] the repetition frequency is led by a change of detuning due to the gain/absorber saturation effects. In our case we operate at low injection currents, where most of the gain section isn't saturated. According to [5] at unsaturated gain conditions the repetition frequency decreases with increasing pulse energy.

Increasing of the current leads to the optical spectrum shift to shorter wavelengths, this is caused by the blue shift of the gain spectra at higher carrier densities. Examples of the RF spectrum, AC trace and optical spectrum at the fixed injected current ($I_{soa}$ = 44 mA) are presented on Fig. 2 (b). Fig. 2 (c) shows a map of height of RF peak (in dB) at the fundamental frequency over the low frequency noise as a function of $I_{soa}$ and $V_{sa}$. The main gray area indicates the presence of RF peak. Since the injected currents were relatively low the signal to noise ratio of the RF analyzer plays a role and therefore RF peak heights don't exceed 40 dB. The maximum observed RF height over the noise floor is 41 dB. Fig. 2(d) shows a map of the full width at half maximum (FWHM) of the optical spectral width. The maximum observed FWHM is 8.5 nm.

## Summary

The ring geometry passively mode-locked laser realized as a PIC fabricated within the Oclaro InP generic technology has been demonstrated. The mode-locking regime over range of the operating conditions was observed. The output signal features a FWHM of 8.5 nm and a minimum pulse width of 3.8 ps.

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