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SINGLE FREQUENCY FREE-RUNNING LOW NOISE COMPACT EXTENDED-CAVITY SEMICONDUCTOR LASER AT HIGH POWER LEVEL

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ABSTRACT

We present a highly coherent semiconductor laser device formed by a ½-VCSEL structure and an external concave mirror in a millimetre high finesse stable cavity. The quantum well structure is diode-pumped by a commercial single mode GaAs laser diode system. This free running low noise tunable single-frequency laser exhibits >50mW output power in a low divergent circular TEM_{00} beam with a spectral linewidth below 1kHz and a relative intensity noise close to the quantum limit. This approach ensures, with a compact design, homogeneous gain behaviour and a sufficiently long photon lifetime to reach the oscillation-relaxation-free class-A regime, with a cut off frequency around 10MHz.

1. INTRODUCTION

Laser technology is maturing rapidly and is finding applications in areas such as high resolution spectroscopy [1], medicine, optical telecoms, metrology [2], space, avionic [3]… where highly coherent tunable high power light sources are required. Single frequency tunable high-power solid-state lasers rely on intracavity filtering, in a commonly bulky and complex optical system. In addition to compactness and low power consumption, semiconductor lasers have the great advantage to cover a wide emission wavelength range, almost spectral hole free from the blue to the infrared at room temperature, exploiting the III-V semiconductor technology.

Here we demonstrate that a compact (<500cm^3) and highly coherent laser design can be achieved using a simple extended-cavity quantum-well semiconductor surface emitting laser in a high finesse stable cavity, so called External-cavity VCSELs (VeCSELs) [1,2,3,4,5,6,7], to develop a high power tunable source. The VECSEL approach overcomes the beam quality limitations of edge-emitting laser diodes and the low output power of conventional microcavity VCSELs. Diode-pumped VeCSEL combine the approach of diode-pumped solid-state lasers and engineered semiconductor lasers, generating both circular diffraction limited output beams (TEM_{00}) and high powers in continuous wave at 300K [2,4]. Moreover, as is demonstrated here, such a source has the potential to boost the spatial and temporal light coherence by lowering the technical limits of solid-state-lasers and the quantum limits of conventional semiconductor lasers by several orders of magnitude. VeCSELs exhibit single-frequency operation in the 0.8-2.5µm range and wide mode-hope-free tuning range [1,2,5,6,7].

In this paper, a compact highly-coherent free-running continuously tunable quantum-well VeCSEL is designed and demonstrated, operating at high power level in a TEM_{00} beam with a linear light polarization. Both the relative intensity noise and the phase noise (linewidth) are measured to be at an ultra low level.

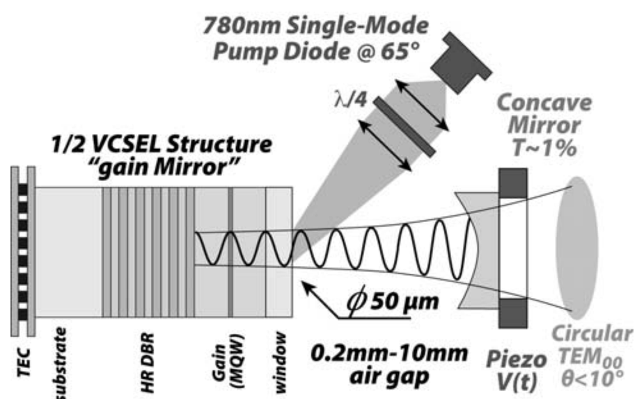

Figure 1: Single frequency Diode-pumped VeCSEL device principle and experimental setup.

