Modelling of a passively modelocked semiconductor-glass waveguide hybrid laser

Youwen Fan,[1] Yvan Klaver,[1] Valentina Moskalenko,[2] Erwin A. J. M. Bente,[2]
Julien Javaloyes,[3] Peter J. M. van der Slot,[1] and Klaus.-J. Boller[1]

[1] University of Twente, MESA+ institute for Nanotechnology, Laser Physics and Nonlinear Optics group, P.O.Box 217, 7500 AE Enschede, the Netherlands
[2] Eindhoven University of Technology, COBRA Research Institute, Electrical Engineering, Den Dolech 2, 5612AZ Eindhoven, The Netherlands
[3] Universitat de les Illes Balears, Dept. of Physics, km 7.5, 07122 Palma, Spain

Monolithic modelocked diodes lasers have seen rapid advancements during the past decade. However, those lasers suffer from large intrinsic phase noise caused by index-gain coupling. To reduce phase noise and more freely chose the repetition rate, we consider hybrid-integration where the active is extended with a glass waveguide feedback circuit. Several advantages might be gained because glass waveguides offer extremely low loss (0.1 dB/cm) and avoid nonlinear effects. In this work, we present a theoretical study of such a passively modelocked hybrid laser. Different operational regimes of the modelocked lasers are identified, as preparation for future experiments.

Introduction

Mode locked lasers (MLLs) are powerful tools enabling both industrial and academic developments. Implemented in different ways, these sources are of interest for a wide range of applications. For example, high pulse repetition rates are preferable for optical communications [1], and ultrashort pulses with high peak power are suitable for nonlinear optical applications [2]. Modelocked semiconductor lasers fabricated as monolithic devices stand out in terms of easy integration with other components while a multitude of available semiconductor compounds enable operation in various wavelength regions. A high stability (in the kHz-range) of the pulse repetition rate (tens of GHz) can be achieved with passive modelocking via on-chip integrated saturable absorbers [3]. Ultra stable (Hz level) pulse repetition rates can be achieved with hybrid modelocking [4] by applying a radio frequency voltage of corresponding frequency stability. However there is one central issue associated with monolithic modelocked semiconductor lasers. Namely, the *optical* linewidth of the individual laser modes is rather broad, amounting tens to hundreds of MHz [5, 6]. This prohibits the use of such lasers for high resolution measurements such as in dual comb spectroscopy [7].

In order to solve this problem of broad optical mode linewidth, we recall a solution that has proven to work with single-mode continuous-wave (CW) lasers. Using a glass waveguide to provide external optical feedback and thereby forming a semiconductor-glass waveguide hybrid laser showed a drastic linewidth reduction [8, 9]. The reasons are threefold: a) the optical cavity length can be extended without a significant loss penalty; b) the nonlinear optical response in glass waveguides is weak; c) only a small fraction of the total cavity contains semiconductor material, which reduces undesired index-gain coupling [10]. These observations suggest that a reduction of the optical linewidth of modes might be achieved in a modelocked laser as well. However, as the extension of the cavity alters the dynamic properties and modelocking operation conditions to a large extent, here we investigate the dynamics and operation conditions for modelocking of such semiconductor-glass waveguide hybrid lasers.

Laser configuration

The configuration of the laser is shown in Fig. 1. A saturable absorber (SA) and gain section are integrated on an InP chip which is butt-coupled to a glass waveguide chip. This set-up is chosen for maximum simplicity and is essentially what is to be explored in according experiments. For a comprehensive modeling, we solved the spatially resolved Max-Bloch equations using a travelling wave model (TWM) for both the InP and glass waveguide parts [11, 12]. The semiconductor waveguide and material parameters are taken from [12]. Other parameters are varied, so far in particular, the length ratio of the SA and active section (SA ratio), the cavity length and the pump current. The complex envelope of the time-evolving electric field is calculated with 30 fs resolution.

