STSM REPORT

STSM Application number: COST-STSM-BM1205-24265

STSM Grantee: Mr Nikola Vukovic (PhD researcher)

STSM title: Investigation of RNGH instabilities in quantum cascade lasers

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: 16/01/2015 - 20/02/2015

STSM purpose: Collaborative efforts between groups to model multimode Risken-Nummedal-Graham-Haken (RNGH) instabilities in quantum cascade lasers which would result in a joint journal manuscript.

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: numerical simulations of RNGH instabilities in QCL under pulsed current - Fabry-Perot case and analysis of conditions for superradiant emission in QCL. My STSM activities were related to both theoretical analysis and numerical simulations on these two closely related tasks mentioned above. During the visit, emphasis was put on justification of RNGH threshold criterion used in our model. This criterion is different from the conventionally used one. RNGH threshold calculated on statistical basis from travelling wave rate equations model is in agreement with definition of RNGH threshold used in the project. Numerical simulations have been realized for different pump levels and noise powers in the system and probability to observe RNGH self-pulsations was calculated as a function of pump excess above lasing threshold and accounting for the standard deviation. In addition, spectral maximum of RNGH instability increment is calculated to be at $\sqrt{2}$ × Rabi frequency.

Description of the main results obtained:

Further expansion of the application domains and emergence of new QCL-based device technologies rely on the possibility of producing ultra-short pulses in the MIR and FIR spectral range. For example, QCLs producing picosecond pulses of high peak power will find applications in the fields ranging from the time-resolved spectroscopy and nonlinear frequency conversion to high-speed free space communication, frequency metrology, skin cancer detection using laser imaging.

The short upper state lifetime (~1 ps) in a QCL prohibits passive mode-locking or Q-switched operation regimes because the gain recovers much faster than the pulse repetition rate. 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 MIR pulses 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. However the second-order interferometric autocorrelation measurements showed that in typical QCL laser cavity (2-4 mm long), pulses have significant stochastic constituent.

Large-signal RNGH self-pulsations have a set of characteristic features that are common with the Dicke superradiance (SR) [6]. Since SR regime is a known approach to produce high power ultra-short pulses, we have quested if QCL subjected to RNGH instabilities are capable of SR emission.

In conventional ring lasers, second threshold for RNGH instabilities is at least 9 times above lasing threshold. In QCLs, short upper state relaxation time and spatial hole burning in the population inversion were only partially attributed in [3] as the origin of low-threshold RNGH instabilities. A saturable absorber, due to Kerr-lensing effect in the ridge waveguide of QCL cavity has been additionally evoked in [3] in order to explain low 2nd threshold.

As medium polarization P is the driving parameter in the system, along with carrier population, we examined the impact of the induced grating of the medium polarization on the CW lasing stability. Such grating is induced by standing wave mode pattern in the cavity, in the same way as the carrier population grating. We find that inclusion of such grating allows us to explain low second threshold in QCLs, without evoking an assumption of a saturable absorber and Kerr-lensing effect in the ridge waveguide of QCL.

CW lasing stability was examined by linear expansion of Maxwell-Bloch equations regarding small perturbations in the field E, medium polarization P and carrier density N as well as their spatial harmonics. The spectrum of the Lyapunov exponent of the resulting 9x9 matrix may show only one mode with positive increment. Applying the spectral conditions for multimode RNGH instabilities [4], we find that second threshold is at p_{th2}=2.35 in 100 µm cavity and p_{th2}=1.05 in 4 mm cavity (Fig.1). Predicted low second threshold in long cavity MIR QCLs is in agreement with numerous experimental reports and QCL spectral data.

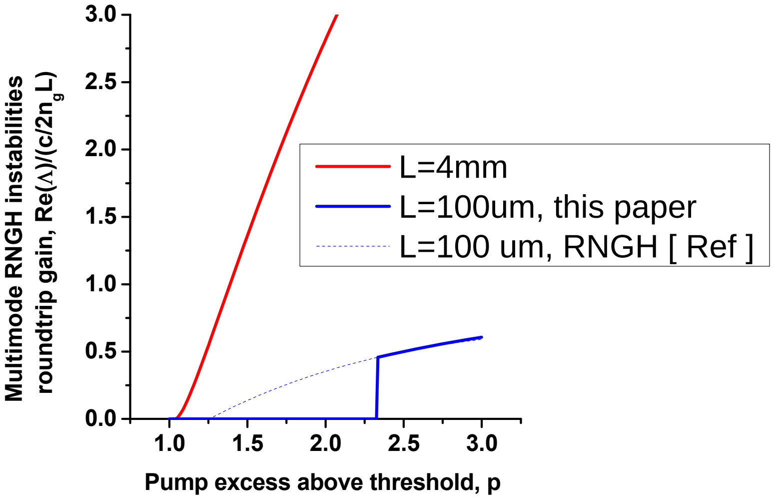

Figure 1. Cavity roundtrip gain for multimode RNGH instabilities in short (L=100µm) and long (L=4mm) cavities.

