STSM REPORT

STSM Application number: COST-STSM-BM1205-29661

STSM Grantee: Mr Nikola Vukovic (PhD researcher)

STSM title: Travelling wave model for external cavity QCL

Home Institution: School of Electrical Engineering, University of Belgrade, Belgrade(RS)

Host Institution: Centre Suisse d'Electronique et de Microtechnique SA, Neuchâtel(CH)

STSM period: 28/09/2015 - 31/10/2015

STSM purpose: Collaborative efforts between groups to model multimode Risken-Nummedal-Graham-Haken (RNGH) instabilities in quantum cascade lasers in external cavity configuration.

Description of the work carried out during the STSM:

The School of Electrical Engineering (ETF) and Centre Suisse d'Electronique et de Microtechnique (CSEM) collaborate on the modelling of ultra-short pulse production regimes in quantum cascade lasers and this STSM facilitated the consolidation and discussion of independent efforts. My STSM activities were related to both theoretical analysis and numerical simulations based on travelling wave model in the external cavity quantum cascade laser (EC-QCL) configuration. During the visit, emphasis was put on realization of numerical simulations for different chip and external cavity geometry as well as for various pump levels. In addition to our main STSM activities, we were able to have many valuable discussions which resulted in preparation of two joint manuscripts for submission in scientific journals.

Description of the main results obtained:

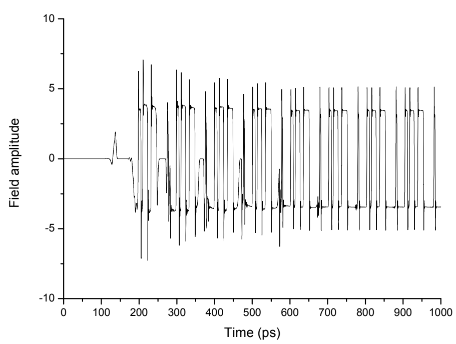
QCLs producing picosecond pulses of high peak power will find numerous novel applications in the fields ranging from the time-resolved spectroscopy and nonlinear frequency conversion to high-speed free space communication, frequency metrology, laser based imaging of human skin for skin cancer detection etc.

The short upper state lifetime (~1 ps) in a QCL prohibits periodic pulse production regimes such as passive mode-locking or Q-switched operation because the gain recovers much faster than the next pulse arrives so as the system does not have a memory to sustain periodic regimes. Gain switched pulse production has been attempted, yielding 120 ps pulse width [1]. Active mode-locking was achieved in QCL structures utilizing diagonal transition, with the upper state lifetime being increased to 50 ps so as to match the cavity round-trip time [2]. However, diagonal transition rendered QCL operation temperature out of the practical use.

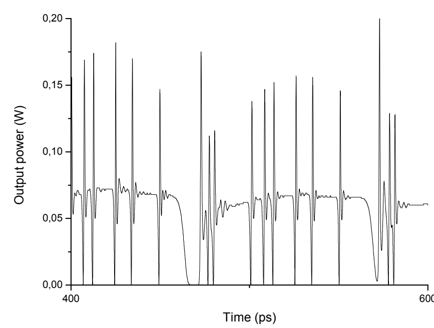
Another possibility to produce short pulses in the MIR spectral range stems from experimental observations that certain QCLs exhibit, at a low threshold [3], features of RNGH instabilities [4,5] and hence might be capable of self-pulsations. In QCLs, the short upper state relaxation time and spatial hole burning in the carrier population can only partially explain the origin of low-threshold RNGH instability [3]. In addition, a saturable absorber due to Kerr-lensing effect in the ridge waveguide of QCL has been evoked in [3] in order to explain low second threshold. In contrast to that, in our previous work [6], we have shown that there is no need to assume a built-in intracavity saturable absorber. Low second threshold in QCLs is in fact due to a combined effect of the carrier coherence grating and the carrier population grating. However we find that the regular RNGH self-pulsations can be obtained only in QCLs with very short cavities, resulting in high repetition rates in the output pulse train.

The purpose of this STSM was to build a travelling wave rate equations model [6,7] for a QCL chip placed in an external cavity so as to reduce the repetition rate of the output pulses. Such model was built and a few preliminary results of the numerical simulations are depicted in Fig.1. Here we show the example of a 3 mm long gain chip placed in the external cavity of 12 mm length. The back facet of the gain chip is AR coated and the external-cavity QCL is pumped with a current twice above the lasing threshold. Figs. 1(a)-(d) show the waveforms of the optical field amplitude, output power, normalized carrier density N and normalized medium polarization P, respectively. Fig. 1(e) displays the P-N attractor. The optical and RF power spectra are shown in Figs. 1(f) and 1(g), respectively.

