STSM REPORT

STSM Application number: COST-STSM-BM1205-32560

STSM Grantee: Dr. Dmitri Boiko

STSM title: Ultrafast pulse production in MIR QCLs

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

Host Institution: Institute for Physics of Microstructures, Nizhny Novgorod (RU),

STSM period: 17/03/2016 - 10/04/2016

STSM purpose: Collaborative efforts between groups towards experimental realization of ultrashort pulse production regimes in mid-infrared quantum cascade lasers and measurements of output pulse parameters.

Description of the work carried out during the STSM:

The Centre Suisse d'Electronique et de Microtechnique (CSEM) and the Institute for Physics of Microstructures of the Russian Academy of Sciences (IPM-RAS) collaborate on the experimental realization of ultra-short pulse production regimes in quantum cascade lasers (QCLs). Ultrashort pulses produced in mid infrared (Mid-IR) range would be very important for many applications relaying on a time-resolved modality in imaging or spectroscopy.

Reaching the ultrafast pulse production regime in QCLs is a very challenging objective and demands large efforts and time. Towards this goal, as a starting point for this STSM mission (i) CSEM has designed and procured dedicated QCL samples with required facet coatings and cavity length 100-120 μm [1] and (ii) IPM-RAS together with CSEM has designed and assembled a dedicated test setup for optical pulse characterization, based on unique facilities available at IPM- RAS such as Fourier Transform InfraRed (FTIR) spectrometer enabling acquisition of time-resolved spectrochronograms in step-scan mode (Bruker, model Vertex 80V).

During this mission we address the following aspects:

(i) The shot cavity QCL has high threshold current density and its performance suffers from important self-heating effects even with the current pulses of low duty cycle. Therefore it was necessary to find an alternative approach for pumping such short-cavity QCLs. In this STSM we study a combined pumping approach that utilizes electrical bias of QCL to form the usual cascaded structure of the lasing transitions in the Mid-IR range and the interband optical pumping in the IR range to produce high electron density on the lasing transition.

(ii) FTIR is based on a Michelson interferometer. It will measure a usual interferogram of the optical field unless its standard detector is replaced by the one operating in the two-photon absorption (TPA) regime. In that case an intensity autocorrelation function will be measured using FTIR, whose correlation maximum half-width yields the optical pulse duration. (Because of the low duty cycle, the average power of our ultrafast QCLs operating at 8 µm wavelength is prohibitively low for attempting second harmonic generation in a non-linear crystal.) So far only two-photon Quantum Well Infrared Photodetectors (two-photon QWIPs) [2] have demonstrated suitable sensitivity in the TPA regime. However these detectors are not commercially available yet. Moreover, their epitaxial structure has to be specifically tailored for a given wavelength in the Mid-IR range because the FWHM of their TPA responsivity curve is only 0.3µm width. Therefore in this STSM we measure TPA sensitivity in several commercially available Mid-IR photodectors .

Description of the main results obtained:

Optical pumping of QCLs

The effect of internband optical pumping on QCL performance is cardinally different from the effect of optical pumping in conventional interband lasers and laser diodes. Existing literature provides confusing data about the effect of the optical pumping on QCL. Thus in [3] the interband optical pumping at 750-780 nm wavelength is applied simultaneously with injection of current pulses and leads to QCL threshold current reduction and output power enhancement at the emission wavelength of 10.5 µm. In [4], the optical pumping at 820 nm also resulted in QCL performance improvement. However in [5], a structure with similar alloy composition in the quantum wells (QWs) and barriers and also emitting at 10.6 µm have shown quenching of the lasing emission when pumped at 820 nm. The effect is attributed to the carrier heating when excitation photon energy is high. (Note that degradation due to carrier heating was not observed in Ref. [3] and [4].) In order to reduce the carrier heating effect, a resonant pumping was applied in [5] at 1550 nm wavelength corresponding to the interband transition in the active QWs, as evidenced by photoluminescence (PL) measurements.

