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Design and properties of high-power highly-coherent single-frequency VECSEL emitting in the near- to mid-IR for photonic applications

A. Garnache[a], A. Laurain[a], M. Myara[a], M. Sellahi[a], L. Cerutti[a], J-.P. Perez[a], A. Michon[b], G. Beaudoin[b], I. Sagnes[b], P. Cermak[c] and D. Romanini[c]

[a] Institut d'Electronique du Sud, CNRS UMR5214, Université Montpellier 2, France;
[b] Laboratoire de Photonique et Nanostructures, CNRS UPR20, Marcoussis, France;
[c] LiPHY, CNRS UMR5588, Université Joseph Fourier de Grenoble, France

ABSTRACT

We demonstrate high power (multiwatt) low noise single frequency operation of tunable compact verical–external–cavity surface–emitting–lasers exhibiting a low divergence high beam quality, of great interest for photonics applications. The quantum-well based lasers are operating in CW at RT at $1\,\mu m$ and $2.3\,\mu m$ exploiting GaAs and Sb technologies. For heat management purpose the VECSEL membranes were bonded on a SiC substrate. Both high power diode pumping (using GaAs commercial diode) at large incidence angle and electrical pumping are developed. The design and physical properties of the coherent wave are presented. We took advantage of thermal lens–based stability to develop a short $(0.5-5\,\mathrm{mm})$ external cavity without any intracavity filter. We measured a low divergence circular TEM_{00} beam ($M^2 = 1.2$) close to diffraction limit, with a linear light polarization ($> 30\,\mathrm{dB}$). The side mode suppression ratio is $> 45\,\mathrm{dB}$. The free running laser linewidth is 37 kHz limited by pump induced thermal fluctuations. Thanks to this high-Q external cavity approach, the frequency noise is low and the dynamics is in the relaxation-oscillation-free regime, exhibiting low intensity noise ($< 0.1\,\%$), with a cutoff frequency $\sim 41\,\mathrm{MHz}$ above which the shot noise level is reached. The key parameters limiting the laser power and coherence will be discussed. These design/properties can be extended to other wavelengths.

Keywords: VECSEL, Quantum-Well, Single Frequency, high power, low noise

1. INTRODUCTION

Surface-emitting semiconductor lasers can make use of external cavities and optical pumping techniques to achieve a combination of high continuous-wave output power[?, ?] and near-diffraction-limited low divergence circular beam quality that is not matched by any other type of waveguide semiconductor source (Fig. ??,??). The ready access to the laser mode that the external cavity provides has been exploited for applications such as intra-cavity frequency doubling,[?] passively mode-locked ultrashort pulse,[?] tunable single-frequency ultra-low noise operation in the 0.8 to $2.3\,\mu m$ spectral range,[?, ?, ?, ?, ?] low noise dual frequency operation for metrology, remote sensing, and communications applications,[?] gyrolaser operation for avionic/space,[?] high sensitivity laser absorption spectroscopy for gas analysis.[?] The growing current interest in Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) is at first sight paradoxical, since these lasers incorporate precisely the feature that conventional semiconductor lasers most prize the lack of; a bulky external cavity that requires alignment. They are frequently, moreover, optically pumped, exploiting the diode beam coupling technologies that have been developed for diode-pumped solid state lasers (DPSSL). Electrical pumping over large area is also possible to reduce chip volume, with reduced power performances and a more complex technology. On further investigation, however, it becomes apparent that this family of devices offers a distinctive combination of properties not easily matched by any other type of laser source. Since the area of the spatial mode on the surface of the gain structure can be large, the power that can be extracted in a fundamental spatial mode before the optical damage threshold is reached greatly exceeds that which can be obtained from a conventional diode laser where

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Further author information: (Send correspondence to A. Garnache)
A. Garnache: E-mail: arnaud.garnache@ies.univ-montp2.fr, Telephone: +33 (0)4 67 14 34 76

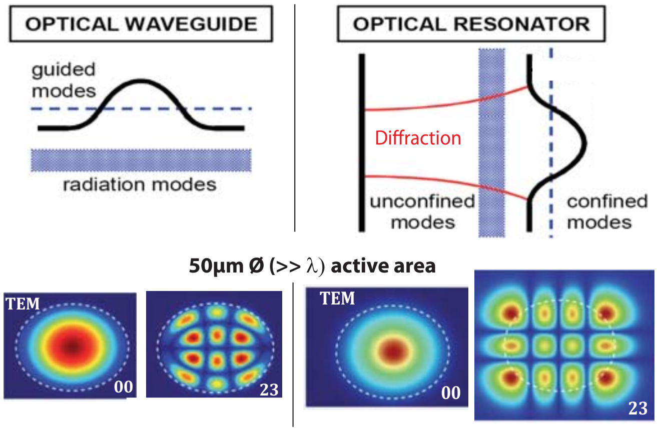

Figure 1. Comparison between a waveguide type laser cavity (diode laser, VCSEL) and a stable free space plano-concave single mode optical cavity (DPSSL, VECSEL).[?] The simulations (bottom) of the confined transverse mode profile for a 50 μm large active diameter (white dash line), are shown for both configurations. It clearly shows that single transverse mode operation is possible for stable plano-concave optical cavity even at large diameters, in contrary to a guided cavity.

