2nd European Workshop on Vertical-External-Cavity Surface-Emitting Lasers

15-17 October 2013

Université Montpellier 2, France

workshop schedule & abstracts

http://vecsel.ies.univ-montp2.fr/?-Events-
Workshop VeCSEL 2013

Organizers
IES, CNRS UMR5214, Université Montpellier 2, France

Organization Committee
Dr. Arnaud Garnache IES CNRS, F, Conference Chair
Dr. Stéphane Blin IES CNRS, F
Dr. Mikhaël Myara IES CNRS, F, Conference co-Chair
Sylvie Tixier IES CNRS, F, Secretary

Scientific Committee
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Dr. Arnaud Garnache IES CNRS Montpellier, F
Dr. Jennifer Hastie IOP Strathclyde, UK
Dr. Gaëlle Lucas-Leclin Institut d’Optique CNRS Palaiseau, F
Dr. Isabelle Sagnes LPN CNRS Marcoussis, F
Dr. Alexei Sirbu EPFL Lausanne, CH
Pr. Anne Tropper University of Southampton, UK
Pr. Hans Zogg ETH Zurich, CH
Foreword

This second European workshop aims to bring together relevant academics and companies working in the field of Vertical-External-Cavity Surface-Emitting Laser for Photonic Applications (agro-environment, security, metrology, inertial sensor, atmospheric physics, lidar, radar, telecom...), to present and discuss the research advances and technological breakthroughs in this new field. This year, the workshop is improved by the insertion of invited tutorials in various fields out of the VeCSEL community in the oral sessions, poster sessions and some exhibitors demonstrating industrial products in various fields (spectroscopy, optical integration, optical systems...) at the state of the art. This workshop is open to young researchers (PhD student, postdoc).

The workshop covers all topics related to Vertical-External-Cavity Surface-Emitting Laser and its photonic applications, including sessions devoted to:

- Design, Growth, Technology and High Power,
- Mode-Locking & Continuum,
- New Concepts,
- Spectral Coverage & Non-Linear Conversion,
- Noise, Coherence & Fundamental Properties,
- Fundamental & Industrial Applications.

The official language of the Workshop is English.

Tutorials are allotted 35 minutes, and regular talks 20 minutes (including discussion). There is two poster sessions, located in the entrance hall, together with the exhibitors booths.

The Scientific Committee
& the Organization Committee.
Acknowledgements

The financial support and infrastructures which helped the workshop organization came from several Institutions that we warmly acknowledge: Institut d’Electronique du Sud (IES), Université Montpellier 2 (UM2), Agence Nationale de la Recherche (ANR), Centre National de la Recherche Scientifique (CNRS), Société Française d’Optique (SFO), Optitec/Popsud, Renatech network, EOS. The organizers also want to thank Innoptics and Resolution Spectra Systems for their participation to the workshop and their financial support.

The organization of this 2nd Workshop VeCSEL in 2013 has been made possible by the work of the local organizers that I thank for their essential contribution, namely the Organization Committee.

I finally acknowledge all the members of the Scientific Committee who helped in building the scientific program.

The Conference Chair
Dr. Arnaud Garnache
IES-CNRS UMR5214
Université Montpellier 2, France
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Localization

The Workshop takes place in the town-center of Montpellier, at “Institut de Botanique”, close to the “Jardin des Plantes”:

Institut de Botanique
Amphithéâtre Charles Flahaut
163 Rue Auguste Broussonnet
34090 Montpellier

The “Institut de Botanique” can be easily joined on foot from the town center. It is also at 5 minutes on foot from the “Place Albert 1er” Tramway-Station (Line 1). Tickets for the tramway are available at vending machines in most Tramway Stations.

You should notice that most useful spots for your venue to Montpellier are in the neighborhood of the town center and along the Tram Line 1, including:

- the workshop itself (“Place Albert 1er” station),
- the town center (“Place de la Comedie” station), with various shops, restaurants or hotels,
- for people joining Montpellier by train, the train-station (“Gare SNCF St Roch” station),
- for people joining Montpellier by plane, the connection with the shuttle to/from the airport (“Place de l’Europe” station). The shuttle itself is called “Navette Aéroport ligne 120”.

![](image.png)
Social Events

(included in the registration)

“Montpellier Old Town” visit (Wednesday 14:00)
Appointment at the "Institut de Botanique".

Montpellier Old Town: the historical centre
The must-do guided tour for your first look at the city.
Relive the prodigious rise and exceptional destiny that Montpellier has forged over centuries. A XIIth century Mikveh (Jewish ritual bath) - an authentic Medieval treasure, a private mansion courtyard, and more, illustrate a 1000-year journey through the maze of alleyways in the city's historical center. A well-planned mix concocted by the tourist office's guides, ending on a surprising note at the top of the triumphal arch.

French wine tasting (Wednesday 18:00 / at Poster Session closing.)
Wine tasting from "Mas de l'Oncle" winery.
Nestled in the north of Montpellier, the village of Lauret at the foot of the Pic Saint Loup has the privilege to host some growers among the elite of the Pic Saint Loup appellation Coteaux du Languedoc. The main soils present are soft limestone, marl, hard limestone and clay-limestone scree. The proximity of the Cevennes gives them a typical continental affecting the profile of the wines and mark their uniqueness (thermal amplitude marked, especially in summer). The harvest is entirely manual. The winemaking is conducted in small tanks capacities promoting good soaking berries. Finesse and fruit are preferred. The wines are then aged 12 to 18 months.

Conference Dinner (Wednesday 19:30)
Lebanese dinner
We are happy to invite the conference attendees to enjoy a Lebanese traditional meal cooked by Ibtissam, who knows how to give her dishes all the magic of East sweetmesses. Her cook is of a great quality, family and authentic. All the meats are marinated in Lebanese way.
You will appreciate the "taboulé citronné" (lemon-flavoured tabbouleh), the "houmous" (chick-pea), the "moutabal" (aubergine), the "fatayer" (cheese stuffed fritter) which are all delights for papillae, as well as a variety of desserts.
## Schedule

**Tuesday 15 October, Afternoon**

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<td>13:00</td>
<td>Registration</td>
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<tr>
<td>14:00</td>
<td>Welcome</td>
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<tr>
<td><strong>14:30</strong></td>
<td><strong>Session 1: Design, Growth, Technology and High Power</strong>&lt;br&gt;Chairman: Dr. I. Sagnes (LPN) &amp; Pr. H. Zogg (ETH)</td>
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<tr>
<td>14:30</td>
<td>IV-VI / II-VI Semiconductor Emitters <em>(Invited Tutorial)</em>&lt;br&gt;Gunther Springholz</td>
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<td>15:05</td>
<td>Tunable lead-salt on Si VECSEL for 3-5 µm mid-infrared spectroscopy <em>(Oral)</em>&lt;br&gt;Hans Zogg</td>
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<td>15:25</td>
<td>Mid-IR VECSEL based on Epitaxial PbTe Quantum Dots Embedded in CdTe <em>(Oral)</em>&lt;br&gt;Amir Khiar</td>
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<td><strong>15:45</strong></td>
<td><strong>Coffee Break &amp; Poster Session</strong></td>
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<td>16:45</td>
<td>Recent progress in THz Quantum Cascade Lasers <em>(Invited Tutorial)</em>&lt;br&gt;Giacomo Scalari</td>
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<tr>
<td>17:20</td>
<td>Improvement of the thermal properties of semiconductor chips at 850 nm <em>(Oral)</em>&lt;br&gt;Iryna Gozhyk</td>
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<tr>
<td>17:40</td>
<td>Study of intensity and frequency noise of 15 Watt single frequency VECSEL <em>(Oral)</em>&lt;br&gt;Alexandre Laurain</td>
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<td><strong>18:00</strong></td>
<td><strong>End of the Day</strong></td>
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### Session 2: Mode-Locking & Continuum
Chairman: Dr. S. Calvez (LAAS) & Dr. A. Garnache (IES)

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<th>Time</th>
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<tr>
<td>09:00</td>
<td>High average power ultrafast thin-disk oscillators <em>(Invited Tutorial)</em></td>
<td>Clara Saraceno</td>
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<td>09:35</td>
<td>Recent Advances in Ultrafast MIXSELs <em>(Oral)</em></td>
<td>Christian A. Zaugg</td>
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<td>09:55</td>
<td>Modeless highly coherent Frequency-shifted-feedback Vertical External Cavity Surface Emitting Laser <em>(Oral)</em></td>
<td>Mohamed Sellahi</td>
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**10:15 Coffee Break**

### Session 3: New Concepts
Chairman: Dr. A. Sirbu (EPFL) & Dr. G. Feugnet (TRT)

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<th>Time</th>
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<tr>
<td>10:45</td>
<td>Non-linearity and noise in semiconductor laser <em>(Invited Tutorial / abstract in Session 5.)</em></td>
<td>Philippe Gallion</td>
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<tr>
<td>11:20</td>
<td>Control of new spatial, temporal and polarization coherent light states with VeCSEL: VORTEX, continuum, THz, spin <em>(Oral)</em></td>
<td>Arnaud Garnache</td>
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### Session 4: Spectral Coverage & Non-Linear Conversion
Chairman: Dr. A. Sirbu (EPFL) & Dr. S. Calvez (LAAS)

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<tr>
<td>11:40</td>
<td>Novel nonlinear materials and frequency control for lasers <em>(Invited Tutorial)</em></td>
<td>Valdas Pasiskevicius</td>
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<td>12:15</td>
<td>High power semiconductor disk lasers for 1.3-1.6 µm and 650-800 nm spectral ranges <em>(Oral)</em></td>
<td>Antti Rantamaki</td>
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**12:35 Lunch**
Wednesday 16 October, Afternoon