Predictions of the Lyapunov stability analysis were verified via numerical simulations with the travelling wave rate equations model of Ref.[7]. In the short cavity and above RNGH instabilities threshold, at p=2.5, the large-amplitude emission burst is followed by steady state oscillations (Fig.2(b)). The system attractor plotted in the plane of carrier density N and medium polarization P exhibits similar features in the first burst and regular oscillations. The amplitude P reaches about half of initial carrier density N/2, indicating (i) SR emission burst at the onset of emission and (ii) large-signal regular RNGH self-pulsation. Note the characteristic 8-shape of the attractor for RNGH self-pulsations. At p=1.5 (below RNGH threshold), amplitude of P is well below N/2 value, indicating that the decay process is not coherent. In long devices and above RNGH instabilities threshold (p=1.5 in Fig.2(c)), the system exhibits irregular pulsations, in agreement with expectations from the long cavity roundtrip time. System attractor exhibits the same 8-shape form attesting for RNGH instabilities. Incoherent emission of different domains across the sample results in the absence of the first SR burst.

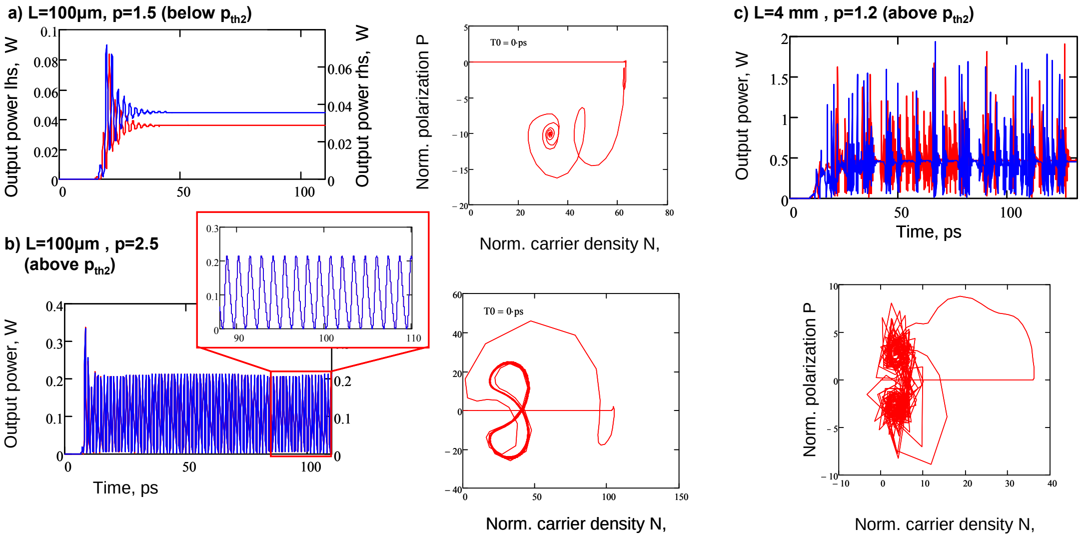

Figure 2. Output power waveform and P-N attractor in the short cavity QCL below (a) and above (b) RNGH threshold, and in the long cavity above RNGH threshold (c).

We noticed that RNGH instabilities observed from numerical simulations are not in a perfect agreement with the second threshold conditions as proposed by Risken, Nummedal [4] and Graham Haken [5]. Specifically, the original RNGH theory for multimode instabilities in a CW laser requires that the increment (real part of Lyapunov exponent) for small variations of the laser parameters is positive at the frequency of the first adjacent cavity mode (Fig. 1 dashed blue curve). However we obtain better agreement between numerical simulations and analytical prediction of the second threshold if we require that the spectral maximum of increment is located at the first adjacent cavity mode (Fig. 1, solid blue curve). In order to unambiguously confirm the value of second threshold, we compare it with the statistical outcome from numerical simulations based on the travelling wave rate equation model [7]. As a model system we use a short cavity sample (L=100μm). The travelling wave rate equation model incorporates Langevin force terms that seed the spontaneous polarization noise into the system. For each pump excess above lasing threshold p, we perform series of numerical simulations at different spontaneous polarization noise power injected into the system. Fig 3 shows that corresponding output power of amplified spontaneous emission P_{sp} varies over 6 orders of magnitude, while the second threshold does not show large variations (Fig 4).