the waveguide section size as to be on the order of few λ (Fig. **??**). This high-finesse mm-long air-filled stable vertical cavity design boosts the spatial (low wavefront phase noise) and temporal (low frequency and intensity noise) light coherence due to its long photon lifetime t_p (Fig. **??**), generating continuously-tunable sub-MHz linewidth single-frequency laser with large diameter TEM$_{00}$ mode **??**, exibiting a linear polarization state.[?,?,?,?] The emitted laser radiation exhibits low Relative Intensity Noise or fluctuations, as the laser is in a class-A regime with a short cutoff frequency $<$ 50 Mhz (Fig **??**), above which the intensity fluctuations reache the shot noise level. It tends to a class-B regime with moderate relaxation oscillations if the cavity length is decreased.[?] This contrasts with conventional monolithic semiconductor lasers which exhibit large amplitude/noise resonance above the GHz frequency level (Fig. **??**,**??**). Single longitudinal mode tunable DFB lasers (Fig. **??**) and high-power solid-state lasers rely on strong intracavity filtering. A compact powerfull laser design can be thus achieved using a short cavity Quantum-Well VECSEL without any intracavity filter,[?,?,?] as it exhibits an ideal homogeneous gain behavior - as with QW's -, where amplified spontaneous emission (Fig. **??**) and non-linear mode interactions - like Spatial hole Burning - are negligible[?] - in constrast to monolithic semiconductor lasers.

We will present an overview of the laser results we achieved with such GaAs-based and Sb-based laser geometry, emitting in the 0.9-1.1μm and 2-2.7μm windows respectively, together with a full physical study of the emitted coherent wave. We will discuss the targeted photonics applications. The Mid-IR window is especially well adapted for gas analysis applications (CH$_4$, NH$_3$, CO, HF and H$_2$O, CO$_2$...). The design principles can be extended to any wavelength.

2. HIGH POWER VECSEL DEVICE DESIGN AND TECHNOLOGY

2.1 1/2-VCSEL structure design and fabrication : the gain mirror - membrane on SiC for thermal management

The 1/2-VCSEL structures are composed of a high reflectivity Bragg mirror, typically 6 quantum-wells and a SiN antireflection coating on top[?,?,?] (Fig. **??**). The GaAs-based structures are grown by MOCVD[?] and the Sb-based ones by MBE,[?] and fully characterized (Fig. **??**) for emission at 1μm, and 2.2-2.7μm. For higher power operation requiring a low thermal impedance, the structures are grown in reverse order, with an etch stop layer added, bonded on SiC by solid-liquid inter-diffusion process, and the substrate removed by selective chemical etching:[?,?] the semiconductor membrane is then bonded on a low thermal impedance carrier substrate. A 300nm gold layer is evaporated on the bragg, before bonding, to enhanced the reflectivity. This design allows reducing the bragg layer number, therfore the thermal device impedance by a factor 3 to 10 depending on the III-V technology (Fig. **??**).[?,?] The resulting Sb-based 1/2-VCSEL membrane is shown in scanning electron

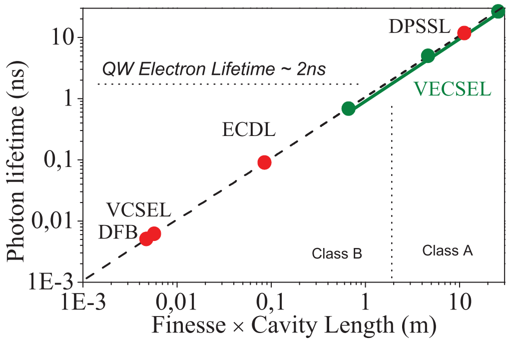

Figure 2. Calculated cavity photon lifetime t_p as a function of the product cavity-finesse times cavity-length for the different technologies (DFB diode laser, monolithic VCSEL, VECSEL, DPSSL). The VECSEL cavity length is varied from 0.1 mm to 5 cm here. The VECSEL can vary from class B to class A laser regime without relaxation oscillations and short cavity cutoff frequency ($\propto 1/t_p$).