14:00  **Social Event: Montpellier Old Town visit**

16:15  **Poster session & coffee**

- A hybrid Photonic Crystal-based semiconductor Bragg mirror: A low loss functional mirror for high-Q external cavity lasers
  - Mohamed Seghilani
- Optical Scattering Losses in VECSELs
  - Dalia Al Nakdali
- CW Monolithic GaSb-VCSEL operating up 70°C
  - Laurent Cerutti
- Mode-locked VeCSELS: high repetition rate pulse sources for nonlinear optics
  - Ed A. Shaw
- Coherent High-order Laguerre-Gauss modes with a high-Q external-cavity semiconductor laser: standing-wave radial pattern and VORTEX
  - Mohamed Sellahi
- Evaluation of a dual-frequency VECSEL emitting at 852 nm for cesium atomic clocks using coherent population trapping
  - Paul Dumont
- Design and physical properties of integrated single frequency VeCSEL
  - Attia Benselama
- Solid State Alternative of Gas Ring Laser Gyroscope
  - Gilles Feugnet
- Dual-Frequency Vertical External Cavity Surface Emitting Laser for Terahertz Generation *(Poster)*
  - Romain Paquet

18:00  **Cocktail with french wine tasting.**

19:30  **Lebanese dinner in the patio of Institut of botanique.**
Thursday 17 October, Morning

09:00 **Session 5: Noise, Coherence & Fundamental Properties**
Chairman: Dr. A. Garnache (IES) & Dr. S. Calvez (LAAS)

09:00 Light-polarization dynamics in surface-emitting semiconductor lasers *(Invited Tutorial)*
Salvador Balle

09:35 Control of light polarization using spin-injected VECSELs *(Oral)*
Julien Frougier

09:55 Square-Wave emission and Dissipative Vector Solitons in a Vertical Cavity Surface-Emitting Laser using polarization degree of freedom *(Oral)*
Mathias Marconi

10:15 Influence of Intra-cavity Losses on the Temporal Dynamics of the Dual-Wavelength Emission in VECSELs *(Oral / abstract in Session 3.)*
Mohammad Khaled Shakfa

10:35 **Coffee Break**

11:05 **Session 6: Fundamental & Industrial Applications**
Chairman: Dr. G. Feugnet (TRT) & Dr. A. Sirbu (EPFL)

11:05 High sensitivity CRDS & CEAS Spectroscopy for gas analysis with semiconductor lasers *(Invited Tutorial)*
Daniele Romanini

11:40 Design and manufacturing of a single frequency compact VeCSEL module in the NIR and MIR *(Oral)*
Vincent Lecocq

12:00 Developments of miniature atomic clocks based on coherent population trapping, VCSELS and MEMS: Technology of fabrication and laser source requirements *(Invited Tutorial)*
Nicolas Passilly

12:35 **Lunch**

Thursday 17 October, Afternoon

13:00 **Organization & Scientific Committees meeting.**

14:30 **Round Table.**

15:30 **Lab Tours.**

17:30 **End of the day.**
ABSTRACTS
Session 1

Design, Growth, Technology and High Power

Chairman: Dr. I. Sagnes (LPN) & Pr. H. Zogg (ETH)

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<td>Dalia Al Nakdali</td>
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<td>CW Monolithic GaSb-VCSEL operating up 70°C <em>(Poster)</em></td>
<td>Laurent Cerutti</td>
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Epitaxial heterostructures of IV-VI and II-VI semiconductors provide interesting perspectives for optoelectronic device applications by combination of narrow gap and wide band gap materials with quite different physical properties. The IV-VI semiconductors, including PbTe, PbSe and SnTe (lead salt compounds), with band gaps in the 100 to 400 meV range have been employed for mid-infrared diode lasers [1], VCSELs [2], microdisk lasers [3] and VeCSELS [4] with emission in the 3 to 10 µm wavelength range, whereas the applications of II-VI compounds (except for HgCdTe) with band gaps well above 1 eV lie mostly in the NIR and visible region. In terms of heteroepitaxial growth, there is a remarkably close lattice matching between PbTe and CdTe, as well as of PbSe with CdSe or ZnTe, but the lattice structure differs as the IV-VI compounds crystallize in the rock salt structure, whereas the II-VI semiconductors usually feature a zinc blende structure. This lattice-type mismatch has important consequences for heteroepitaxial growth.

In this presentation, the growth, structural and electronic properties of IV-VI / II-VI heterostructures [5,6] is reviewed and examples for optoelectronic device applications presented. A particularly interesting feature is the possibility for fabrication of strain-free lead salt quantum dots embedded in CdTe based on the morphological transition of 2D epilayers by phase separation due to the Rayleigh-Plateau instability of two phases systems. Figure 1 shows examples of such quantum dots which resemble heterogeneous nanocrystals embedded in a single crystalline matrix material. These quantum dots show a widely tunable optical emission as shown by Fig. 1, with emission wavelength tunable from 1.5 to 5 µm by size [5] and composition control [6]. Based on such quantum dots, mid-infrared light emitting diodes and microdisk lasers are demonstrated.

Acknowledgments. This work was supported by the Special Research Program IR-ON of the Austrian Science Funds (FWF), the FWF Project P20970-N20 and the GME of Austria.

References
VECSELs emitting in the mid-infrared range above ~3 µm wavelengths have been realised with IV-VI narrow bandgap semiconductors like PbXSe, PbXTe or PbXS (X = Eu, Sr or Sn) only. The devices are fabricated by solid state MBE on lattice mismatched Si-substrates [1-3]. Promising devices emitting between 2.5 and 10 µm have so far been realised using optical pumping and without delineating the active area. However, the observed pump threshold powers were much higher than expected from theory, even taking into account the high dislocation density in the lattice mismatched structures.

For the threshold gain calculations, a 1-d model had been used previously assuming that the refractive indices n do not change due to the temperature rise under the pump beam. A more detailed numerical gain calculation [4] was recently performed by one of the authors (P.D. at IEIIT-CNR) taking into account the negative temperature dependence of n (Δn/n = -2.5·10^-4/K for PbSe). Note that Δn/n is positive in III-V materials. This calculation (performed for a PbSe based QW laser with PbSrSe barriers emitting at ~3.3 µm and a 40°C temperature rise at the center of the pump beam) lead to a much higher threshold gain than obtained with the 1-d model. This is because of the antiguiding effect due to the negative Δn/n. A significant improvement is calculated when etching pillars with eg. 30-50 µm diameter in the active QW PbSr/PbSrSe layer stack. This is to reduce the antiguiding.

Devices fabricated in this manner indeed showed up to ~10 times reduced threshold power compared to the unetched samples. Threshold power is now <1 W (when pumped with 1.55 µm laser diodes) near room temperature. With variable cavity lengths around 20 µm employing Piezo-crystals, tunable true monomode emission from ~3.2 to 3.45 µm wavelength was obtained. These devices are intended for spectroscopically probing the C-H bonds of the different hydrocarbons.

Mid-IR VECSEL based on Epitaxial PbTe Quantum Dots Embedded in CdTe

A. Khiar*, M. Witzan, V. V. Volobuev, A. Hochreiner, M. Eibelhuber, G. Springholz
Linz University, Altenbergerstr. 69, A-4040 Linz, Austria
* amir.khiar@jku.at

Vertical External Cavity Surface Emitting Lasers (VECSELs) operating at wavelengths above 2.8 µm have been realized using IV-VI semiconductors, such as PbSe, PbTe and PbS [1-3]. However, the gain regions have been restricted to quantum well or bulk-like structures. Here, we demonstrate the first mid-IR VECSELs based on PbTe quantum dot (QD) active regions.

A schematic sketch of our VECSEL layout is presented in figure 1a. The active structure of the VECSEL is grown by MBE on a (100) GaAs substrate. It consists of 24 layers of PbTe QDs embedded in a CdTe host matrix. The QD have a diameter around 22 nm and are situated close to the cavity antinodes. The MBE growth is typically done at low substrate temperature (250-300°C), where the deposition of PbTe results in a 2D-layer growth. By subsequent post-growth annealing at higher temperature (350-400°C) the 2D PbTe layers break up and form isolated quantum dot layers. This is illustrated by figure 1b, which shows a TEM image of a stack of five QD layers. The dot formation is driven by a interface energy minimization between the PbTe and CdTe rather than by heteroepitaxial strain [4,5]. The Bragg mirrors of the VECSEL cavity consist of separately grown high reflecting PbSrTe/BaF2 λ/4-layer pairs. The bottom Bragg mirror consists of 4.5 pairs to reach a reflectivity of more than 99.9% and the top external mirror is realized with 2.5 pairs deposited on a curved polished BaF2 substrate.

Figure 1c shows laser emission spectra at different temperatures. The active region was in-dot pumped using 1.064 µm pump laser with 100 ns pulses and 30 kHz repetition frequency. The laser emission is tunable from 4.2 µm down to 3.6 µm by changing the temperature from 85 K to 230 K. At low temperature the absorbed threshold pump power is below 1 W and the output power is more than 50 mW. Additionally, the emission wavelength can be changed by controlling the size of the QDs or adding Strontium to the PbTe QDs. An increased operating temperature of the VECSEL is expected by optimizing the active region design and with help of a suitable heat spreader, such as diamond or SiC.

Fig. 1: (a) VECSEL layout. (b) A TEM image of a stack of five PbTe QD layers in CdTe. (c) VECSEL spectra at different temperatures.

References
Recent progress in THz Quantum Cascade Lasers

G. Scalari1, ⋆, D. Turčinková1, K. Otani1, M. Rösch1, C. Bonzon1, M. Beck1 and J. Faist1
1. Institute of Quantum Electronics, ETH Zürich, Wolfgang-Pauli Strasse 16, Zürich, Switzerland
⋆ scalari@phys.ethz.ch

The THz frequency range (1-10 THz) presents a number of potential applications (imaging, chemical sensing, telecommunications among others) but still presents a lack of compact and coherent radiation sources. The THz quantum cascade (QC) laser is a semiconductor laser based on intersubband transitions in quantum wells [1, 2]. It presently covers a wide spectral window ranging from 4.9 THz to 0.73 THz. The possibilities to extend its operating frequency range as well as its maximum operating temperature are related to an efficient quantum design of the active material as well as to the development of low loss waveguides. In this talk we will review the principal features and the recent progress in the realization of terahertz (THz) quantum cascade lasers. Active region design together with laser resonators design will be discussed. We will then focus on recent developments about ultra-broadband operation [3] and new material systems for THz QCLs [4]. We recently demonstrated a THz QCL based on an heterogeneous cascade concept which shows laser action over a bandwidth of more than 1 THz between 2 and 3 THz (see Fig.1(a)). With CW operation up to 50-60 K such a device constitutes and excellent candidate for a mode-locked laser with pulse length of less than 1 ps [5]. High performance THz QCLs are generally realized in the GaAs/AlGaAs material system. On the contrary, the In0.53Ga0.47As/Al0.48In0.52As/InP is a powerful material system for the fabrication of mid-infrared quantum cascade lasers (QCLs). The quite large band discontinuity offered by this material system is not needed at THz energies and brings problems related to excessively thin barriers. For such reason we developed an alternative approach based on the use of a quaternary alloy AlInGaAs for the barrier material. First results are encouraging showing lasing at 3.4 THz with maximum operating temperatures of 130 K in pulsed mode (see Fig.1(b)) for a 4-quantum well design.