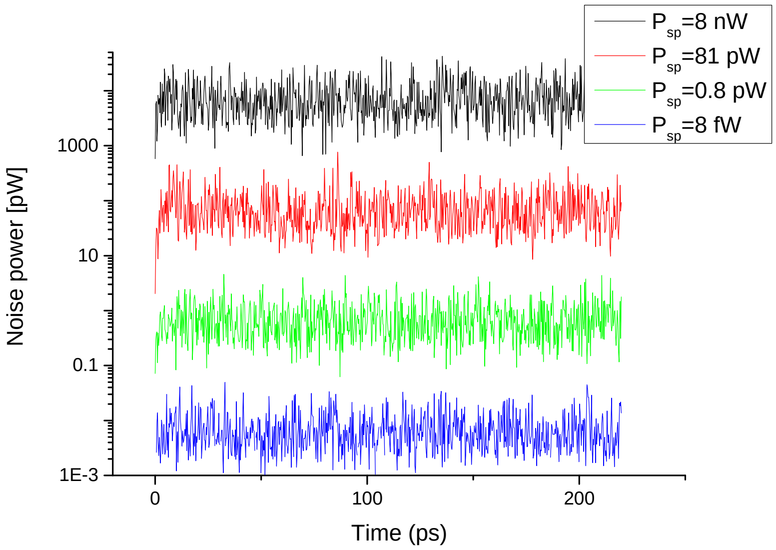

Figure 3: Output power of amplified spontaneous emission at below lasing threshold (p=0.9 for different levels of spontaneous polarization noise used in numerical simulations.

In Fig 4, for each set of parameters (p,P_{sp}) we perform a series of 20 simulations and indicate a probability to observe RNGH instabilities as a ratio n/20, with n being a number of realizations with RNGH instabilities. These data are displayed in Fig. 4 as columns and indicate that there is no RNGH instabilities for pump excess above lasing threshold p=1.5. This is in contradiction with traditional RNGH threshold conditions. (In Fig 1, dashed blue curve indicates the second threshold of 1.25).

At the same time, few realizations at p=2 indicates RNGH instabilities. Moreover, there is no systematic correlations at higher p between probability to observe RNGH instabilities and spontaneous noise power P_{sp}. Therefore in Fig 4 we also plot a curve indicating the average probability (at different P_{sp}). Each p, the indicated probability of RNGH instabilities is thus based on 80 realizations and has a dispersion of 0.056.

The RNGH instabilities start to develop at p between 2 and 2.5, with p=2.5 being the first point for which such probability exceed the uncertainty range. This is in reasonable agreement with the second threshold value of 2.35 obtained in Fig 3 (solid blue curve) using modified condition that the spectral maximum of instability increment shall be located at the first adjacent cavity mode.

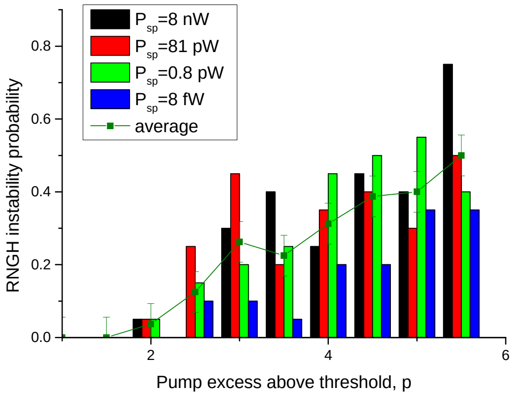

Figure 4: Probability to observe RNGH instabilities is plotted as a function of pump excess above lasing threshold p, with standard deviation. See further explanations in the text.

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 multimode RNGH instability modelling in QCLs discussed between the visitor and host. A draft of joint manuscript was difficult to complete without possibility to have discussions in person, as it requires having 10-15 such meetings during 1 month period. 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):

Planned joint publication, conference presentation at 8th Photonics Workshop: Kopaonik, 8-12. 3. 2015, submitted abstract for CLEO/Europe-EQEC 2015 conference is under evaluation.

References

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[6] R. H. Dicke, “Coherence in spontaneous radiation processes,” Phys. Rev. **93**, 99 (1954).
[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, 20.02.2015

Concern COST-STSM-BM1205-24265 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-BM1205-24265	School of Electrical Engineering, University of Belgrade, Serbia	Centre Suisse d'Electronique et de Microtechnique SA, Neuchâtel(CH), Switzerland	WG2	Collaborative efforts on modeling multimode Risken-Nummedal-Graham-Haken (RNGH) instabilities in quantum cascade lasers.	Theoretical analysis and numerical simulations, justification of criterion for 2nd threshold.

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.

Kind regards,

Dmitri Boiko,
Expert,
Time & Frequency,
Systems