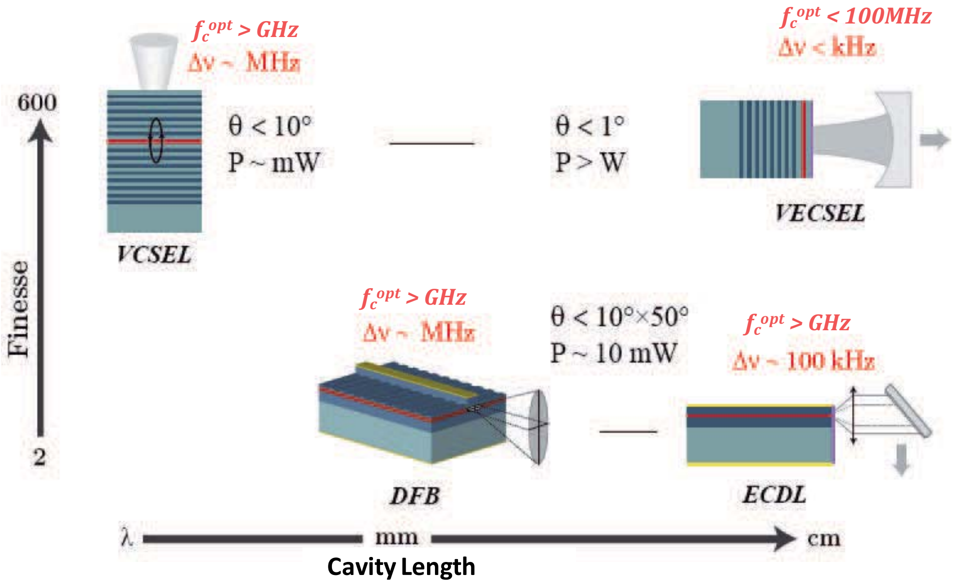

Figure 3. Fundamental properties of single mode semiconductor lasers: monolithic μc-VCSEL, V**E**CSEL, DFB diode laser and External-cavity diode laser.[?] The beam divergence θ, the achievable output power P, the laser cavity cutoff frequency f_c, and the achievable laser linewidth $\Delta\nu$ are given.

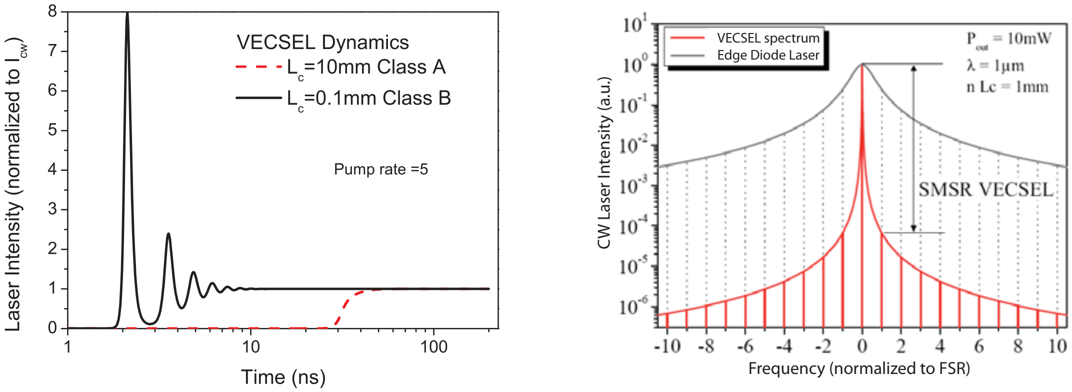

Figure 4. (left) Simulated VECSEL transient dynamics of the intensity, after switching on the pump, for an ultra-short (0.1 mm) and a short (10 mm) cavity length, showing the transition between class B to A regime. (right) Simulated Laser spectrum at the steady state showing the SMSR limited by spontaneous emission, for a VECSEL without any intracavity filter and an Edge emiting diode laser without any DFB technology (same cavity lenght).

microscopy cross section on Fig. **??**. We measured a device thermal resistance in rather good agreement with the 2D symmetric simulation (FEMLAB) [Fig. **??**].

2.2 Device design: short plano-concave cavity principle pumping at large angle

The devices are formed by a 1/2-VCSEL, a small 0.3-15 mm air gap to stabilize single transverse and longitudinal mode operation in a plano-concave type stable cavity. The cavity is closed by a commercial dielectric mirror on glass or CaF2 (99% of reflectivity) having either a concave surface (2-10 mm radius of curvature) or a plane surface (taking advantage of pump induced thermal lens). A Piezoelectric Transducer (PZT) is used to tune the cavity length over $5\,\mu$m, thus the laser frequency over several cavity free-spectral-range (FSR). The main advantage of VECSEL for broad continuous frequency tuning, in contrary to monolithic semiconductor devices, is that the ultra-thin gain chip is not coupled with the optical cavity: the gain wavelenght and the cavity frequency comb postion can be tuned independently, with the pump power/chip temperature and with the cavity length (PZT voltage) respectively. The external mirror is held by an ultra-stable mirror mount (New Focus 9882). High power 8 W and 200mW singlemode 800nm commercial diode lasers are used as pump sources, lunched at large incidence angle on the chip ($> 45\,^\circ$).[?,?] All the components are glued in a compact lab prototype (sealed box) to reduce mechanical and thermal fluctuations (Fig. **??**). In the plano-plano type configuration[?] at high power, we calculated that our thermal lens-based cavity behaves like a single transverse mode optical resonators,[?] where higer transverse modes can not oscillate. To be in a single frequency light state, the laser has to operate on a single transverse and longitudinal mode, and light polarization state (linear along [110] here).[?] To stabilize only one longitudinal mode in the gain bandwidth, we took advantage of the ideal homogeneous gain behavior of QW VECSEL,[?] where non-linear mode interactions are weak. Then we chose a short cavity length $L < 10$ mm, without the need of any intracavity filter, to prevent from multimode operation, or mode hopping, due to technical perturbations, specially while using a multimode noisy pump.[?,?,?] We chose a cavity length short enough so that the characteristic time ($\ll 1$ ms here) to stabilize a single longitudinal mode[?] is shorter than the characteristic time of strong technical fluctuations (mechanical, thermal...), already potentially large in the kHz frequency range (see Fig. **??**,**??**).