Fig. 1: (a): Series of spectra as a function of the injection current in pulsed mode at T=10K for the heterogenous cascade device of Ref.[3]. (b): Pulsed current density (J)-voltage(V)-light (L) output characteristics as a function of temperature for the quaternary sample of Ref. [4]. The ridge width was 150 µm wide and the cavity length was 1.5mm long.

References
Improvement of the thermal properties of semiconductor chips at 850 nm

Iryna Gozhyk, Grégoire Beaudoin, Sylvie Janicot, Xavier Lafosse, Arnaud Garnache, Isabelle Sagnes, Patrick Georges, and Gaëlle Lucas-Leclin

1. Laboratoire de Photonique et de Nanostructures, CNRS, Marcoussis, France
2. Laboratoire Charles Fabry, Institut d’Optique, CNRS, Univ Paris-Sud XI, Palaiseau, France
3. IES – CNRS UMR 5214 – Université Montpellier II, Montpellier, France

* iryna.gozhyk@lpn.cnrs.fr

Vertical external cavity surface emitting lasers (VECSELs) combine the advantages of solid-state lasers and diode lasers, such as wavelength versatility and fine adjustment of both spectral and spatial properties of the laser beam. In particular in the 850 nm range, a single-frequency high-power (>200 mW) VECSEL could simplify the optical benches of Cs atomic clocks and inertial sensors. However, this still requires to increase the emission power of VECSELs in the spectral range around 850-nm (150 mW in single-mode regime [1]), currently limited by strong thermal saturation and substantially decreased with additional intra-cavity wavelength-control elements. Thereby, a thorough design and thermal management are indispensable for the semiconductor chips for CPT experiments at 852 nm.

We report a theoretical and experimental study on the thermal resistance of 852-nm VECSEL active chips bonded on an electroplated gold substrate. The semiconductor chip was designed for emission at 852 nm and consists of a high-reflectivity (99.5 % at 850 nm) Bragg mirror and an anti-resonant (29 λ/4) active cavity (seven 8 nm-thick GaAs quantum wells embedded in Al0.22Ga0.78As pump-absorbing barriers), grown in the given order on a 350 µm-thick GaAs substrate with the MOCVD technique. The chip is covered with an anti-reflection coating (λ/4 of Si3N4). In order to improve its thermal resistance [2], the GaAs substrate is removed with chemical etching (NH3 to etch GaAs then HF and HCl to relove the etch-stop layer) and a 50 µm Au layer is deposited with evaporation (200 nm of Au atop 20 nm of Ti, added for adhesion) followed by electrolytic deposition. To preserve the sample flatness, chip surface was divided into 5*5mm squares with polymer lines, deposited with the e-beam lithography before the electrolytic deposition.

Experimentally, the thermal resistance of the semiconductor chips (as grown on GaAs substrate, and on the Au substrate) is evaluated from the evolution of the laser line with the incident pump power and the substrate temperature through the relationship

\[ R_T = \frac{\Delta T_s}{\Delta P} \]  

where \( \Delta T_s \) is defined at the threshold. For a pump waist radius \( w_p=42\mu m \), we measure a thermal resistance of 46 K/W (with regard to the incident pump power) for the structure on GaAs, and 23 K/W for the structure on Au. These values are in satisfactory agreement with numerical predictions from a finite element analysis using the software COMSOL, respectively 43 K/W and 18 K/W for the GaAs and Au substrates assuming a thermal load of 30 %. The twofold reduction of the thermal resistance of the Au-substrate sample, as compared to the GaAs-substrate, permitted to postpone the thermal roll-over of the laser power to higher pump powers (Fig.1.a).

**Fig. 1:** Output power (a) and emission wavelength (b) as a function of input power with a pump spot diameter 84µm and Toc=1.1%.

**Acknowledgments.** This work was supported by RTRA/Triangle de la Physique (AO’12) and the French RENATECH network.

**References**

Optically-Pumped Semiconductor Lasers (OPSL) are emerging as the key technology for directly generating high brightness, high-power and highly coherent lasing emission. The semiconductor active medium combined with the external cavity geometry offers enormous flexibility for generating high quality beams at wavelengths ranging from mid-infrared to the deep-ultraviolet via efficient intra-cavity harmonics generation. Recently, an output power of more than 100W has been demonstrated with a single chip VECSEL in multimode operation [1,2]. Here, we demonstrate more than 15W at 1020nm in single frequency continuous wave operation with a free running linewidth of 21kHz over a sampling time of 1ms. As shown on Fig.1.a), we reached a maximum output power of 15.1W in single frequency operation for an incident pump power of 95W, without noticeable sign of thermal rollover. At this power, the transverse intensity profile exhibits a TEM$_{00}$ mode with very low phase fluctuations leading to a M²<1.2.

To evaluate the intrinsic laser linewidth and identify the main noise sources, we measured the frequency noise spectral density of the laser (Fig.1.b). For this measurement, we used a homemade plano-concave Fabry-Perot as frequency discriminator. The two mirrors of the interferometer were spaced by an ultra-stable zerodur material and enclosed in an insulation box for noise reduction. For a sampling time of 1s, the RMS frequency noise is 720kHz and decreases to 44kHz for a 1ms sampling time. The frequency noise is clearly limited by the mechanical resonances around 200Hz, mainly due to the water cooling system. The associated linewidth was deduced from integral computation of the frequency noise spectral density. The laser linewidth exhibits a quasi-gaussian shape with a FWHM of 21kHz (995kHz) for a sampling time of 1ms (1s). With this device, we also measured a wavelength tuning range of 10nm and a mode hop free tunability >9GHz.

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References


A hybrid Photonic Crystal- semiconductor Bragg mirror: A low loss functional mirror for high-Q external cavity lasers


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Achieving highly coherent high power semiconductor lasers requires the use of spatially stable and high finesse cavities, which are usually realized using commercial dielectric concave mirrors in a concave-type stable cavity; another solution is to use the thermal lens to realize a stable Laguerre-Gauss or Hermite-Gauss laser cavity [1], but this is difficult to control, furthermore it introduces aberrations in the laser beam, moreover the two solutions are very limited if we want to add some functionalities to the mirror like beam shaping, polarization control... etc.

Among many other functionalities, Photonic crystals (PC) can allow a precise control of the transverse phase and intensity profile. In this work we demonstrate a low-loss, high reflectivity and aberrations free Photonic Crystal bragg Mirror with focusing capability, for single mode cavity operation, using a planar III-V semiconductor technology, for highly coherent high power external cavity semiconductor laser using a 2D PC on Bragg mirror. We demonstrated that Vertical External Cavity Surface Emitting Laser (VECSEL) is a very promising laser technology to achieve compact highly coherent high power semiconductor laser, with a beam shaping PC-based planar mirror in a short mm long cavity [1].

Fig. 1: PC-based Concave Bragg mirror design, used in highly coherent VECSEL. (b) PC Phase variation curves as function as the filling factor; (c) Laser far field phase & intensity map recorded with a wavefront sensor (field curvature removed).

To obtain the adequate design we used Rigorous Coupled Wave Analysis (RCWA) to obtain the dispersion curves as function of the fill factor (hole diameter / PC period); The semiconductor structure holding the PC was grown by MOCVD on GaAs substrate : the multilayer DBR is made of AlAs/GaAs layers, the last layer being a GaAs spacer; on top, a 312nm thick SiN was deposited by sputtering; finally after an e-beam lithography of the SiN layer (1.25nm resolution), the holes of the PC were obtained by reactive ion etching. (Fig1 -b).

We used the PC M to form a tunable single frequency TEM00 stable laser cavity, using a GaAs-based ½-VCSEL quantum-well gain structure designed for λ=1.01µm emission grown by MOCVD. The obtained single frequency laser performances are totally comparable with those obtained with dielectric commercial laser-quality mirrors: low threshold density of 2.1kW/cm², high efficiency, TEM00 beam close to diffraction limit (2% of rms fluctuations) (Fig1-c), linear light polarization (>32dB) and Side Mode Suppression Ratio > 43dB. This demonstration paves the way to highly coherent, high power compact semiconductor laser with embedded functionalities, like Bessel-Gauss lasers, high order transverse mode lossless selection, thermal lens compensating, polarization and spectral filtering,...etc [3].

Acknowledgments: This work is supported by ANR Micphir, ANR Natif, RENATECH network

References
During the last two decades vertical-external-cavity surface-emitting lasers (VECSELs) have attracted increasing interest due to their potential scientific and industrial applications [1]. They not only combine advantages of solid-state and semiconductor lasers, they can even exhibit mode-locking operation with 400 fs pulses at 4.35 kW peak powers [2]. Indeed, VECSELs have been shown to generate a record-high continuous-wave output power of 106 W at an emission wavelength of 1028 nm [3]. However, the thermal roll-over effect in a VECSEL generally limits the output efficiency [4]. Thus, further optimization of such systems requires advanced heat management. Besides heating losses, also non-heating power losses are expected. These mainly consist of optical losses [5], i.e. spontaneous emission in the chip and intra-cavity scattering. In this context, we report on an analysis of surface-scattering losses in VECSELs. A simple model for the extraction of the laser chip’s thermal resistance from experimental input-output characteristics is expanded taking into account non-thermal losses.