We perform a series of measurements on optical pumping of our QCLs at several different wavelengths. The optical pumping have been attempted at 870 and 930 nm, 1.3 and 1.5 µm wavelengths. The interband PL, time–resolved electroluminescence and photoluminescence excitation (PLE) measurements have been performed with excitation wavelength in the range 700-1700 nm and detection either in the IR or Mid-IR range for QCL temperature -18°C or 0°C.

In these measurements, QCL was pumped with current pulses of several tens of microsecond width and low duty cycle. The optical pumping was made either from CW operating semiconductor lasers, OPO or with stretched pulses from a mode-locked Ti:S laser. QCL response was analyzed using FTIR spectrometer that records time-resolved spectrochronograms of the QCL emission.

We find that the optical pumping speeds up the transient processes at the begging of the current pulse. Once the main lasing mode sets in, the effect of the intraband optical pumping depends on whether or not the pump wavelength is below the gap in the QW barriers. Optical pumping at near the QW barrier edge results in quenching of the lasing emission. Interband pumping with photon energies at below the QW barriers results in fast increase of QCL output power and exhibits saturating behavior with the optical pump power. Interband pumping above the QW barriers results in a gradual increase of the QCL output power with the optical pump rate.

A manuscript communicating details of this study is under preparation.

Two photon absorption sensitivity of commercial Mid-IR detectors

We have tested several commercial Mid-IR detectors. Our QCLs operates at the wavelength of 8 µm. Therefore we select the photodiodes and photoresistances with sensitivity cutoff in the range of 4.5-5 µm. Their TPA sensitivity was characterized using OPO Solar laser Systems tuned at 8 µm emission wavelength. The results of the measurements are summarized in the Table 1 and Figure 1 below.

The TPA contribution to the average photocurrent of a detector is

$$I_{2\hbar\omega} = k_2 P^2 K / A_D$$

where A_D is the beam area, P is the incident average power. This expression is valid for the beam size being smaller than the sensitive area of the detector. The coefficient K accounts for the width and repetition rate of the optical pulses and was estimated prior to the tests and kept fixed throughout these measurements. The parameter k_2 shown in Table 1 is the most important parameter extracted from these measurements. It characterizes the TPA responsivity per unit beam area. However all detectors have different noise current. Therefore the ratio of k_2 to the power spectral density (PSD) of the noise current i_n provides an actual estimate for the TPA detector performance in terms of the signal to noise ratio (SNR).

Table 1 . Characteristics of commercial detectors tested in the TPA regime. Their models and manufacturers will be disclosed in the journal paper under preparation

	Detector #2	Detector #3	Detector #4
Description	InSb photoresistor	InAsSbP photodiode	InAsSbP photoresistor
Detector area, A_D	5x5 mm^2	$\pi(0.3/2)^2$ mm^2	2x2 mm^2
Linear response characteristics			
Cut-off wavelength	4.6 µm (TBC)	4.8 µm	4.5 µm
Responsivity, R_1 [A/W]	0.065 A/W	0.91 A/W	0.02 A/W
Noise equivalent power NEP [$W/Hz^{1/2}$]	1.123×10^{-9} W / $Hz^{1/2}$	N.A.	N.A.
specific detectivity D* [$cm \cdot Hz^{1/2}$ /W]	4.45×10^8 cm $Hz^{1/2}$ / W	2.5×10^{10} $cm \cdot Hz^{1/2}/W$	5×10^8 $cm \cdot Hz^{1/2}/W$
Current noise PSD, i_n [A/ $Hz^{1/2}$]	73×10^{-12} A/$Hz^{1/2}$	0.97×10^{-12} A/$Hz^{1/2}$	8×10^{-12} A/$Hz^{1/2}$
TPA sensitivity characteristics, 8 µm wavelength			
TPA responsivity per unit area k_2 [$A \cdot mm^2/W^2$]	1.2×10^{-6} A mm^2/W^2	4.3×10^{-8} A mm^2/W^2	5.4×10^{-10} A mm^2/W^2
SNR performance figure k_2/i_n [$Hz^{1/2} \cdot mm^2/W^2$]	1.7×10^4 $Hz^{1/2} mm^2/W^2$	4.4×10^4 $Hz^{1/2} mm^2/W^2$	68 $Hz^{1/2} mm^2/W^2$
Operation temperature	77 K	300 K	300 K