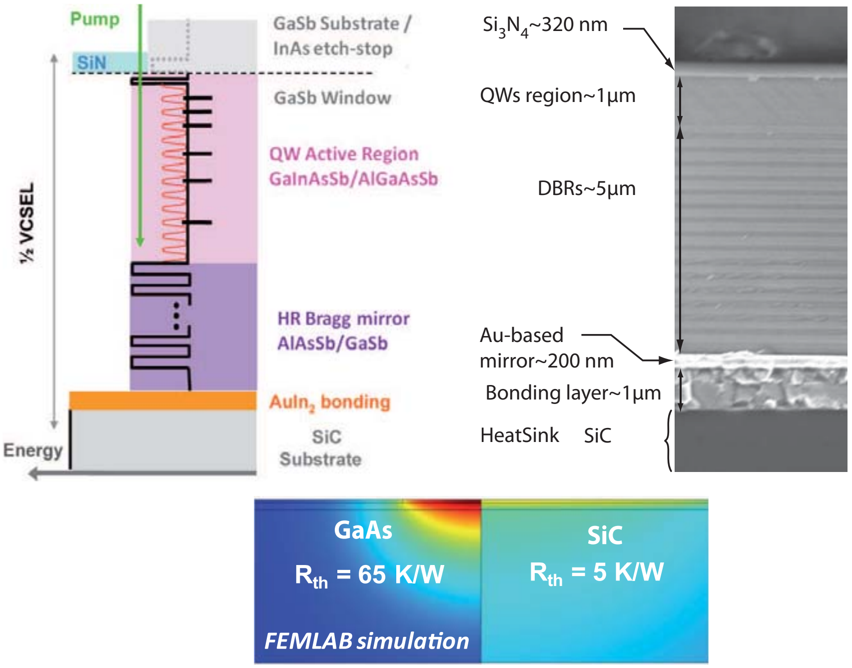

Figure 5. VECSEL gain structure design and membrane technology for thermal management. (top left) design, (top right) scanning electron microscopy cross section of the Sb-based membrane on SiC. (bottom) FEMALB simulation of the temperature distribution on GaAs and SiC, showing the low impedance of membrane bonded on SiC.

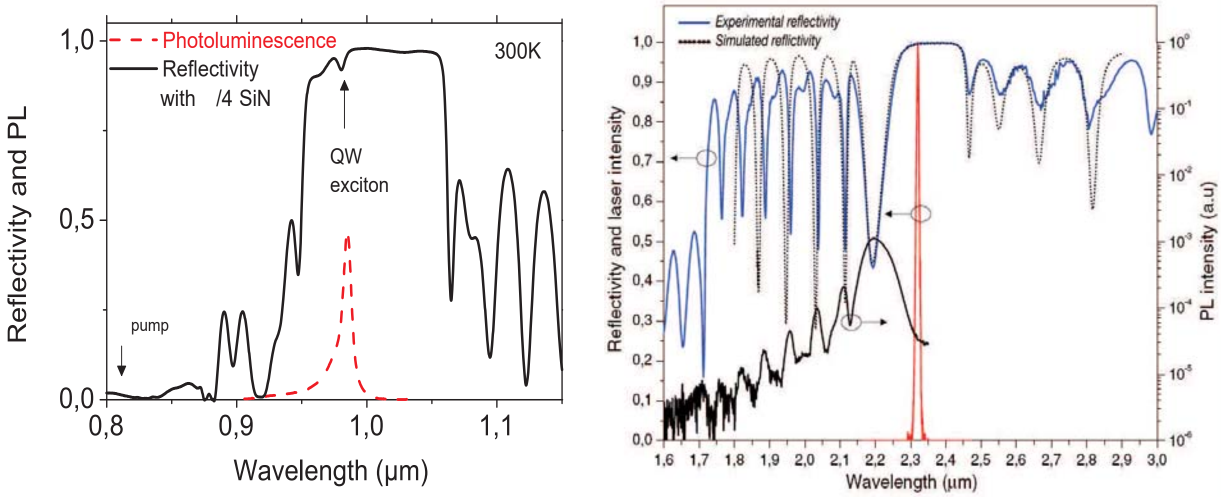

Figure 6. Reflectivity and photoluminescence of the GaAs-based and Sb-based VECSEL gain structure bonded on SiC emitting at 1 μm and 2.3μm.

