Analysis of the phase-locking dynamics of a III-V-on-silicon mode-locked laser

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Abstract: We present the detailed phase-locking analysis of a telecom III-V-on-silicon passively mode-locked laser with a ring cavity and quantum wells as active region. We use a stepped-heterodyne measurement to quantify the modal phase chirp and reconstruct the pulse envelop. With this technique we are able to identify the causes of pulse broadening and rippling from the spectral phase dispersion as a function of saturable absorber bias variation.

1 Introduction

Passive mode-locking (PML) is a well-known technique that uses a saturable absorber (SA) inside a laser cavity to generate a pulsed laser output with a broad optical frequency comb (OFC). Nowadays PML is used for many applications including optical signal processing [1] or spectroscopy [2], and can now be implemented with integrated semiconductor technologies [3]. For spectroscopy, dense OFCs are required, which is now made possible with integrated devices thanks to the hybrid III-V-on-silicon technology [4]. OFC lasing in PML hybrid lasers has recently been demonstrated with a 1 GHz Free Spectral Range (FSR), providing a ultradense comb spectrum containing more than 1400 lines [5]. Hybrid III-V-on-silicon PML lasers are now coming close to applications and better understanding of the performances of these lasers is required. Noise performances are typically well-assessed via the measurement of the fundamental RF tone and optical linewidths [6,7]; on the other hand the pulse width is usually determined via a nonlinear autocorrelation setup, since typical timescales are too fast for current photodetectors technologies. However, this technique relies on a nonlinear process that requires high peak powers and is therefore not appropriate for weak average power integrated photonic sources. In this work, we propose to assess the mode-locking performance and pulse formation in hybrid III-V-on-silicon PML quantum well (QW) laser by monitoring the spectral phase of the frequency comb output. We therefore choose to use a stepped-heterodyne (SH) measurement to access phase and amplitude of each comb line which allows us to reconstruct the temporal envelop and phase chirp of the pulse with a temporal resolution smaller than the picosecond [8]. The SH technique is a linear, simple and powerful tool that has been used for example to quantify the group velocity dispersion of quantum dash and quantum dot single section frequency comb laser diodes [9], or to assess the temporal envelop and phase chirp of pulses emitted from monolithic QW PML lasers [3]. In [3], the SH measurement allowed to evidence that the monolithic PML QW lasers were not emitting transform-limited (TL) pulses. In this work we characterize the pulsed operation of a PML III-V-on-Si QW ring lasers and give for the first time a quantitative description of the deterioration of the phase-locking between the OFC lines when the SA bias voltage (VSA) values depart from optimal ones.

2. Experimental setup

The laser under study has a ring cavity with a 8 GHz FSR and a configuration similar to the one presented in [4]. The laser is temperature controlled and pumped with a low noise current source. We intend to analyse the characteristics of the phase-locking of spectral lines during PML operation. Using the SH technique, we are able to monitor the phase relationship between consecutive comb lines and further reconstruct the temporal envelop of the pulse. SH technique is described in Fig. 1 (see [8] for further details). SH allows to obtain a complete phase spectrum by beating a CW laser with consecutive spectral lines of the hybrid laser comb. At each step the CW tunable laser wavelength is increased by one FSR of the comb laser, the beating signal with the nearest comb lines are acquired with a fast photodiode. After filtering in the Fourier space, an operation is performed between the beating signals at each step in order to retrieve the phase difference between consecutive lines. The amplitude of each line is obtained from the integration of the RF power spectral density of the beating tones.

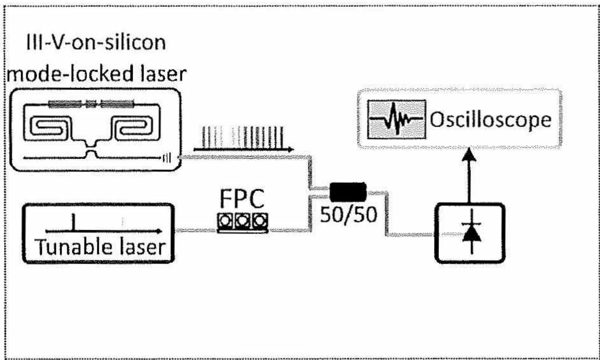

Figure 1: Stepped-heterodyne (SH) technique setup. FPC: fiber polarization controller.