Furthermore, based on a systematic analysis of the VECSEL’s thermal roll-over at different heat sink temperatures and for various output coupler mirrors, the corresponding scattering coefficient is determined. In this study, the optically pumped chip structure used is designed for operation at 1010 nm. To promote the effects of surface scattering for an improved investigation, a sample chip was chosen that features an enhanced surface roughness, also allowing the implication that surface scattering poses the predominant optical-loss channel. Here, a V-cavity is employed with different plane output coupler mirrors with transmittance ranging from 1% to 15%. Since the thermal resistance basically depends on the VECSEL chip material and the heat-sink geometry, which are constant qualities in the experiment, no correlation with transmittances or other resonator components is expected. In this context, our thermal-resistance analysis shows that in contrast to a simple model, only a model taking into account a power-loss component proportional to an optical surface-scattering-loss coefficient in relation to photon out-coupling rates can deliver a constant value for the resistance (Fig. 1). Moreover, such analysis allows us an estimation of power losses via optical surface-scattering.

Fig. 1: Thermal resistance vs the output-coupler transmittance; blue circles represent the results obtained from a simple model while the thick violet line depicts a constant value with area of uncertainty obtained from a model which takes into account optical scattering losses.

References

Vertical Cavity Surface Emitting Lasers (VCSELs) present several interesting characteristics such as longitudinal single-mode operation, circular output beam and low power consumption. These properties combined with a large continuous tunability make VCSELs good candidates for gas sensing via Tunable Diode Lasers Absorption Spectroscopy (TDLAS). The wavelength range above 2 \( \mu \)m is rich of interest due to the presence of atmospheric windows and strong absorption lines of several pollutants such as NH\(_3\), CH\(_4\), CO\(_2\), ... GaSb-based materials allow covering this wavelength range by exploiting efficient GaInAsSb/AlGaAsSb type I quantum wells (QWs) system.

Up to now, GaSb-based VCSEL operating in CW are based either on buried tunnel junction (BTJ) or a monolithic etched mesa. The first technology allowed demonstrating single mode operation up to 70 \( ^\circ \)C at 2.3 \( \mu \)m [1] and up to 50 \( ^\circ \)C at 2.6 \( \mu \)m [2]. However device processing is complex and relies on an epitaxial re-growth step. The second technology is simpler but lacks an efficient electro-optical confinement which limits CW operation to temperatures below 20 \( ^\circ \)C and precludes single mode emission [3].

In this paper, we report the first single-mode monolithic GaSb-based VCSELs based on a lateral etching of the InAs/GaSb tunnel junction to provide efficient electro-optical confinement. The structure is grown by solid source molecular beam epitaxy (MBE) on n-doped GaSb substrate. It consists of 2 N-type lattice matched AlAsSb/GaSb distributed Bragg reflectors (DBRs), a MQWs active region for emission at 2.3 \( \mu \)m, and an InAs/GaSb TJ positioned above the QWs at a standing wave null position in order to reduce absorption losses.

Device processing involved first a wet etching of the top DBR down to the InAs TJ. Then, InAs is selectively etched with a solution of citric acid and hydrogen peroxide to form the thin air gap aperture. Figure 1 illustrates the device structure after the whole process. We focus on a device with 35 \( \mu \)m pillar diameter, a top aperture of 25 \( \mu \)m and 6 \( \mu \)m TJ aperture diameter.

Figure 1.b presents the light-current-voltage (L-I-V) characteristics in CW mode at various temperatures. CW operation was obtained up to a temperature of 70 \( ^\circ \)C. The threshold reaches a minimum value around 1.9 mA at 30\( ^\circ \)C, which is the temperature where the QWs emission and the microcavity resonance match perfectly. The inset in figure 2 shows the emission spectra taken at 20 \( ^\circ \)C under various driving currents. The laser exhibit single-longitudinal mode emission with a Side Mode Suppression Ratio (SMSR) around 25 dB in the whole range of driving current. From these measurements an electro-thermal continuous tunability of 14 nm has been measured. This large continuous wavelength tuning with a single mode emission demonstrates that this device is well suited to scan several gas absorption lines as requested for TDLAS applications.

References


Session 2

Modelocking & Continuum

Chairman: Dr. S. Calvez (LAAS) & Dr. A. Garnache (IES)

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Ultrafast laser sources are one of the main scientific achievements of the past decades. Finding new avenues to obtain higher average powers from these sources is currently a topic of important research efforts. Such high peak power and high repetition rate sources have a strong impact on a wide range of applications both in industry and in scientific research. Semiconductor saturable absorber mirror (SESAM) modelocked thin-disk lasers (TDLs) currently enable the highest average powers and pulse energies of any oscillator technology, making them excellent table-top sources for these applications. To-date, an average power of 275 W with 583 fs pulses has been achieved directly from an Yb:YAG oscillator [1]. In addition, a pulse energy of 80 μJ was recently demonstrated at an average power of 240 W in 1.1 ps pulses. These results set the performance frontiers of ultrafast oscillators in terms of average power and pulse energy.

In this presentation, we will review the current state-of-the-art of this technology. We will present the key elements for average power and pulse energy scaling in this laser geometry. In particular, guidelines to optimize SESAM technology to withstand demanding intracavity conditions will be highlighted [3]. In addition, we will discuss pulse duration scaling using different promising novel gain materials to extend the state-of-the-art average power and pulse energy performance of such oscillators to the sub-100 fs regime [4], as well as carrier-envelope phase stabilization. As an outlook, we will discuss perspectives and future steps towards further scaling to kW average powers and several hundreds of μJ.

References

Recent Advances in Ultrafast MIXSELs

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Optically pumped vertical external cavity surface emitting lasers (VECSELs) evolved to high-power laser sources offering excellent beam quality, wavelength flexibility and low-noise performance in a compact and simple cavity [1]. Passively modelocked with a semiconductor saturable absorber mirror (SESAM), VECSELs demonstrated femtosecond pulses with multi-Watt average output powers at gigahertz repetition rates [2, 3].

![Autocorrelation](image1.png)

**Fig. 1(a)** Autocorrelation (blue) and sech²-fit (red) of 620-fs-pulses from a QW-MIXSEL, modelocked at a repetition rate of 4.8 GHz with an average power of 101 mW at a wavelength of 964 nm. **(b)** Sketch and picture of the high-power, low-noise MIXSEL in a closed housing.

The modelocked integrated external-cavity surface emitting laser (MIXSEL) [4] combines the gain of the VECSEL with the saturable absorber of a SESAM in one single semiconductor structure. This concept enables a higher level of integration to reduce complexity, packaging, and manufacturing cost, and allows for stable and self-starting passive modelocking in a simple straight cavity. With quantum-dot (QD) based saturable absorbers, record-high watt-level average output power was demonstrated [5]. However, the pulse duration was limited to 17 ps. Most recently, we have been able to demonstrate the first femtosecond operation of a MIXSEL, generating 620-fs-pulses, as shown in Fig. 1(a), at a repetition rate of 4.8 GHz and 101 mW of average output power [5].

Furthermore we present most recent timing-jitter measurements of both a free-running and actively stabilized MIXSEL, set up in a home-built closed housing as shown in Fig. 1(b). The laser generated picosecond pulses around 2-GHz repetition rate and more than 600 mW of average output power with excellent 0.11% rms amplitude noise (in the frequency range of 1 Hz to 10 MHz) [6]. The free running rms timing-jitter was 127 fs (100 Hz to 10 MHz) and 70 fs (300 Hz to 10 MHz), which is the lowest timing-jitter of a free-running passively modelocked semiconductor disk laser to date. With active stabilization of the repetition rate to a low-noise reference-source using a piezo-actuator, an rms timing-jitter of 31 fs was obtained, representing the lowest value measured from a passively modelocked semiconductor disk laser between 100 Hz and 100 MHz.

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**References**


Modeless highly coherent Frequency-shifted-feedback Vertical External Cavity Surface Emitting Laser

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A modeless laser is a device which provides intense coherent broadband light fields. It finds applications in areas such as high resolution spectroscopy, medicine, radar-lidar, metrology [1] where a coherent broadband radiation is needed.

In a modeless laser, the constructive interference of the optical wave, which would lead to spectral mode structure, is prevented by the insertion of an intra-cavity frequency shift on each round trip. In order to eliminate the mode structure, the frequency shift should occur by a mechanism which does not simultaneously change the cavity length. A common technique to achieve this is to use an acousto optic frequency shifter device (AOM) that will cause a discrete frequency shift of \( \Delta = 2 \times \nu_{AOM} \) on each round trip. We note that in order to achieve broadband continuous emission the ratio of \( \Delta/FSR > 0.01[2] \) where FSR is the free spectral range of the cavity without AOM.

In this paper, we demonstrate for the first time a 300GHz bandwidth (FWHM) continuous wave operation of a modeless Vertical External Cavity Surface Emitting Laser (VECSEL). The laser cavity design (fig1) is based on a frequency-shifted-feedback laser design using an intracavity acousto optic frequency shifter with \( \nu_{AOM} = 110\text{MHz} \) and 92% 1st order diffraction efficiency. The gain is provided by high gain GaAs based multiple quantum well (12QW) semiconductor chip emitting at 1070nm. This semiconductor structure includes a backside DBR HR mirror (99.9%). It is pumped with a 250mW single-mode pump (785nm), focused on the semiconductor chip with a 50µm waist. To reach a low laser threshold operation, a M-shaped cavity has been designed (overall length of 1.5 m) as it permits two passes per round trip in the gain medium, compared to linear cavities. The emitted power reached 30mW, with TEM00 emission and strongly linear polarization (>20dB).

Acknowledgments. This work is supported by ANR Miciphir, ANR Natif, RENATECH network.

References


Fig. 1: a) FSF-VecSEL design. b) FSF-VecSEL spectrum and TEM00 emitted beam profile.
Advances in the thermal management of VeCSEL gain structures have recently enabled these lasers to reach continuous-wave output power in excess of 100 W from a single chip. The challenge for mode-locked VeCSELs is therefore to realize designs that can deliver stable femtosecond pulse trains with average power around the 10-W mark or beyond. A notable feature of the mode-locked VeCSEL as a pulse source is the ease with which it can operate at microwave pulse repetition frequency (PRF) in the 1-100 GHz range; but the combination of high PRF with the kW-level peak power required for key applications (supercontinuum generation, frequency combs, four-wave mixing, difference generation etc.) sets stringent performance targets for both power and pulse duration.