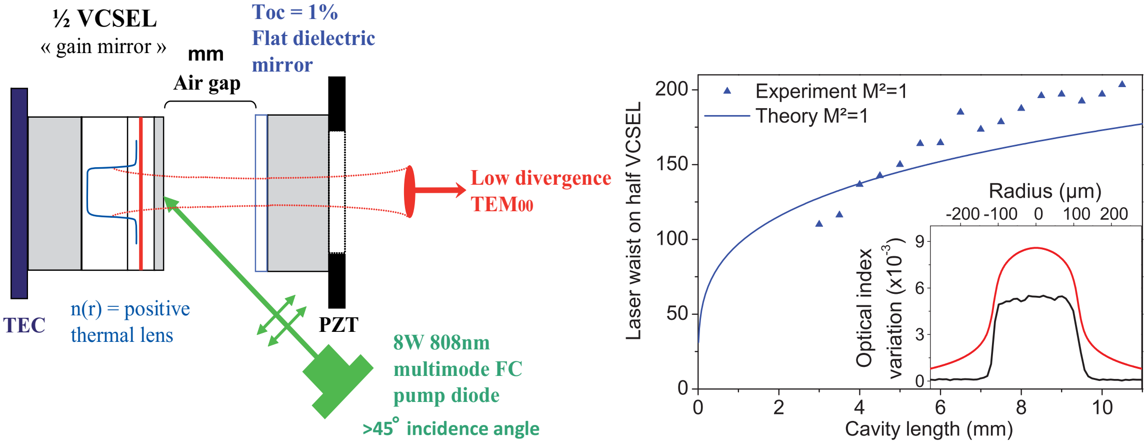

Figure 7. (a) High power single frequency tunable VECSEL design, and (b) Thermal lens-based cavity stability showing a plano-concave type stability: experimental and calculated Gaussian waist w_0 (@$1/e^2$) on the VECSEL gain mirror varying with L; in inset : experimental pump profile and temperature induced index profile (FEMLAB simulation) in the VECSEL structure (8 W pump power).[?]

3. FREE RUNNING TUNABLE SINGLE FREQUENCY OPERATION AT HIGH OUTPUT POWER

3.1 Single longitudinal and transverse Mode operation at the quantum and diffraction limit

These low noise sources operate in cw at RT, with up to 2.1 W of output power (pump limited; with thermal management)[?] at 1μm (Fig. **??**), and $>$ 7mW at 2.3μm and 150μW at 2.7μm without thermal management (Fig. **??**) in a single transverse and longitudinal mode (Fig. **??**). The short stable external optical cavity enforces circular TEM_{00} diffraction limited beam (RMS phase fluctuation $< \lambda/100$ measured) (Fig. **??**) with a very low divergence, and single frequency broadly tunable operation (SMSR=60dB) without any intracavity spectral filter (Fig. **??**). The far field phase map was recorded with a wavefront sensor. The second moment measurement and far field phase map shows that the beam is close to diffraction limit with a quasi-Gaussian shape, in spite of a poor quality elliptical multimode pump diode beam, in good agreement with the simulation. VeCSELs are linearly polarized due to QW gain dichrosm along the [110] crystal axis ($>$ 30 dB orthogonal polarization exctinction ratio), which breaks the circular symetry.[?,?,?] A wide mode-hope-free tuning range $>$ 500 GHz is obtained by moving the external mirror of a short cavity with a PZT as shown in Fig. **??** at 2.3μm for absorption spectroscopy application.[?]

3.2 Intensity and frequency noise in free running operation

This high-Q VECSEL design leads to low RIN and frequency noise operation despite the use of multimode high power pump diode. These free running lasers were studied in terms of Relative Intensity Noise and linewidth showing a highly coherent wave. Thanks to the high-Q external cavity approach, the dynamics is in the relaxation oscillation-free regime with a laser cutoff frequency of 41 MHz for a 7 mm long cavity here (Fig. **??**). The dynamics is thus in the relaxation-oscillation-free regime, in contrary to conventional monolithic semiconductor lasers, as the photon lifetime $t_p > \tau_e$ the carrier lifetime **??**, with a laser cutoff frequency f_c^L below 100 MHz. The laser is in a class-A regime (Fig. **??**) and tends to a class-B regime if the cavity length is decreased.[?] The emitted optical power is ultra stable - much more than conventional solid-state lasers - exhibiting relative RMS fluctuations lower than 0.1% (Fig. **??**) in the frequency range 10Hz-40MHz even at 2.1 W of output power, and reaches the shot noise limit above 41MHz.[?] Between laser cutoff frequency f_c^L and the cavity Free-Spectral-Range value (f=40 MHz - 20 GHz), the laser intensity noise is at the shot-noise fundamental limit, leading to an ultra low noise source in this frequency range. We performed frequency noise measurements with a Fabry-Perot interferometer. Below 1 kHz the frequency noise is limited by thermal/mechanical contributions and 1/f