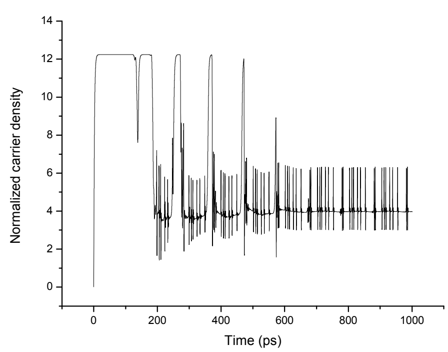
(a)



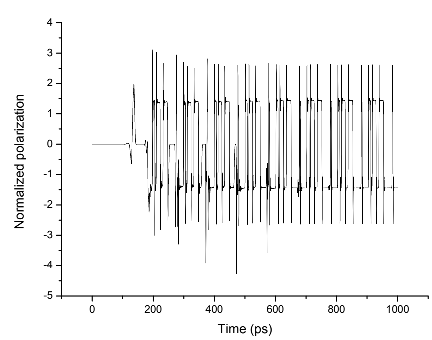
(b)

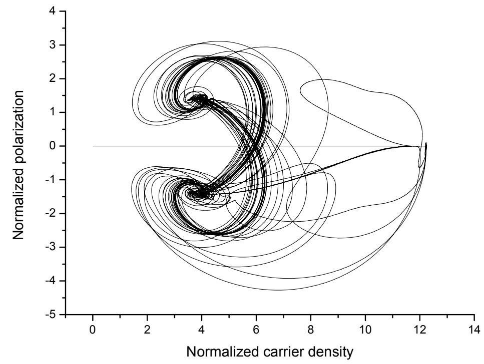


(c)



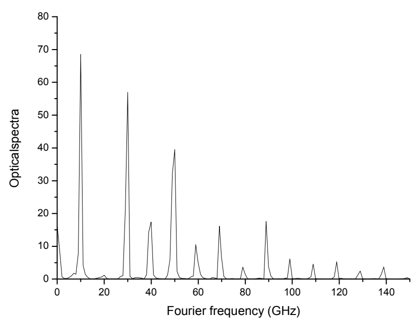
(d)





(e)

(f)



(g)

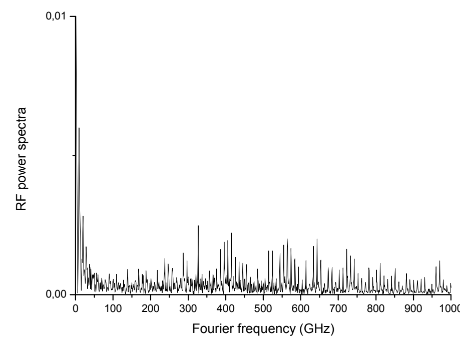


Fig.1: Time traces of field amplitude (a), output power (b), normalized carrier density N (c) and normalized polarization P (d); P-N attractor (e), optical power spectra (f) and RF power spectra (g). Parameters used in simulation: wavelength is 10 um, gain recovery time T_1=1.3 ps, dephasing time T_2=140 fs, reflectivities of the front chip facet and external cavity mirror $R_1=R_{ext}=0.27$, diffusion coefficient D=180 cm^2/s.

Mutual benefits for the Home and Host institutions:

Collaboration with the host Dr Dmitri Boiko at CSEM was very useful and stimulating, with many aspects of modeling discussed between the visitor and host. The working visit was the most efficient way to accomplish this objective. By discussing challenges encountered and the work completed to date, both groups have a better understanding of possible critical areas which require further elucidation.

Future collaboration with the Host institution (if applicable):

ETF and CSEM will continue their collaboration on this topic. In the short-term it is desirable to complete the manuscript for publication.

Foreseen journal publications or conference presentations expected to result from the STSM (if applicable):

N. Vukovic, J. Radovanovic, V. Milanovic and D. L. Boiko, "Low-threshold RNGH instabilities in quantum cascade lasers", in preparation

N. Vukovic, J. Radovanovic, V. Milanovic and D. L. Boiko, “Second instability threshold in quantum cascade lasers,” in preparation

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References

[1] R. Paiella *et al.*, “High-speed operation of gain-switched midinfrared quantum cascade lasers,” *Appl. Phys Lett.* vol 75, p 2536, 1999.
[2] C. Wang *et al.*, “Mode-locked pulses from mid-infrared Quantum Cascade Lasers,” *Opt. Express* vol 17, p 12929, 2009.
[3] A. Gordon *et al.*, “Multimode regimes in quantum cascade lasers: From coherent instabilities to spatial hole burning,” *Phys. Rev. A* vol.77, p.053804, 2008.
[4] H. Risken and K. Nummedal, “Self-Pulsing in Lasers,” J. Appl. Phys. **39**, 4663, (1968).
[5] R. Graham and H. Haken, Quantum Theory of Light Propagation in a Fluctuating Laser-Active Medium, Z. Phys. vol 213, 420, 1968.
[6] N. Vukovic, J. Radovanovic, V. Milanovic, D.L. Boiko, "The Role of Carrier Diffusion in RNGH Instabilities of Quantum Cascade Lasers", Conference: CLEO/Europe-EQEC 2015.
[7] D. L. Boiko, P. P. Vasil'ev, “Superradiance dynamics in semiconductor laser diode structures,” Opt. Express **20**, 9501, (2012).

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Neuchâtel, 10.11.2015

COST-STSM-BM1205-29661 STSM outcome

Dear Sir,

Please find below the aforementioned STSM outcome report table

STSM application number	Home institution & country	Host institution & country	BM1205 WG	Objective of the collaboration	Results of the collaboration
COST-STSM-BM1205-29661	School of Electrical Engineering, University of Belgrade, Serbia	Centre Suisse d'Electronique et de Microtechnique SA, Neuchâtel(CH), Switzerland	WG2	Collaborative efforts on modeling RNGH instabilities in quantum cascade lasers in external cavity configuration.	Theoretical analysis and numerical simulations

I acknowledge that the described short term scientific mission was successfully carried out in the conditions here specified, and prospects for potential collaborations are expected in the coming months out of the agreements reached.

Sincerely,

Dmitri Boiko,
Expert,
Time & Frequency,
Systems