2. VeCSEL DESIGN AND DEVICE TECHNOLOGY

2.1 Laser geometry and technology

The VeCSEL device is formed by a ½-VCSEL semiconductor structure (the "gain mirror"), a 0.2-10mm air gap to stabilize single longitudinal mode operation, and a commercial spherical concave mirror with a reflectivity of 99% (fig. 1) and a radius of curvature between 2 to 10mm. The chip is soldered on a small Peltier element to stabilize the chip temperature down to 10^{-3}K (>100Hz frequency response). A Piezoelectric Transducer (PZT ceramic) is used to tune the cavity length over 5µm, thus the laser frequency. The external mirror is held by an ultra-stable mirror mount (New Focus 9882). A 200mW single transverse mode 780 nm commercial pump laser diode (Sanyo DL-LS2075, battery biased) is used as a relatively "low" intensity noise pump source (low compared to fibre-coupled high power laser diode). Indeed, any excitation intensity noise will be transfer to the VeCSEL intensity and frequency noise. The uniform pump excitation avoids any potential transverse spatial-hole-burning effects (multi transverse mode operation) and hot spots over the gain area. The Gaussian-like elliptical (2:1) pump beam is focused with two commercial aspheric lenses on a 30-50µm (FWHM) spot size at a large incidence angle (65°). This geometry ensures a quasi-circular pump area, a high pump transmission to the QW active region (T>90%), and allows to design ultra-short external cavity below 1mm. The components are glued on a home made breadboard and inserted in a metallic box (Thermal and acoustic noise isolation). The whole box temperature is stabilized with a Peltier element (few Hz frequency response), to avoid long term frequency drift and mode hops.

The typical diode-pumped ½-VCSEL structure (fig. 2) is composed of a high reflectivity Bragg mirror (99.9% of reflectivity), an active region with 5 to 10 strain compensated quantum-wells (QW's) embedded in a thick pump absorbing barrier layer, a top confinement layer also acting as a laser window, and a thin cap layer to prevent from oxidation. The QW's are distributed in the active region among the optical standing-wave antinode positions with a distribution function such as the excited carrier density remains almost equal in all QW's to ensure a low laser threshold and a homogeneous gain. The number of QW's is optimized to obtain a low threshold and a large enough differential gain at 300 K, adapted for 1-2% of optical cavity losses. These design principles are valid at any wavelength in the 0.8-2.7µm spectral window by using III-V semiconductor materials [1,2,7].
For the spectral region around 1µm, the 1/2-VCSEL structure (fig. 2) designed for 800 nm pumping used in the present work, was grown by MOCVD using TMGa, TMAl, TMIn, and AsH3 at 60 mTorr and at a temperature of 700°C. The multilayer mirror on top of the GaAs (100) substrate, is obtained by using 27.5 pairs of GaAs/AlAs layres. Next is a 7 (to 13) half-wave thick active region with 6 strain compensated 8 nm $In_{0.2}Ga_{0.8}As/GaAs(P)$ QW's. A 30nm thick AlAs confinement layer and a 10nm thick GaAs caping layer were grown on top. With this design the pump absorption at 800 nm is >70 % in the thick GaAs barrier layers.
The chip fabrication was ended by a quarter-wave SiN antireflection coating evaporated on top of the stack. The substrate back side is mechanically polished with a wedge (~2°) and gold covered (200nm) to avoid any etalon effect arising from back reflection.

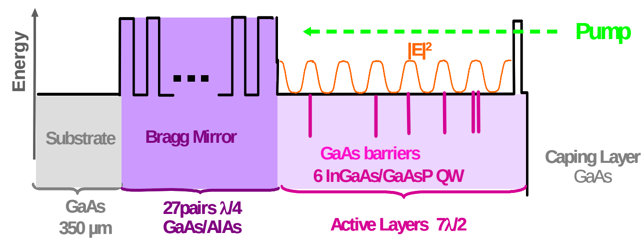

Figure 2: Typical ½-VCSEL structure design grown by MOCVD exploiting GaAs based materials.

For this simple technology device, no post-growth processing is required for carrier injection, as a low cost commercial 800nm GaAs laser diode is used for optical excitation (Fig. 1) [1,7]. Thus the structure is optimized optically, rather than electrically: reduction of optical losses and heating (mirror); no need for interface grading; volume generation of carriers avoids problem of charge separation. Note that for the target applications, where the whole system volume is > 100 cm^3 and weight is >1 kg, a diode-pumped VCSEL device is compact enough. Electrical pumping of a VCSEL structure based on III-V materials would render even more compact the device with potentially similar laser properties, except from a much lower output power.