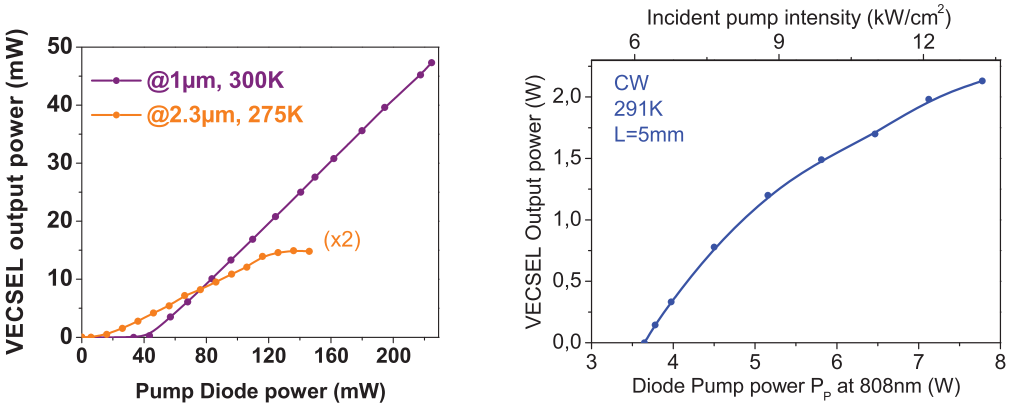

Figure 8. Single frequency VeCSEL output in cw at RT: output power without thermal management on GaAs and GaSb (left), and with (right) thermal management on SiC at 1μm.

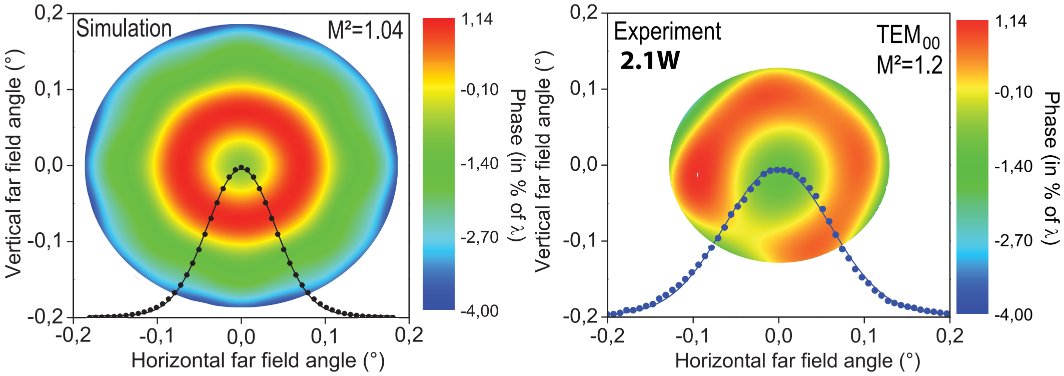

Figure 9. Single transverse TEM$_{00}$ mode operation at the diffraction limit: (a) Simulated (Fresnel approximation) far field phase map and horizontal intensity profile (dotted line) after 100 round trips for $L = 7.5\,\mathrm{mm}$; (b) Far field phase map at high power recorded with a wavefront sensor based on lateral shearing interferometry technology (SID4-PHASICS); the field curvature zernike term is removed; intensity profile (dotted line) at high power (2.1 W) recorded with a beam profiler (solid line : Gaussian fit).?

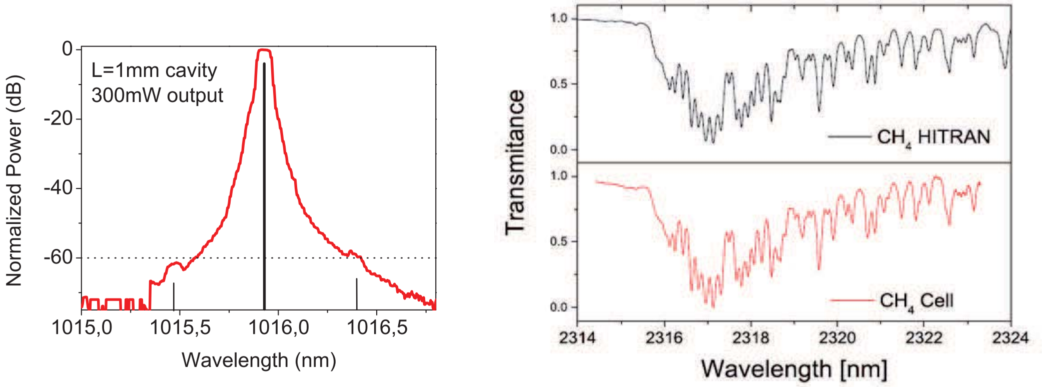

Figure 10. (left) Laser spectrum at high power recorded with an optical spectrum analyzer (15 GHz resolution).? (right) Broad continuus frequency tunability at 2.3μm with a short mm-long cavity and a PZT (the beam is sent through a methane cell).?