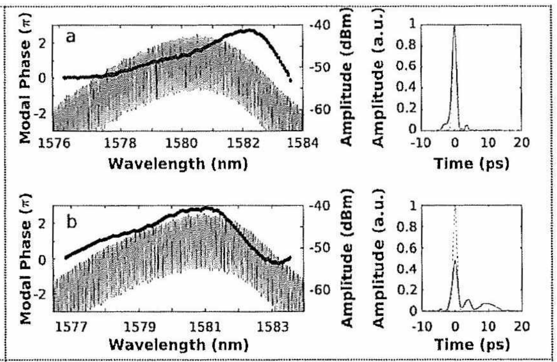

Figure 2: Pulse envelop reconstruction (right, red) from modal phase measurement with SH (left, red) for different V_{SA} values and fixed I = 170 mA. a) V_{SA} = -1V. b) V_{SA} = -1.1 V.

3. Results and discussion

The phase and amplitude information of each comb line allows to reconstruct the temporal phase and pulse envelop. Fig. 2a,b shows the result of the SH measurement for two different mode-locked operations with identical pumping current (I = 170 mA) but different V_{SA} values. The optical spectra are shown in blue, the corresponding phases of the comb lines are marked by circles. Fig. 2 evidences the major impact on the pulse shape caused by a small change in V_{SA}. In Fig. 2a, for V_{SA} = -1 V, we observe that dispersion occurs mainly on the side modes of the spectrum, causing small broadening and rippling of the outgoing pulse. However, for V_{SA} = -1.1 V, dispersion is affecting the central and more intense modes of the spectrum, causing more dramatic distortion of the pulse. Each time the reconstructed pulse is compared with a perfect TL pulse that we have computed by setting numerically a constant value for the phase of each comb line (light blue dots).

4. Conclusion

In conclusion, we have presented the first stepped-heterodyne analysis of the mode-locking operation of a III-V-on-Si frequency comb laser. The SH technique provides information on the pulse envelop through the phase relationship between the comb lines, which is a clear advantage over nonlinear autocorrelation measurement. Moreover this technique does not require any pulse amplification and is therefore perfectly suited for the characterization of the frequency comb emitted by low power integrated laser sources. The SH technique has allowed to evidence how sensitive the phase-locking dynamics is with respect to the SA bias voltage. In fact, this work shows how the mode-locking deviates from the transform-limited operation in terms of the modal phase dispersion, provocating rippling and broadening of the pulse envelop. Our analysis paves the way for further exploration, modeling and potential manipulation of the phase dynamics in semiconductor mode-locked lasers, with particular focus on the hybrid III-V-on-Si technologies where very long cavities can be fabricated [8, 9].

5. References

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Poster 6 **Neuromorphic rate-coded representation of digital image data with a VCSEL-neuron**
Matěj Hejda, J. Robertson, J. Bueno, J. A. Alanis and A. Hurtado
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Poster 7 **Dispersive instabilities in Passively Mode-Locked Integrated External-Cavity Surface-Emitting Lasers**
C. Schelte, D. Hessel, J. Javaloyes, S. Gurevich
Departament de Física, Universitat de les Illes Baleares, Institute for Theoretical Physics, University of Münster

Poster 8 **High power laser structures at 905nm for LIDAR**
M. Krakowski, P. Afuso-Roxo, J.P. Legoec, C. Theveneau, B. Vinter, P. Resneau, E. Vinet, Y. Robert, M.Garcia, O.Parillaud, B.Gerard
III-V Lab – Palaiseau - France

Session 5 Chair: Julien Javaloyes moderator: Rachel Jones

16:30-16:45 **Frequency comb generation by optical injection locking**
Christoph Weber, Dominik Auth, Jan Lautenschläger, Dmitry Kazakov, Andreas Klehr, Andrea Knigge, Johannes Hillbrand, Benedikt Schwarz, Federico Capasso, and Stefan Breuer
Institute of Applied Physics - Technische Universität Darmstadt, John A. Paulson School of Engineering and Applied Sciences - Harvard University, Ferdinand-Braun-Institut - Leibniz-Institut für Höchstfrequenztechnik – Berlin, Institute of Solid State Electronics - TU Wien

16:45-17:00 **Dual-comb spectroscopy application of a 100 MHz line spacing optical frequency comb generated by gain-switching a laser diode**
Clara Quevedo-Galán, V. Durán, A. Rosado, A. Pérez-Serrano, J.M.G. Tijero and I. Esquivias
CEMDATIC - E.T.S.I. Telecomunicación - Universidad Politécnica de Madrid (UPM), GROC-UJI - Institute of New Imaging Technologies (INIT) - Universitat Jaume I

17:00-17:15 **Analysis of the phase-locking dynamics of a III-V-on-silicon mode-locked laser**
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