Earlier this year our group reported a VeCSEL delivering optical pulses with a peak power of 4.4 kW (duration 400 fs at prf 1.7 GHz and average power of 3.3 W) [1]. The gain chip, which contained 10 InGaAs/GaAs quantum wells, was grown and processed at NASP, by the team of Wolfgang Stolz, who previously reported the 100-W cw result. The pulse train was launched into photonic crystal fibre (PCF), where it generated 0.5 W of supercontinuum radiation spanning 175 nm.

The semiconductor saturable absorber mirror (SESAM) that controls passive mode-locking in such a laser must combine sufficient modulation depth and fast absorption recovery with high damage threshold, negligible non-saturable loss and low dispersion. To define a specification for the SESAM, it is necessary to characterise the gain dispersion of the VeCSEL gain structure. We report a transient measurement that allows the evolution of the VeCSEL gain spectrum to be tracked as cw laser operation builds up from noise to a steady state, showing how the gain profile alters as the gain becomes saturated.

The broadest gain bandwidth for ultrashort pulse generation is exhibited by short-microcavity gain structures driven close to the roll-over point, with elevated temperature and carrier number in the active region. We have reported the generation of 205-fs pulses from a 4-InGaAs/quantum well with a microcavity length of $L/2$. The 2-mW average power of this device was limited by insufficient absorption bandwidth in the SESAM, allowing the device to jump to a longer wavelength where it operated cw, once the pump power was raised above a critical level [2].

The high PRF that characterizes mode-locked VeCSELs is of interest in a pump laser generating single photons, created, for example, by non-degenerate 4-wave mixing in photonic crystal fibre. For this application a source of wavelength-tunable picosecond pulses is particularly useful, relaxing the required tolerance on the dispersion properties of the fibre. We have reported a 2-ps mode-locked VeCSEL that exhibited continuous tuning over 14 nm around 1042 nm, controlled by an intracavity etalon [3]. More recently it has been possible to scale up the power of this tunable laser from the few-mW levels demonstrated initially to 0.5 W, although with a restricted tuning range.

A more complex route towards high power, high repetition frequency sources involves using the mode-locked InGaAs VeCSEL as a seed laser for a high-power ytterbium-doped fibre amplifier. We recently reported supercontinuum generation using a mode-locked VECSEL emitting 400-fs pulses at a 3-GHz repetition rate, amplified with a cascaded ytterbium-doped fiber amplifier system up to 40 W of average power. The recompressed pulses were used to generate supercontinuum, reaching spectral bandwidths up to 280 nm. [4]

Acknowledgments: We acknowledge the support of the Engineering and Physical Sciences Research Council.

References

Session 3

New Concepts

Chairman: Dr. A. Sirbu (EPFL) & Dr. G. Feugnet (TRT)

Control of new spatial, temporal and polarization coherent light states with VeCSEL: VORTEX, continuum, THz, spin \textit{(Oral)}
by Arnaud Garnache. 31

Influence of Intra-cavity Losses on the Temporal Dynamics of the Dual-Wavelength Emission in VECELS \textit{(Oral)}
by Mohammad Khaled Shakfa. 32

Dual-Frequency Vertical External Cavity Surface Emitting Laser for Terahertz Generation \textit{(Poster)}
by Romain Paquet. 33
Control of new spatial, temporal and polarization coherent light states with VeCSEL: VORTEX, continuum, THz, spin

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Since years, the VeCSEL concept is pointed out as a technology of choice for beyond-state-of-the-art laser light sources, demonstrating wavelength flexibility, high power, high spatial, temporal and polarization coherence, CW or fs ultra-short pulsed operation, compactness and functionalities. The targeted coherent state is typically a common circular low divergence fundamental gaussian TEM00 mode, linearly polarized state, single frequency state [1] or modelocked comb. Such high-Q laser cavity exhibits a class-A dynamics with low intensity noise at shot noise level in MHz RF range, as well as a quantum limit optical frequency noise at the Hz level [1]. Integration and packaging of such high performances sources is in progress (see COHERENT, INNOPTICS, Fraunhofer ILT...).

In this work, we take advantage of diode-pumped VeCSEL III-V technologies (quantum-well, Bragg mirror, photonic crystal, metallic mask) and fundamental physical features (axial symmetry and orthogonality, high finesse, homogeneous gain, birefringence, dichroism, spatial hole burning...) for the generation of other kinds of highly coherent states, thanks to the insertion of new intracavity functions. These new kinds of large photon number (high power) coherent states, close to the shot noise limit in the MHz RF range, target many applications including optical tweezers, telecommunications, fundamental physics, sensors, spintronic...

A first part of this work aims at demonstrating new spatial coherent states. For this purpose, we developed technological process and careful designs for transverse phase and intensity control inside the cavity, exploiting integrated III-V semiconductor planar technologies. A robust intensity control is obtained thanks to low loss metallic masks deposited on the surface of the chip. For phase (and intensity) control, we developed a low-loss aberration free hybrid photonic-crystal Bragg mirror. These GaAs-based devices allow the generation of highly coherent - degenerated or non generated - high order Laguerre-Gauss mode(s), preserving the spatial, temporal and polarization coherence properties (diffraction limited beam, ultra low noise, highly linear polarization) of usual TEM00 VeCSELs. We thus demonstrated low divergence highly coherent VORTEX beam [2], standing-wave radial pattern beam, dual-frequency operation for THz generation, with a linewidth quantum limit at the Hz level and a RIN< 140 dB/Hz. It also paves the way for the generation of other coherent states (Bessel beams, circularly polarized beams...) exploiting new functionalities (spectral filtering, birefringence, dichroism, chirality...).

In a second part, we explore a new time domain coherent state, to generate a continuum broad band light in cw [3, 4]: owing to a high gain broadband GaAs-based semiconductor structure design, a high finesse stable cavity design including an intracavity Acousto-Optic-Frequency-Shifter, we demonstrated the first GaAs-based modeless Frequency-Shifted-Feedback VeCSEL emitting around 1 μm, with a Fourier-Limited broadband continuum coherent state. It exhibits an optical spectrum as wide as 300 GHz and a coherence time > 10 μs in a TEM00 beam.

In a third part, we explore the photon polarization state in a VeCSEL. The control of the polarization light state - photon spin - is of great interest [5]. Laser light states can be linearly or circularly polarized, depending on the confined optical cavity modes, created and selected by intracavity birefringence and dichroism. We studied the semiconductor structure optical susceptibility anisotropy to control the nature, stability and coherence of the laser polarization state. We demonstrated a coherent polarization state at the quantum limit (80 dB PER).

Acknowledgments. This work is supported by ANR Micphir, ANR Natif and RENATECH network.

References

Influence of Intra-cavity Losses on the Temporal Dynamics of the Dual-Wavelength Emission in VECSELs

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Optically-pumped vertical external cavity surface emitting lasers (VECSELs) have recently emerged as an important category of semiconductor laser. Over the past years, considerable efforts have been made to understand and improve the performance of VECSELs. Owing to its external cavity, a VECSEL is well suited for the exploitation of intra-cavity frequency conversion processes. For instance, a high power continuous wave room-temperature terahertz source was demonstrated based on difference frequency generation within a nonlinear crystal, which is placed inside a VECSEL cavity [1]. However, a stable dual-wavelength operation is mandatory for this kind of application [2,3].

In this work, we present a systematic investigation of the temporal dynamics of the dual-wavelength emission from a VECSEL by performing two experiments employing a high-Q and a low-Q cavity (Fig. 1). Dual-wavelength laser operation is provided by a Fabry-Pérot etalon of about 100 μm width, which is placed inside the cavity. For the high-Q case, a plane end mirror with a reflectivity higher than 99.999% is used whereas for the low-Q cavity this mirror is replaced by an output coupler with a transmittance of 3.25%. Furthermore, a SF-57 glass block with 10 mm thickness is inserted inside the cavity to introduce additional reflection losses. A streak camera, operated in the single-sweep mode, is employed to temporally and spectrally resolve the laser emission. The obtained data is evaluated via a quantitative statistical approach focusing on the dual wavelength correlation and the relative intensity fluctuations.

In the case of a high Q-cavity, a stable dual-wavelength regime is clearly observed over a wide range of pump powers. The breakdown of stability occurs near the lasing threshold and the thermal roll-over. Furthermore, the laser threshold increases by increasing the losses within the cavity. Nevertheless, a stable dual-wavelength emission is still observed, at least for the losses set to 8.7%. Here, the region of stability is narrower in comparison to the high-Q cavity and tends to shift to higher pump powers as well. When the losses are increased up to 10%, an unstable dual-wavelength operation is obtained.

Fig. 1: A schematic sketch of the setups of (a) a high-Q and (b) a low Q-cavity. The dotted arrows in (b) indicate the reflections occurring at the glass block surfaces.

References
Continuous high-purity terahertz generation through photomixing is a very promising technique for THz local oscillators. Consequently, we propose an innovative photomixing architecture based on a dual-frequency highly-coherent laser. We demonstrate that Vertical-External-Cavity Surface-Emitting Laser (VeCSEL) is a very promising laser technology to obtain a highly-coherent (high-Q cavity, low amplified spontaneous emission, low technical noise) dual-frequency continuous-wave operation, based on simultaneous coexistence of two Laguerre-Gauss (LG) transverse modes in a common laser cavity. Therefore, any noise would modify the two frequencies in the same manner, and beating frequency would stay constant (low jitter).

As both frequencies share the same gain medium, competition occurs and only the stronger mode remains. If modes are partially uncoupled, e.g. if spatial uncoupling occurs (spatial hole burning), dual-frequency operation can be reached. We will take advantage of transverse spatial hole burning and the orthogonality of LG mode basis in a concave-type stable cavity to allow stable simultaneous operation of the two transverse modes. The VeCSEL can select a robust dual-frequency light state characterized by two transverse LG modes, where each LG mode operates at a single longitudinal mode with a single linear-polarization state. These physical points were investigated thanks to theoretical modeling of VeCSEL transverse non-linear dynamics, as well as experiments.