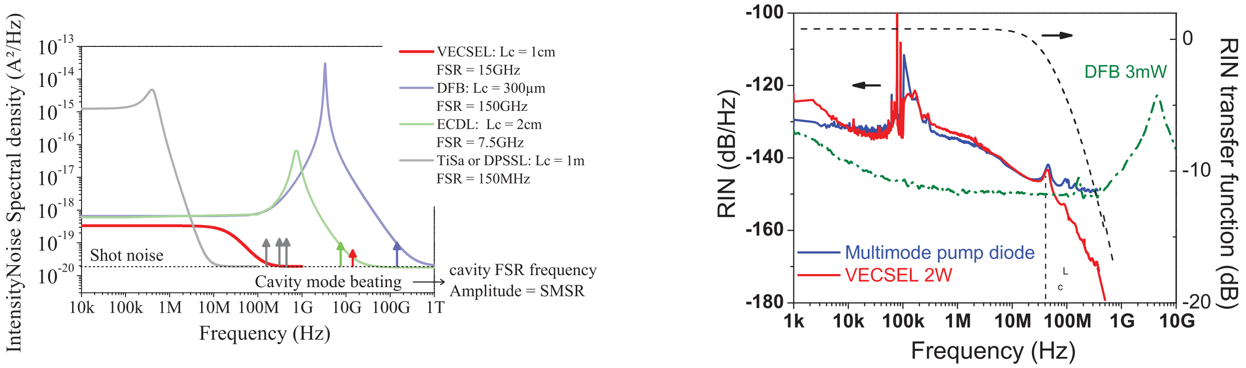

Figure 11. (left) State of the art RIN for the different laser technologies, and (right) Pump RIN$_p$, VECSEL RIN at $P_{out} = 2W$ W and theoretical RIN transfer function spectra. The RIN of a commercial monolithic DFB diode laser at low power is shown for comparison.[?]

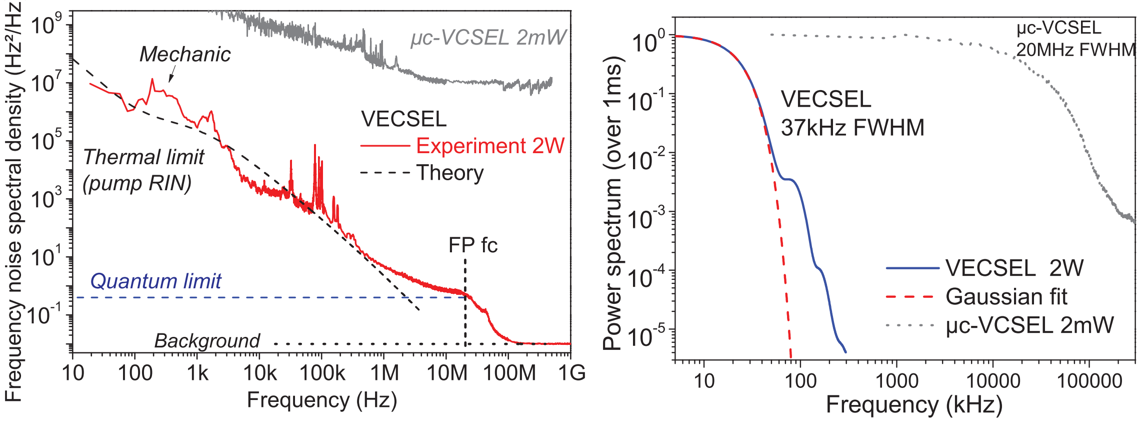

Figure 12. (a) Frequency noise spectral density at 800 mW output power (L_c=7.5 mm) : experiment (solid line) and theory without mechanical noise (dash line); in inset Fabry Perot transmission spectrum. The Frequency noise of a monolithic commercial μc-VCSEL at low power is shown for comparison. (b) Laser power spectral density deduced from experiment showing a 37 kHz linewidth (FWHM) over 1 ms[?] at the watt level. For comparison a commercial monolithic μc-VCSEL device shows a linewidth > 10 MHz at the mW output level (measured with a standard fibre heterodyne technique).