2.2 VeCSEL physics principles

To operate single frequency, i.e. in a single light state, first of all the laser cavity has to oscillate on only one transverse mode, usually the fundamental TEM_{00} mode, which puts strain on the cavity stability design (cavity length and mirror radius of curvature). Secondly, only one polarization state must be selected (via transition selection rules in the QWs or loss dichroïsm). Last, only one longitudinal cavity mode has to be selected in the ~5THz gain bandwidth (via modal gain competition plus a filter usually).

Amplified-Spontaneous-Emission (ASE) and any non-linear mode/polarization coupling will generate non ideal light state with reduced coherence (finite linewidth) and non-negligible side mode intensities. For a guided plan-plan monolithic laser cavity, like edge-emitting diodes or conventional microcavity VCSELs, ASE and non-linear mode coupling, via longitudinal or transverse Spatial-

Hole-Burning (SHB), are strong: the devices usually operate multimode, thus the side-mode-suppression-ratio (SMSR) is strongly reduced. In addition, due to the guided nature of light in this geometry, the guide section has to be small enough (~few wavelengths, depending on the guiding strength) to force $TE(M)_{00}$ operation, reducing the output power achievable. This is the reason why single mode narrow-ridge edge emitters require a DFB-based narrowband spectral filter, and why a few wavelength diameter (strongly elliptical) active area is needed for microcavity VCSELs.

This stress on the design disappears in the VeCSEL case. Indeed, the transverse mode is stabilized by free space diffraction in a stable optical cavity using spherical mirrors. Thanks to the Hermite-Gauss mode type of the transverse distribution, in contrast to guided monolithic devices of few microns wide, here only the fundamental TEM_{00} mode is selected by adjusting the pump spot size to its waist. Thus the beam diameter can be as large as few hundred microns for high power operation still in a fundamental Gaussian mode.

It has been recently showed that there is no SHB and very weak ASE in a 1-20mm long linear cavity VeCSEL [6]. It thus allows stable highly coherent single light state operation at high power without any obvious need of an intracavity filter: the gain shape curvature is sufficient, via mode competition dynamics to select one mode after a characteristic time of 1ms (for a 10mm long cavity), thus shorter than typical acoustic/thermal perturbations. Any additional spectral filter would strength the single frequency operation, like for uncoated 1/2-VCSEL where the residual microcavity acts as a broad filter (~700GHz width).

One of the drawbacks of the circular VCSEL geometry is that light polarization is not perfectly stable. At first order, the polarization states are circular. However, crystal birefringence along the [110] and [-110] axis breaks the circular symmetry, and gives rise to a polarization mode degeneracy break. This leads to a frequency splitting on the order of 10 MHz for a 10mm long VeCSEL. Another channel for breakdown symmetry is the QW gain dichroism between these axis in the QW plane. In our case, we measured a relative QW gain difference of about ten percents at threshold, stronger on the [110] axis, which should stabilize a linear light polarization. This gain dichroïsm is amplified by using an elliptical spot along [110].

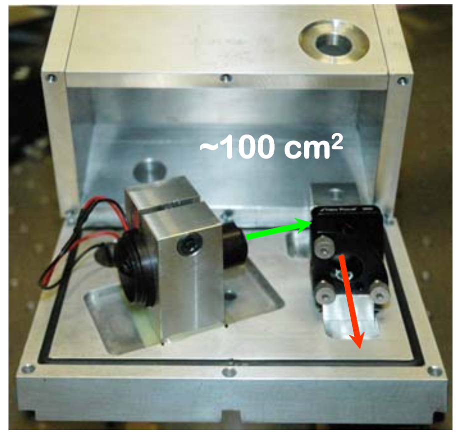

Figure 3: Laboratory low noise diode-pumped VeCSEL prototype.

2.3 <u>Laser results</u>

The compact laboratory prototype we developed is shown in figure 3, here for a 9mm long optical cavity. This kind of simple prototype can be applied to any wavelength achievable with III-V materials. The laser threshold density is as low as 1 kW/cm2 (30mW) at 300K in continuous wave. The stable optical cavity enforces low divergent circular TEM00 beam operation close to diffraction limit (fig. 5). We measured a beam quality factor of M2<1.2, by measuring the near filed to far field product using commercial achromat lenses and a CCD camera. Thanks to gain dichroïsm, the laser electric field was linearly polarized along the [110] crystal axis with an orthogonal polarization extinction ratio >20dB. Single frequency operation is obtained up to 50 mW output power (pump power limited, 35% slope efficiency) at 300K in continuous wave.