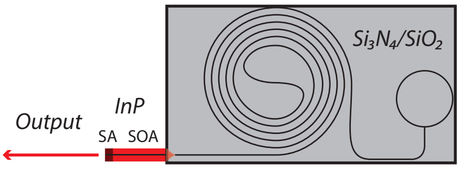
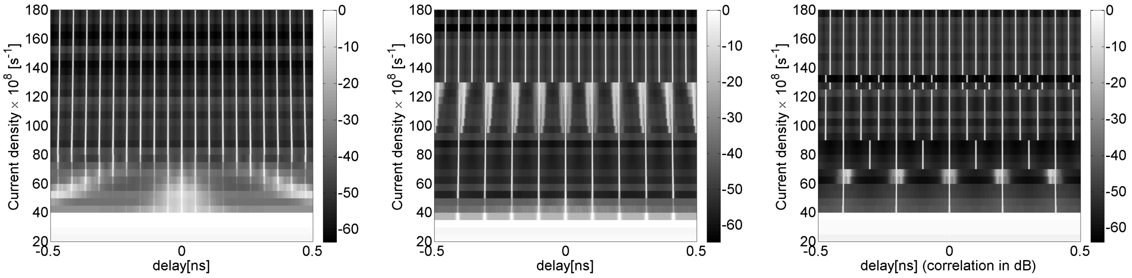


Figure 1: A sketch of the semiconductor-glass waveguide hybrid laser. The InP chip contains a saturable absorber (SA) and a semiconductor optical amplifier (SOA) while the glass waveguide chip provides optical feedback and a long cavity length (terminated with a loop mirror).

Modelling results

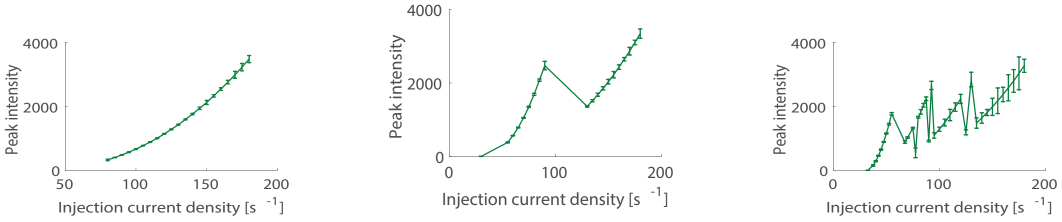


(a) 20GHz (b) 10GHz (c) 5GHz

Figure 2: Normalized intensity autocorrelation for stepwise increasing lengths of the external cavity (decreasing repetition rates). The SA ratio is 4.5%.

Typical examples of calculated results for repetition rates of 20 GHz, 10 GHz and 5 GHz are summarized in Figs. 2, 3 and 4. With choosing a SA ratio of 4.5% we find that the laser

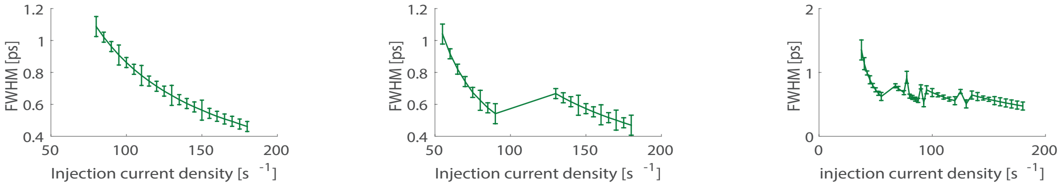
shows a wide range of pump currents within which stable modelocking occurs. Intensity auto-correlation traces are shown in Fig. 2. When analyzing the traces to more detail, they display the full scenario of the dynamics of modelocked lasers, such as Q-switching induced instabilities and harmonic modelocking.
The peak intensity *vs.* pump current is given in Fig. 3. Discontinuities in the growth of the peak intensity mark the appearance of additional pulses per round-trip, consistent with the data in Fig. 2.



(a) 20GHz (b) 10GHz (c) 5GHz

Figure 3: Peak intensity *vs.* injection current at a SA ratio of 4.5%.

Fig. 4 shows the pulse duration *vs.* pump current. It can be seen that the pulse duration lies in the range of approximately 500 fs to 1 ps. A decrease in pulse duration with increased current is observed in both fundamental and harmonic modelocking regimes.



(a) 20GHz (b) 10GHz (c) 5GHz

Figure 4: Full width at half maximum (FWHM) pulse duration *vs.* injection current at a SA ratio of 4.5%.

We have further decreased the repetition rate to 2 GHz and we have found stable fundamental modelocking sufficiently close to threshold. For the 2 GHz-laser also harmonic mode locking can be observed at higher currents.