We demonstrate dual-frequency operation ($\Delta f \approx THz$) of a diode-pumped GaAs-based quantum-wells VeCSEL (see figure 1) emitting on two transverse LG modes. The VeCSEL device consists of the 1/2-VCSEL gain mirror, a millimeter-long air gap and a commercial flat mirror with a reflectivity of 99% (figure 1(left)). The laser is operating at room temperature at a wavelength of 1 µm. The power efficiency, the transverse field profile, the optical spectrum and the polarization state of the emitted beam are studied.

Fig. 1: (left) VeCSEL configuration. (right) Spectrum of the laser on the LG$_{00}$ and LG$_{02}$ modes and normalised intensity profile (upper right corner).
Session 4

Spectral Coverage & Non-Linear Conversion

Chairman: Dr. A. Sirbu (EPFL) & Dr. S. Calvez (LAAS)

- **Novel nonlinear materials and frequency control for lasers** *(Invited Tutorial)*
  by Valdas Pasiskevicius.  
- **High power semiconductor disk lasers for 1.3-1.6 µm and 650-800 nm spectral ranges** *(Oral)*
  by Antti Rantamaki.
Novel nonlinear materials and frequency control for lasers

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In recent years we witnessed impressive advances in development of vertical external cavity surface emitting lasers (VECSELs) exploiting all advantages of one-dimensional heat flow, low thermal lensing and engineerable gain medium to reach very impressive and useful output powers over several spectral ranges covered by arsenide, nitride, phosphide and antimonide semiconductor alloys. High intracavity powers in perfect TEM00 beams are readily achievable in VECSELs owing to their unique geometry. These are advantageous for exploiting intracavity second-order frequency conversion schemes to reach other spectral ranges from ultraviolet to THz. Short lifetime of the excited states in semiconductor gain medium renders the CW VECSELs with intracavity frequency converters inherently stable against relaxation oscillations which can be a serious problem in other types of lasers, owing to nonlinear coupling of longitudinal modes.

On the other hand, VECSELs normally have rather broad gain spectrum, which also depends on pumping level and cavity losses. In order to realize efficient and robust intracavity frequency conversion schemes such as frequency doubling or optical parametric oscillation, some means of spectral control and locking are required. In this respect, the design strategies for intracavity frequency converters in VECSELs are similar to those used in broadband vibronic laser as well as lasers exploiting transitions between closely coupled multiplets as in Yb$^{3+}$ and Tm$^{3+}$.

This tutorial will look into recent developments in nonlinear crystals with emphasis being placed on engineerable materials exploiting quasi-phase matching. We will investigate specific challenges and opportunities of intracavity frequency conversion schemes in VECSELs, including means for spectral locking and control.
High power semiconductor disk lasers for 1.3-1.6 µm and 650-800 nm spectral ranges

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The power and wavelength scalability of semiconductor disk lasers (SDLs) has made them useful for numerous applications [1]. However, the performance of monolithically grown InP-based SDLs emitting at 1.3-1.6 µm suffers from the poor quality of distributed Bragg reflectors (DBRs), because the available compounds lattice-matched to InP exhibit low refractive index contrast and poor thermal conductivity. This issue can be overcome by wafer fusion that allows the integration of InP-based active regions with high quality GaAs-based DBRs. Using this technique, multi-watt output powers in the wavelength range 1.3-1.6 µm have been demonstrated [2, 3]. Further extension to the 650-800 nm range can be achieved by intracavity frequency doubling.

The output characteristics of the frequency doubled SDLs are shown in Fig. 1. Output powers up to 3 W and 1 W were obtained at 650 nm and 785 nm, respectively. At the fundamental frequencies of 1.3 µm and 1.58 µm the lasers produced 6.6 W and 4.6 W. Hence, frequency-doubled InP-based SDLs allow watt-level output powers at the wavelength range 650-800 nm that is essential for various applications including spectroscopy, atom cooling, medicine and biophotonics [4].

Fig. 1: Frequency-doubled output power from 1.3 µm SDL (left) and 1.58 µm SDL (right)

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References
Session 5

Noise, Coherence & Fundamental Properties

Chairman: Dr. A. Garnache (IES) & Dr. S. Calvez (LAAS)

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Nonlinearities and noise in semiconductor lasers

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The laser noise is a key issue for most of the optical communication and remote sensing systems. Optical noise mainly originates from the fundamental quantum nature of the optical signals itself and from the additional noise mechanisms in the semiconductor laser producing them. A first manifestation of fundamental noise character of the light is the well-known shot-noise. It is derived by the description the light as a classical particle flows and it leads to the optical Schottky's relationship \( < (\Delta P)^2 > = 2hPB_e \) for the optical power fluctuation \( \Delta P \) or to its well-known electrical counterpart \( < (\Delta I)^2 > = 2eIB_e \) for the corresponding photocurrent fluctuation \( \Delta I, B_e \) being the observation (electrical) bandwidth.

The development of coherent systems as well as deeper understanding required a more sophisticated noise description. Keeping with a classical model, let use a two-quadrature description, considering the complex optical field as the sum of a deterministic component, with complex amplitude \( A \exp(j\phi) \), and an additive band-limited stationary Gaussian noise \( N(t) \), with a flat spectrum in a single-sided optical pass-band bandwidth equal to \( B_e = 2B_c \). As shown on Figure 1, the complex amplitude noise \( N \) is split into an in-phase \( N_I(t) \) and a quadrature (i.e. out of phase) \( N_Q(t) \) components. These 2 components equally share the total noise power \( P_N = S_N B_e \), where \( S_N \) is the single-sided optical power spectral density. It easy to show that the amplitude noise required to produce the shot noise power fluctuation have the power density \( S_N = h\nu/2 \). This minimum additive optical amplitude noise, which accompanies any optical field, is usually referred, in quantum electrodynamics, as the zero-point field fluctuations or the vacuum fluctuations. It correspond to the minimum energy \( E_r = (n+1/2)h\nu \) of a quantified oscillator with frequency \( \nu \).

Let us consider now a slice of width \( dz \), of a semiconductor medium, with both a lineic gain coefficient \( \beta = aN_2 \), where \( N_2 \) is the population of the upper level of an equivalent 2 level laser, and a lineic attenuation coefficient \( \alpha = aN_1 \), where \( N_1 \) is the the population of its lower level. Accordingly with the fluctuation-dissipation theorem, the single-sided spectral density \( S_\phi(\omega,z) \) of optical noise follows the propagation equation

\[
\frac{dS_\phi(\omega,z)}{dz} = (\beta - \alpha)S_\phi(\omega,z) + \left( \frac{\hbar\nu}{2\omega} \right) Rz + \left( \frac{\hbar\nu}{2\omega} \right) Cz
\]

As the signal decays in a pure attenuating medium, the spectral density of noise is kept constant since the noise generation by momentum fluctuation of the electrons at the optical frequency cancels out the attenuation of the incoming fluctuations \( S_\phi = h\nu/2 \). In an amplifying medium, the initial noise is amplified and an exta noise contribution is added. The total noise is usually interpreted as spontaneous emission. The inversion population factor \( nsp = N_2/(N_2 - N_1) \), expressing an extra noise price to pay for incomplete inversion is usually introduced.

In a semiconductor laser, interband gain saturation and intra band gain compression act as stabilization mechanisms for the intensity and therefore for the amplitude of the emitted light. However the laser output power frequently undergoes additional fluctuations taking origin in mode partition and or in technical noises, the main part of the pump fluctuations being damped out by the population inversion. The excess of noise is usually expressed as a Relative Intensity Noise (RIN), despite its usual definition is not invariant through attenuation.

Because no internal restoring force exists for the optical phase of a free running, the phase undergoes a Wiener-Levy diffusion, leading to a finite single mode line width determined by the speed of diffusion allowed by the laser cavity. The line width is related to the rate \( R \) of spontaneous emission events and to the average number of stimulating photons \( P \) inside the cavity by the relationship \( \Delta \omega = R/2P \). Furthermore, in a semiconductor laser, the maximum of gain do not corresponds to the maximum of the differential gain and the phase fluctuation are enlarged by the so-called phase-amplitude coupling factor, also called \( \alpha \) Henry's factor, despite it was first introduced by Lax. Therefore the line with is enlarged by a \( (1 + \alpha^2) \) factor.

If the equal partition of noise energy between the 2 quadratures of the optical field is the natural maximizing entropy situation, the uncertainty principle only imposes a constant product of the corresponding fluctuations. Non-classical or so-called squeezed states of light, exhibiting for instance a below standard shot noise power fluctuation, may be obtained by modification of the noise power partition.

References

Light-polarization dynamics in surface-emitting semiconductor lasers

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Vertical-Cavity Surface Emitting Lasers (VCSELs) have short optical cavities that confer them single-longitudinal mode character. At the same time, their transverse structure can be designed such that VCSELs support a single-transverse mode over most of the operation range of the device. The gain region usually consists of Quantum Well (QW) material grown perpendicular to the optical axis, normally aligned with the [100] axis of the material. This axial symmetry is not perfect due to the underlying crystal structure, and the polarization of the light emitted by VCSELs is usually aligned with the [110] or [110] crystallographic axis. In addition, residual birefringence in the VCSEL cavity removes the frequency degeneracy the two states of polarization for each transverse mode, which have slightly different optical frequencies ($\Delta\nu \sim 1 – 10$ GHz). As a consequence, the two polarization states for each transverse mode also experience slightly different gain and losses. However, the resulting differences in gain are quite small, hence VCSELs lack any effective mechanism for selecting and fixing the polarization of the emitted field, which often displays instabilities as the bias current is increased.