According to Table 1, the InAsSbP photodiode (detector #3) shows the best k_2/i_n ratio in the TPA regime. However its dynamic range is quite limited (panel (b) in Figure 1). In practical application for intensity autocorrelation function measurements, the InSb photoresistor (detector #2) provides both good SNR ratio and large dynamic range (panel (a) in Figure 1).

A manuscript communicating further details of this study is under preparation.

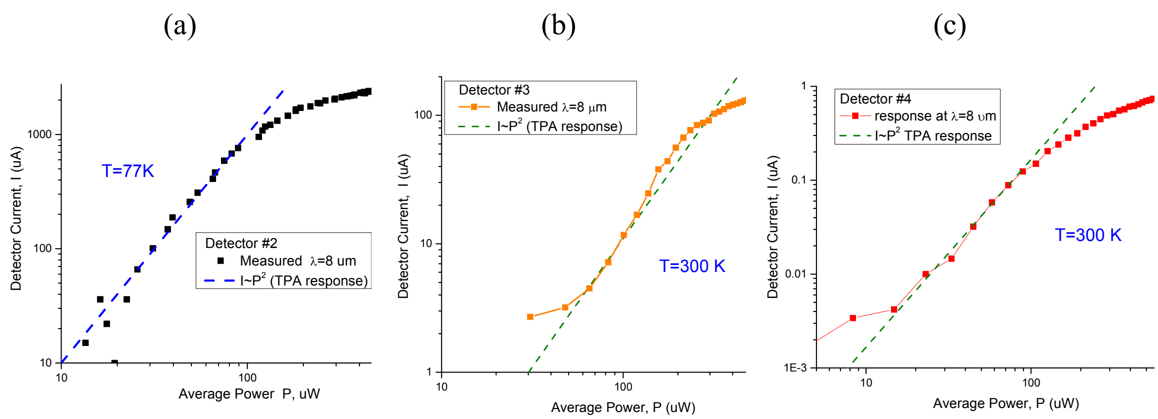

Figure 1. Measured response of detectors #2 [panel (a)], #3 (b) and #4 (c). The dashed line indicates the slope due to detector response in the TPA regime.

Mutual benefits for the Home and Host institutions:

Joint work of CSEM and IPM-RAS was successful and mutually beneficial. The results obtained show feasibility of optical pumping of QCLs and possibility to use standard Mid-IR detectors in the TPA regime for intensity autocorrelation function measurements. The joint work towards experimental realization of ultrafast pulse production in QCLs will be continued. The results will pave a way to novel application modalities of QCLs in imaging and spectroscopy, thus being beneficial for the entire COST action BM1205.

Future collaboration with the Host institution (if applicable):

CSEM and IPM-RAS will continue their collaboration on this topic. In the short-term perspectives it is desirable to prepare two manuscripts for publication.

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

"Optical Pumping of Quantum Cascade Lasers", in preparation
“Two Photon Absorption in the Mid-Infrared InSb and InAsSbP Photoresistances and Photodiodes” in preparation

References

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COST-STSM-BM1205-32560 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-BM1205-32560	Centre Suisse d'Electronique et de Microtechnique SA, Neuchâtel (CH), Switzerland	Institute for Physics of Microstructures, 603950, Nizhny Novgorod (RU), Russia	WG2	Collaborative efforts on ultrafast pulse production in MIR QCLs.	Experimental measurements on (i) two-photon detector sensitivity for pulse width measurements (ii) optical pumping approach for QCLs designed for short pulse production.

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,

Dr. Vladimir Vaks 27.05.2016