In another VECSEL setup, we obtained single frequency operation with 240mW output power (pump limited) using a 1W commercial fibre-coupled multimode pump diode focused on a 100µm spot, but with such a noisy and spatially non-uniform pump system, a much shorter cavity length (400µm long) was needed to stabilize only one longitudinal mode without any intracavity filter. The noise properties of this source are under study.

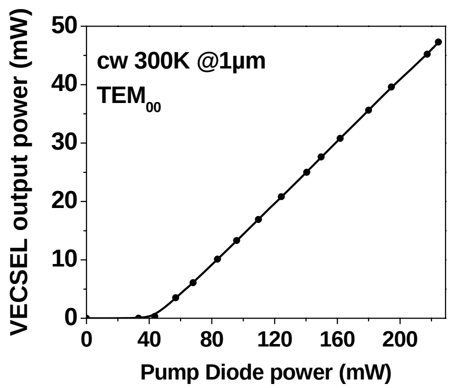

Figure 4: Continuous-wave outpout power at 300K for a VeCSEL emitting at 1µm, pumped by a low power diode.

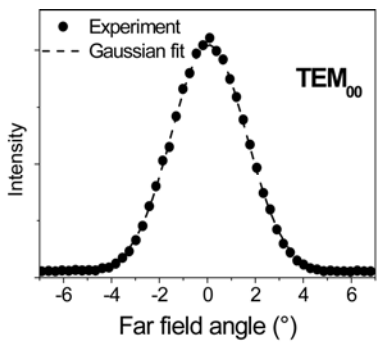

Figure 5: Transverse beam far field distribution at the output (circular symmetry), close to diffraction limit.

3. FREE RUNNING SINGLE FREQUENCY OPERATION

3.1 Stable high purity single-longitudinal mode state

In the previous section, we demonstrated that the VeCSEL device reached an eigenstate of light: it oscillates on a single spatial transverse mode, it has linear polarization state, and we show here that the single longitudinal mode state is stabilized. Indeed, free running single frequency operation is obtained (fig.6) without any intracavity spectral filter, thanks to the QW homogeneous gain [1,5,6,7], for cavity length typically shorter than 25mm for our device. For longer cavities, the characteristic time (see ref. [6] and section 2.2 and 3.2) for the homogenous gain laser to reach a stable single longitudinal mode state after any strong perturbation (from pump, frequency signature depending on the diode, vibration/thermal below 1kHz), becomes too long relative to technical perturbations. Here we show the results for a 9mm long cavity, having a single mode characteristic time below 1ms without any intracavity filter.

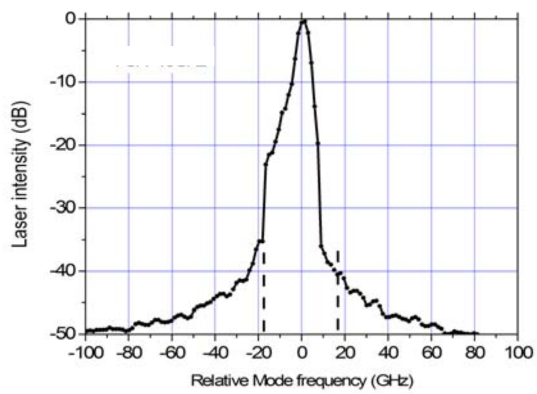

Figure 6 : Experimental laser spectrum showing single frequency operation (9mm long cavity, FSR≈17GHz).

In this device configuration, we obtained a SMSR as high as 48 dB (fig. 7) at moderate power (10 mW), very close to the quantum noise limit for an ideal homogeneous laser [6]. This measurement has been obtained using a high-finesse confocal Fabry-Perot interferometer and a set of low-noise transimpedance amplifiers. Such a high SMSR value clearly exhibits the ideal homogeneous gain behaviour of the VeCSEL.