The most often encountered polarization instability in VCSELs is polarization switching (PS) that involves a jump in orientation of the field polarization from the [110] axis to the [110] axis or vice versa. Such PS often occurs in the fundamental transverse mode, but it may be accompanied by the excitation of higher-order transverse mode. In addition, it may proceed from the low-frequency mode to the high-frequency mode (type I PS) or vice versa (type II PS) and display hysteresis, anti-phase dynamics and the excitation of elliptically polarized states depending on the device characteristics and the working conditions. Different mechanisms and models have been proposed for explaining the behavior of such a rich dynamical system and the influence of the different design parameters and

The impact of PS on applications requiring polarization stability has stimulated the search for mechanisms that allow polarization control and polarization pinning in VCSELs. Polarization control of VCSELs can be achieved by introducing a polarization-dependent gain, an asymmetric resonator, or strong dichroism in the cavity via mirrors with a polarization-dependent reflectivity.

At the same time, the strong sensitivity of the polarization state to perturbations of the working point (current variations, optical injection, feedback, etc.) offers opportunities for optical-clock generation and all-optical data processing in different forms.

In this presentation, I shall review polarization dynamics and instabilities in VCSELs and their theoretical description in the framework of the Spin-Flip Model. I shall also discuss the effects of feedback and crossed-polarization reinjection on the dynamics of the system, which lead to pulsations in the VCSEL emission either in the form of a square-wave modulation or of short optical pulses.
Control of light polarization using spin-injected VECSELS

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In the past decade, continuous interest and research efforts have been dedicated to the study of spin injection into Semiconductor based Light Emitting Device such as Spin-Light Emitting Diodes (Spin-LEDs) [1] and more recently Spin-LASERs such as Vertical Cavity Surface Emitting LASERs (VCSELs) [2]. Our study mainly focuses on the possibility to manipulate the polarization state of the electromagnetic field emitted by a Vertical External Cavity Surface Emitting Laser (VECSEL) thanks to spin-polarized carriers injected in the active medium of the structure.

Our work on Spin-LASER is based on our expertise on III-V Spin-LEDs AlGaAs/GaAs/AlAs heterostructures [3-4-5] providing the emission at 800 nm of a circularly-polarized light (Spin polarization rate in the QWs greater than 30%). To overcome this limitation, we grew by sputtering a (2.6nm MgO/1.8nm Co/3nm Pt) ferromagnetic Metal-Tunnel-Junction spin-injector in one node of the stationary electric Bragg mirror (AlAs/GaAs), and an active medium made of 6 to 12 InGaAs QWs confined by GaAs/GaAs barriers. As a first step to get electrically injected and spin controlled VECSELs, laser oscillations with a VECSEL incorporating an intra-cavity ferromagnetic spin-injector is needed. This step was challenging given the high absorption of classical ferromagnetic spin injector (typically 10% for 5 nm thickness) compared to optical gain in ½-VCSELs, limited to few %. To overcome this limitation, we grew by sputtering a (2.6nm MgO/1.8nm Co/3nm Pt) ferromagnetic Metal-Tunnel-Junction spin-injector in one node of the stationary electric field on the surface of the antiresonant ½-VCSEL structure. By optimizing the filtering and absorption effects of the spin-injector, we succeed to obtain laser oscillation within the new ½-VCSEL. This encouraging result is a first step towards the realization of an electrically pumped VECSEL with spin-polarized electrons.

Another way to control electron spin-polarization state in ½-VCSELs consists in using circularly polarized optical pumping. Unfortunately, the polarization state of a laser depends on the competition between the gain dichroism, ΔG, and phase birefringence, γ, in the laser cavity. In order to evaluate the influence of such parameters on the emitted polarization state, we developed a dedicated vectorial model describing the laser eigenstates when taking into account laser parameters as gain dichroism (linear, circular) and phase parameters. Our first experiments showed that a ½-VCSEL implemented in a linear external cavity is in the regime where the linear birefringence is higher than the gain circular dichroism γ >> ΔG resulting in a linear polarization state at the pump circular polarization orientation when switching from Left (σ−) to Right (σ+) Circular polarization.

References:

Square-Wave emission and Dissipative Vector Solitons in a Vertical Cavity Surface-Emitting Laser using polarisation degree of freedom

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Single-mode VCSELs exhibit polarisation instabilities due to the absence of a strong anisotropy capable of fixing the polarisation emission. Thus they have been proposed for implementing useful dynamics taking advantage of their polarisation degree of freedom [1]. In this contribution, we analyse the polarisation dynamics of a single-transverse mode VCSEL submitted to both Polarisation-Selective optical Feedback (PSF) and Crossed-Polarisation Reinjection (XPR). Depending on parameters, the VCSEL may emit a regular square-wave signal or vectorial temporal solitons.

XPR consists in selecting a single polarisation output, turning its polarisation orientation of $\pi/2$ and reinjecting it back into the VCSEL. When the VCSEL exhibits a dichroism strong enough to allow for a single polarisation emission, a very regular square-wave signal can be obtained with XPR only [2]. In VCSEL with small dichroism -which may display polarisation bistability in some parameter range- it is possible to obtain square-wave emission by submitting the VCSEL to both XPR and weak Polarization-Selective optical Feedback (PSF)[3]. The presence of PSF decreases the losses of the selected polarisation providing a mechanism which effectively increases the dichroism and that reinforces the effectiveness of XPR. A very regular square-wave emission is obtained, which is robust versus parameter changes (current, XPR and PSF delays). In Fig. 1, we observe a square-wave signal in each polarisation output at a period corresponding to twice the XPR delay. Both signals are in antiphase while total signal remain constant (green trace).

On the other hand, it has been shown in a theoretical paper that passive mode-locking can be obtained with a VCSEL that is submitted to both XPR and PSF [4]. We have analysed this situation experimentally and we report evidence of the existence of vectorial temporal solitons. While the external cavity provides the longitudinal modes set that will be locked, XPR induces a pulsed solution through cross-gain modulation. We observe that, for a proper choice of the system parameters, the polarisation resolved output of the system (Fig 2a) exhibits narrow pulses (< 80 ps) at the repetition rate of the free spectral range of the PSF cavity. These pulses are in antiphase on both polarisation axes, while total signal remains constant. The calculated power spectrum for the red trace of Fig. 2a is shown in Fig. 2b and reveals that several PSF cavity modes are locked in phase during this regime.

References:
Coherent High-order Laguerre-Gauss modes with a high-Q external-cavity semiconductor laser: standing-wave radial pattern and VORTEX

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Laser beams operating at high-order Laguerre-Gauss (LG) modes have lots of applications in many areas including laser drilling and writing, optical manipulation, trapping and guiding of atoms[1, 2]. Beyond the possible applications of the degenerate modes, the non-degenerate modes, also known as optical vortices, are of particular interest since they carry orbital angular momentum as suggested by Allen et al[3]. In fact, the LG modes are the natural modes for a linear cavity using spherical mirrors and having axial symmetry of revolution[4]. We demonstrated that the Vertical External Cavity Surface Emitting Laser (VECSEL) is a very promising laser technology for the generation of this kind of light beams [5]. Indeed, the VeCSEL design relies on small thickness quantum-well (QW) gain medium which minimizes non-linear optical interactions, thermal lens and possible astigmatism inside the semiconductor structure. The interplay of this 2 dimensions (2D) transverse gain medium with a low-loss cavity design permits the generation of single frequency high quality diffraction limited beam profiles.

Our strategy for selecting a given transverse mode with fixed intensity and phase profiles consists in introducing, on the surface of the semiconductor chip, radially and azimuthally selective losses via a sub-wavelength metallic mask while adjusting the pump beam size. Moreover, by exploiting the non-linear dynamics of the laser (Spatial Hole Burning), the VECSEL can select a single light state characterized by a unique longitudinal and transverse mode with single linear field polarization state. These physical points were investigated thanks to the modeling of VeCSEL transverse non-linear dynamics, as well as experiments.

In this work, the first demonstrations were carried out on a GaAs-based QW VECSEL on which we deposited a very thin metallic mask (5nm) see figure 1.

We demonstrate single frequency operation for a VECSEL emitting on single high-order transverse LG mode. Both the degenerate and non-degenerate modes (vortices) have been generated. The laser is operating at room temperature at 1μm wavelength. The power efficiency, the transverse E-field profile, the optical spectrum and the polarization state of the emitted beam as well as the relative intensity noise and the frequency noise are studied.

Fig. 1: a) Technology for the metallic masks realized on the 1/2 VCSEL structure. b) Experimental transverse intensity output beam distribution for some LG-gauss modes where we have added the corresponding mask. c) Vortex mode (LG∗01) : up far-field intensity distribution, bottom : Interference pattern with reference spherical wave showing the forked pattern due to phase singularity.

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References


Session 6

Fundamental & Industrial Applications

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Solid State Alternative of Gas Ring Laser Gyroscope (Poster)
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High sensitivity cavities are clearly a new trend in the development of ultrasensitive methods in absorption spectroscopy [1]. The number of research groups choosing this tool against more traditional multipass cells or modulation schemes, is steadily increasing. A few companies also successfully propose devices based on high finesse cavities for many applications of trace gas detection.

I will first recall some basics of optical cavities in view of their use for high sensitivity cavity-enhanced or cavity ring-down absorption spectroscopies (CEAS and CRDS, respectively). Then, I will discuss specific methods that can be implemented to optimize the coupling and detection of light from different types of laser sources, in particular semiconductors. One of these schemes, presently exploited for the realization of commercial trace gas analysers, uses the strong sensitivity of semiconductor lasers to optical feedback (OF-CEAS). Another interesting scheme which appears conceptually simpler but is more complex at the realization stage, just uses the injection of laser light at the passage through a cavity resonance. This CRDS method is also exploited for commercial purposes since about 10 years. Another CEAS scheme adapted to modelocked lasers will also be described, given the development of modelocked semiconductor systems.

References

Design and manufacturing of single frequency compact VeCSEL modules emitting in the NIR and MIR

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The VeCSEL technology has been identified for years as a good candidate for applications requiring high spatial, temporal and polarization coherence, low noise and wavelength tunability, such as scientific instrumentation, LIDAR, single frequency seed lasers or gas analysis/detection. Indeed, this unique architecture combines the advantages of Diode Pumped Solid State (DPSS) lasers (low divergence diffraction limited beam, narrow linewidth, low intensity noise) together with those of semiconductor lasers (reliability, wavelength flexibility, compactness). Lab demonstrations have been performed at IES (together with LPN) that confirm the potential of this technology, so that both III-V semiconductor gain and cavity design rules have now reached a good level of maturity [1]. Innoptics and IES have hence started a collaboration in order to develop and manufacture an industrial module that will integrate all driving and monitoring functions in one module and that will enhance the performance of lab prototypes, regarding noise properties (coherence) and broad tunability for instance.