Conclusion

We have numerically investigated the dynamics of a novel type of passively modelocked laser, a semiconductor-glass waveguide hybrid laser. Modelocking is observed at different repetition rates. Besides Q-switching instabilities, harmonic mode locking is also observed for all the repetition rates with stronger pumping. The pulse duration decreases with increasing pump current, regardless of whether the laser is in the fundamental or harmonic modelocking regime. In summary of the numerical calculations, such hybrid lasers are stably operating in certain parameter ranges that are easy to access in experiments. Further enlargement of the stable mode locking range might be obtained via implementation of intra-cavity filters such as asymmetric Mach Zehnder interferometers [12] and via dispersion compensation using cross-section engineering of the glass waveguides [13]. The results pave the way to further explore the potential of such modelocked hybrid lasers to verify optical linewidth reduction of the individual modes.

References

[1] H. Takara. High-speed optical time-division-multiplexed signal generation. *Opt. Quantum Electron.*, 32:795–810, 2001.

[2] D. A. B. Miller, A. C. Gossard, W. Wiegmann, D. S. Chemla, and P. W. Smith. Nonlinear optics with a diode-laser light source. *Opt. Lett.*, 8(9):477–479, Sep 1983.

[3] S. Keyvaninia, S. Uvin, M. Tassaert, Z. Wang, X. Fu, S. Latkowski, J. Marien, L. Thomassen, F. Lelarge, G. Duan, G. Lepage, P. Verheyen, J. Van Campenhout, E. Bente, and G. Roelkens. III-V-on-silicon anti-colliding pulse-type mode-locked laser. *Opt. Lett.*, 40(13):3057–3060, Jul 2015.

[4] S. Latkowski, V. Moskalenko, S. Tahvili, L. Augustin, M. Smit, K. Williams, and E. Bente. Monolithically integrated 2.5 GHz extended cavity mode-locked ring laser with intracavity phase modulators. *Opt. Lett.*, 40(1):77–80, Jan 2015.

[5] T. Habruseva, S. O'Donoghue, N. Rebrova, F. Kéfélian, S. P. Hegarty, and G. Huyet. Optical linewidth of a passively mode-locked semiconductor laser. *Opt. Lett.*, 34(21):3307–3309, Nov 2009.

[6] V. Moskalenko, S. Latkowski, S. Tahvili, T. de Vries, M. Smit, and E. Bente. Record bandwidth and sub-picosecond pulses from a monolithically integrated mode-locked quantum well ring laser. *Opt. Express*, 22(23):28865–28874, Nov 2014.

[7] I. Coddington, W. C. Swann, and N. R. Newbury. Coherent multiheterodyne spectroscopy using stabilized optical frequency combs. *Phys. Rev. Lett.*, 100:013902, 2008.

[8] R. M. Oldenbeuving, E. J. Klein, H. L. Offerhaus, C. J. Lee, H. Song, and K.-J. Boller. 25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity. *Laser Phys. Lett.*, 10(1):015804, 2013.

[9] Y. Fan, R. M. Oldenbeuving, E. J. Klein, C. J. Lee, H. Song, M. R. H. Khan, H. L. Offerhaus, P. J. M. van der Slot, and K.-J. Boller. A hybrid semiconductor-glass waveguide laser. *Proc. SPIE*, 9135:91351B–91351B–6, 2014.

[10] C. H. Henry. Theory of the linewidth of semiconductor lasers. *IEEE J. Quantum Electron.,* 18(2):259–264, Feb 1982.

[11] J. Javaloyes and S. Balle. Freetwm: A simulation tool for multisection semiconductor lasers [online]. available: http://nova.uib.es/onl/softwares/softwares.html.

[12] V. Moskalenko, J. Javaloyes, S. Balle, M. K. Smit, and E. A. J. M. Bente. Theoretical study of colliding pulse passively mode-locked semiconductor ring lasers with an intracavity Mach−Zehnder modulator. *IEEE J. Quantum Electron.,* 50(6):415–422, June 2014.

[13] J. P. Epping, T. Hellwig, M. Hoekman, R. Mateman, A. Leinse, R. G. Heideman, A. van Rees, P. J.M. van der Slot, C. J. Lee, C. Fallnich, and K.-J. Boller. On-chip visible-to-infrared supercontinuum generation with more than 495 THz spectral bandwidth. *Opt. Express*, 23(15):19596–19604, Jul 2015.