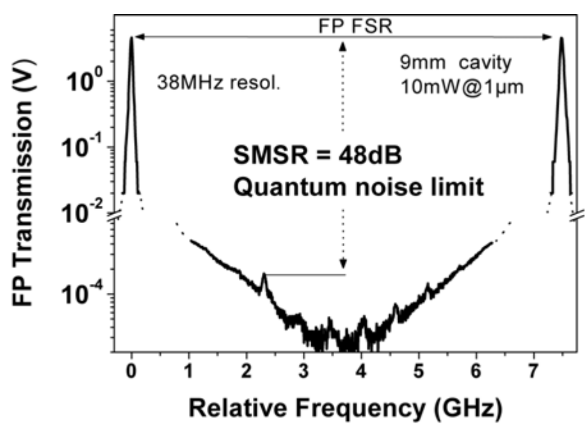

Figure 7 : SMSR Measurement obtained with a 38 MHz Confocal Fabry-Perot Interferometer.

At any power and temperature, a mode hope free laser frequency tuning over ~40 GHz was obtained by translating the mirror with PZT voltage over ~2µm at 100Hz frequency (measured by transmission through a 2cm thick glass Fabry-Pérot etalon). In addition a broad laser gain wavelength tuning (with mode hops) was achieved over >2THz (7nm @1µm) varying the chip temperature (10-30°C) and the pump power.

3.2 Non-linear multimode dynamics: Influence of Cavity Dispersion on Single-Mode Stability

In order to investigate the influence of mode phase dispersion in the ½-VCSEL structure on single longitudinal mode stability, we tuned the laser wavelength (with temperature) around the Bragg centre wavelength (λ=1010nm) in a structure designed to exhibit a relatively strong dispersion (>10^4 s^{-1}) around this spectral position. We observed strongly multimode operation for large positive or negative cavity dispersion and stable single longitudinal mode operation near zero dispersion (fig. 8). We believe that this behaviour can be explained by the interplay between non-linear mode interactions (originating from four-wave-mixing induced population pulsation in the quantum-well gain) [6] and mode phase dispersion after one reflection in the structure.

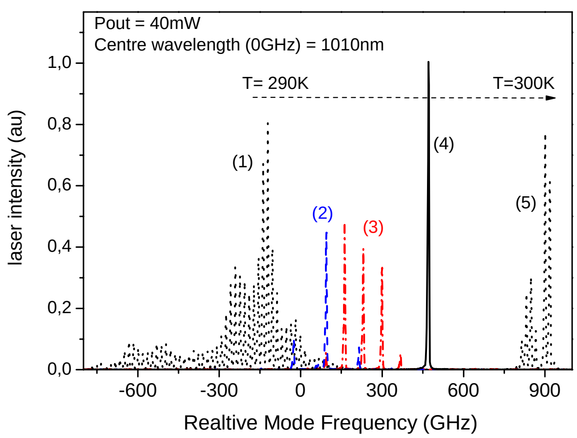

Figure 8 : Steady state Laser spectra taken at different temperatures, showing single mode stable operation at a wavelength ~1010nm where the 1/2-VCSEL structure phase dispersion is close to zero. (9mm cavity length).

For this purpose, we simulated the non-linear dynamics of this multimode laser system as in ref. [6] but taking into account the cavity dispersion. Without any non-linear mode coupling, like in an ideal homogenous gain laser, a regular transient can be observed, leading to stable single mode operation after typically less than 1ms (fig. 9). Switching on non-linear mode interactions, we obtained a strongly multimode non-linear dynamics during the transient after the laser start-up, for large positive or negative cavity dispersion (fig. 10). In contrast, stable single longitudinal mode operation is obtained after the transient near zero dispersion as in the experiment. These dynamics behaviours are still under study. This shows that for single frequency applications, as for ultra-short pulse modelocked laser system, the dispersion value has to be as low as possible in the VeCSEL cavity design to avoid any unstable deterministic non-linear dynamics.

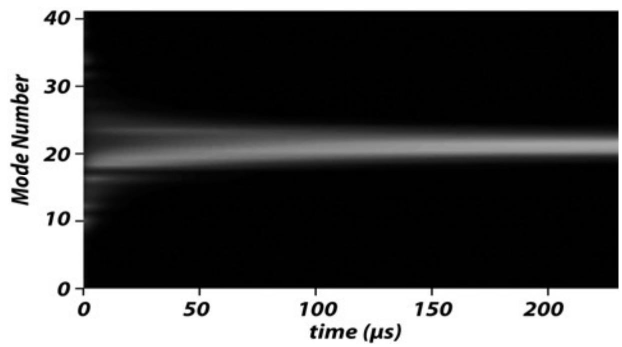

Figure 9 : Simulated VECSEL transient after start-up for an ideal homogeneous laser dynamics (electric field amplitude) without non-linear mode coupling.