The first goal was to develop a compact package (73.5mm x 58mm x 27mm, see fig.1) with a modular architecture, that will enable the use of chips at various wavelengths with minor changes in the module design. The module presented here features a GaAs-based 1µm device, but chips at 2.3 µm will be used in the near future. A special care has been taken in the design of the integrated optical pumping system, with a very compact low noise design (see fig.2) that enables focusing the beam of a multimode pump on a small adjustable spot. Spot size can therefore be adjusted from a few tens of µm up to > 100 µm, depending on the chip properties and the desired VeCSEL output power.

We will finally present some features of the opto-mechanical design of the cavity, which is intended to enable significant improvement in noise characteristics, while allowing broad continuous tunability with a PZT actuator. The latest measurements of the complete module at 1µm will be presented.

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References
Developments of miniature atomic clocks based on coherent population trapping, VCSELs and MEMS: Technology of fabrication and laser source requirements

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The combination of coherent population trapping (CPT) physics with micro electro-mechanical systems (MEMS) technologies as well as vertical-cavity surface-emitting lasers (VCSELs) has allowed during the last decade the development of highly-miniaturized atomic clocks. Such clocks exhibit a fractional frequency instability better than $10^{-11}$ at 1 hour and 1 day integration times [1], outperforming the one of traditional crystal oscillators over long time scales. These performances are reached although their total volume can be as small as a few cm$^3$, and their typical power consumption of about 100 mW. Such frequency references are devoted to provide excellent base timing for numerous battery-operated portable applications, such as, telecommunication networks synchronization, navigation systems or even power distribution and underwater sensors.

CPT is obtained in a hermetically sealed microfabricated cell containing alkali (Cs or Rb) vapor and a buffer gas atmosphere. The sealed cavities are based on a silicon wafer with through-holes sandwiched between two glass plates assembled by means of anodic bonding. Challenges concerning such micro-cells consist in their filling with alkali vapors and buffer gases while ensuring purity of their atmosphere [2,3].

Since CPT enables an all-optical interrogation of the ground-state hyperfine splitting of alkali atoms, VCSELs are employed, in miniaturized atomic clocks, in order to generate optical sidebands for the CPT excitation without requiring microwave cavity. These compact, low-power, low-threshold current and high-modulation bandwidth lasers—despite their broad linewidth (100 MHz typically)—have demonstrated their potential to detect narrow-linewidth CPT resonances in alkali vapor cells [4,5,6].

This contribution concerns the results of the European collaborative research project MAC-TFC (MEMS Atomic Clocks for Timing, Frequency Control & Communications) aiming at the development of an European version of MEMS atomic clock. The project relied on a consortium made of five major academic institutions (University of Besançon, University of Ulm, University of Neuchâtel, EPFL-Lausanne, Technological University of Wrocław); two research institutes (VTT and CEA/Léti) and three industrial partners (SAES Getters, SWATCH R&D and Oscilloquartz).

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Evaluation of a dual-frequency VECSEL emitting at 852 nm for cesium atomic clocks using coherent population trapping


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Coherent population trapping (CPT) allows the miniaturization of atomic clocks with high stability. It is obtained by interaction of cesium atoms with two phase-coherent and resonant laser fields. The atomic clock stability will depend on the laser amplitude and frequency fluctuations, which are additional sources of noise affecting the frequency stability of the microwave atomic signal [1]. We describe the design and evaluation of a dual-frequency vertical external-cavity semiconductor laser (VECSEL) emitting on two cross-polarized modes at 852 nm, with a frequency difference between the laser modes tunable around 9.192 GHz.

The semiconductor chip is grown on a 350 µm thick GaAs substrate and includes 7 GaAs quantum wells (8 nm-thick) embedded in Al0.22Ga0.78As barriers, and a high reflectivity Bragg reflector composed of 32.5 pairs of AlAs/Al0.22Ga0.78As. The semiconductor micro-cavity, consisting in the Bragg mirror and the air/semiconductor interface (30% reflection), is resonant at the emission wavelength and thus enhances modal gain by a factor 3.3. The chip is pumped with a fiber coupled laser diode emitting 1 W at 670 nm. Dual frequency emission on two cross-polarized modes is obtained using a 500 µm thick YVO4 plate which induces a spatial separation between the ordinary and extraordinary polarizations on the semiconductor chip of 50 µm. Frequency difference between laser modes is tuned in the microwave range using an electro-optic crystal (MgO:SLT). The output coupler has a transmission of 0.5% at 852 nm and a radius of curvature of 15 mm. The cavity free spectral range is 12 GHz, larger than the requested frequency difference of 9.192 GHz between the two laser modes (fig. 1).

A saturated absorption set-up is used to lock the ordinary-polarized line onto the Cs D2 line; the correction signal is applied to a piezoelectric transducer glued on the output coupler. The bandwidth of the servo-loop is 600 Hz, and the frequency noise is reduced up to 70 dB at 1 Hz. The frequency difference between the laser modes is locked to a local oscillator at 9.192 GHz with a phase-lock loop which applies a correction signal to the E.O. crystal. In those conditions, the linewidth of the RF beatnote signal between the laser modes is below 30 Hz, which validates the strong correlation between the modes; the phase noise of the beatnote signal is lower than -100 dB/Hz²/Hz in the frequency range from 100 Hz to 10 kHz (fig. 2). The laser relative intensity noise is flat up to 1 MHz at a level of -110 dB/Hz, and is limited by the pump intensity noise [2]. Based on those performance, we estimate that the stability of a CPT atomic clock using our laser source would be about 3.10⁻¹³ over 1 second, which would be one order of magnitude better than commercial atomic clocks.

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References

**Design & physical properties of integrated single frequency III-V VeCSEL**

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The VeCSEL technology exhibits exciting physical features which make it the ideal nominee to address demanding applications, like LIDAR, velocimetry, seeding, gas analysis or atomic clock, relying on a highly coherent laser source. It combines high coherence (diffraction limited TEM$_{00}$ mode emission, high SMSR, highly linear polarization state), with low intensity noise and narrow line-width (down to kHz level in free running). It allows also broadband tunability (up to THz), a circular low divergence beam (few mrad) and a compact design [1]. All these specifications can be reached mainly because the VeCSEL technology is based on a high finesse cavity (F~ 600, mm-cm long) associated to nearly ideal homogeneous laser QW gain medium behavior, giving a class A laser without relaxation oscillations. Those characteristics are very advantageous comparing to DPSSL, which can reach nearly the same coherence properties [2], but lacks of wavelength flexibility and broadband continuous tunability, and comparing to monolithic semiconductor lasers that lacks of coherence and power.

Our goal here is to develop VeCSELs emitting at 1µm and 2.3µm, pushing up their coherence and power performances and integrate them in a compact package using the same architecture and III-V semiconductor technologies. For 1µm emitting GaAs-based VeCSEL, we improved single longitudinal mode and the linear polarization state stability (theoretical SMSR=65dB and PER=75dB). A commercial pump diode provides a low-cost low noise high power supply. A cm long cavity limits the laser intensity noise bandwidth and allows to reach the shot noise level at Fc~100MHz. Bonding the structure a heatsink and integrating the VeCSEL in a compact module reduces respectively the thermal and the mechanical noise, and will reduce both low RF frequency laser intensity and frequency noise (<100kHz).

Assuring a TEM$_{00}$ mode operating laser needs a careful cavity-pump design, indeed the thermal lens generated on the sample by pump heat load can induces a high threshold power, limits the output power, adds beam astigmatism and aberrations (as shown in Fig.2), or even stabilizes a multimode beam. So it deteriorates the spatial coherence (increases M$^2$). A thermal study of structures, followed by numerical modeling of intracavity beam diffraction using Fresnel algorithm allowed us to optimize the cavity design and counteract the thermal lens at high power.

To obtain the targeted performances, we developed the semiconductor structures, the pumping module, and a newly designed pump cavity; our firsts characterizations show a maximum output power of 250mW, PER > 40dB (apparatus limited), a SMSR > 50dB (apparatus limited) and high TEM$_{00}$ beam quality (M$^2$<1.2). We will discuss the physical and the technical limits of VeCSEL’s design, how to assure TEM$_{00}$ stability, present some further characterizations, and witch are the main improvements we can perform.

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Solid State alternative of gas ring laser gyroscope

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Usual ring laser gyroscope (RLG) use a mixture of Helium and Neon gas as laser gain media. This type of RLG is now a standard product and RLGs are implemented in a large broad range of navigation applications for space, military or civilian airplanes... However, they are complex to build, they require specific finely tune mirrors to cope with a very low gain, their lifetime is limited by the cathode aging, the purity of the gas mixture is critical for the performances... There is thus an interest to identify the potential of alternative technologies leading for instance to longer lifetime longer or top easier production process.

We will compare two alternative technologies that are developed by Thales, both with the objectives of replacing the gaseous laser media by a diode-pumped solid-state laser media. First approach is based on a usual Nd doped YAG crystal while the second one is based on a half VECSEL (½-VECSEL : Vertical Cavity Surface Emitting.

In order to measure rotation, bidirectional emission must occur in any RLG so that a beat signal, with a frequency depending on the rotation rate thru Sagnac effect, can be obtained from interferences between the two counter propagating waves. This is easy to obtain in gaseous HeNe mixture thanks to the thermal agitation that slips the ions into two populations that can interact with only one of the two counter-propagating waves, suppressing any mode competition. In homogeneous solid-state laser media such as a Nd:YAG or VECSEL, this bidirectional emission is more complicated to obtain and the mode-competition tends to suppress one of the two necessary counter-propagating waves or to induce energies exchanges the counter propagating waves preventing the existence of a stable and useful beat note signal. We will describe the scheme that we developed to stabilize the bidirectional emission and compare the implementation with Nd:YAG and with VECSEL.

We will finish by comparing both RLG in term of performances and noises that ultimately affects the achievable performances.

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