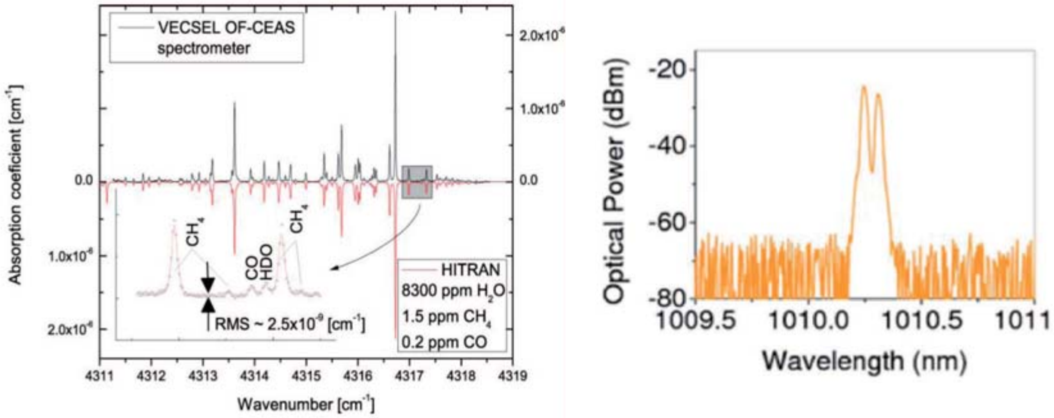

Figure 13. Photonic applications of high power low noise tunable VECSELs: tunable source in the mid-IR for gas analysis by cavity-enhanced-absorption-spectroscopy technics (left);[?] tunable dual frequency operation device in the near-IR for metrology, remote sensing, and communications[?] (right).

technical noise. The frequency noise spectral density comes close to the Hz level fundamental quantum limit at high frequencies. We experimentally deduced a Gaussian-like shape linewidth of 37 kHz over 1 ms even at 2.1 W of output power,[?] limited by pump induced thermal fluctuation (Fig. **??**). This linewidth value is similar to what would be measured using a standard heterodyne technique, and is 2-3 order of magnitude lower than the limit of conventional semiconductor integrated lasers above 5 MHz. Longer cavity design (cm) would allow to reach a linewidth below the kHz level. By frequency locking to a high finesse fabry-perot or to an atomic transition, this source would allow to reach a linewidth close to the Hz level still at high power.

4. CONCLUSION

We demonstrated a compact highly coherent and efficient high power QW semiconductor laser in the near and middle-IR range (1-2.7μm range) at the multiwatt level. The single frequency laser exhibits low intensity and frequency noise (sub-40 kHz linewidth) and is broadly continuously tunable. It is based on a short plano-concave type cavity VECSEL, where a VECSEL membrane is bonded on SiC for thermal management. We obtained diffraction limit quasi-Gaussian beam even pumping with a low beam quality beam diode laser. We showed that our thermal lens-based cavity behaves like a single transverse mode optical resonators. We showed that pump properties define the cavity design and laser coherence. The laser RIN and linewidth can be further reduced using noiseless excitation, like low noise pump or electrical pumping.

This design principle and the laser properties obtained can be extended to any wavelength by using suitable semiconductor materials, and is scalable to higher output powers using larger active diameters. This low noise compact device shows higher quality than standard commercial laser diodes or solid-state lasers, with noise levels several order of magnitude lower together with output powers several order of magnitude higher.

These highly coherent high power semiconductor sources are now being used in various photonic applications: high sensitivity spectroscopy instruments,[?] tunable dual frequency operation device for metrology, remote sensing, and communications,[?] gyrolaser operation for avionic/space,[?] atomic clock for atomic frequency standards as well as atomic inertial sensors.[?]

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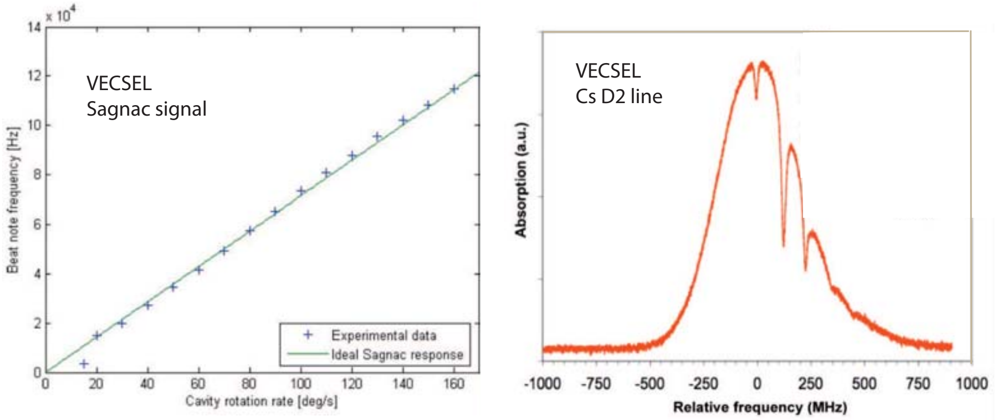

Figure 14. Photonic applications of high power low noise VECSELs: Gyroscope laser in the near-IR for avionic/space (left);[?] narrow linewidth tunable source for atomic clock at 850nm for atomic frequency standards and atomic inertial sensors (right).[?]

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