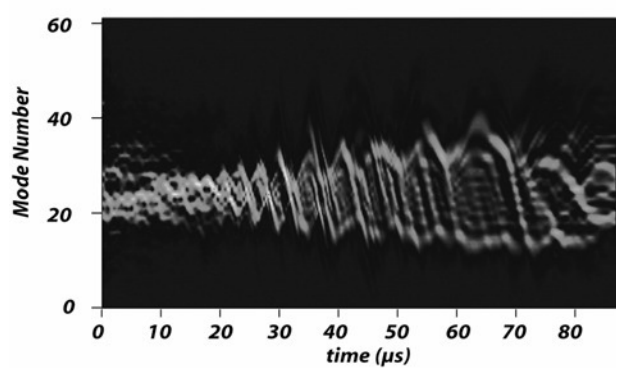

Figure 10: Simulated VECSEL transient non-linear dynamics (electric field amplitude) after start-up, for a relatively strong cavity dispersion ~10^4 s^{-1}.

4. INTENSITY NOISE

The free running single frequency VeCSEL was studied in terms of Relative Intensity Noise (RIN). The RIN level is close to the shot noise level (~-160dB/Hz @2mW output power) below the laser cavity cut-off frequency, in spite of a highly super-poissonian pump (-158dB/Hz @80mW pump power, fig. 11). The emitted power is thus ultra-stable, leading to relative RMS fluctuations as low as 0.015% at 2 mW, over a 10Hz to 10MHz frequency range. Such a tiny RMS fluctuation is, integrated on similar bandwidths, three to four times smaller than in ultra-low noise commercial laser diodes and more than ten times smaller than in state-of-the-art diode-pumped solid-state lasers.

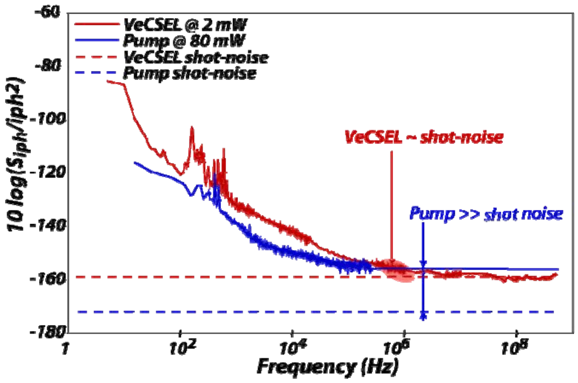

Figure 11 : Pump & VECSEL RIN versus frequency.

The quantum noise limit is also investigated near the laser cavity cut-off frequency (fig. 12). The VeCSEL noise is very low as it exhibits a very small quantum noise level, only twice stronger than the shot-noise level. We have to notice that this measurement has been obtained with a moderate partition: half an electron at the photodetector per emitted photon at the laser, taking into account the attenuation of all discrete optics (lenses, isolator …) and the quantum efficiency of the photodetector.

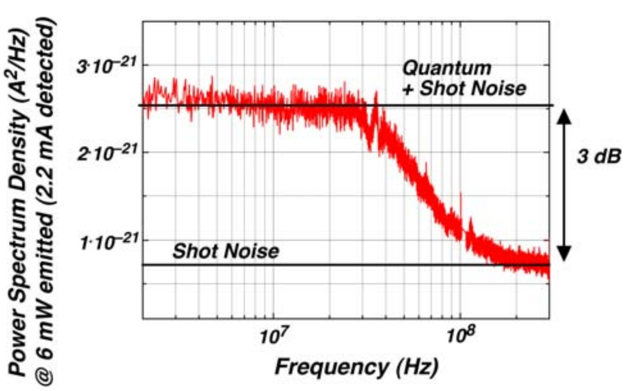

Figure 12: Intensity noise spectrum at the quantum limit.

5. FREQUENCY NOISE & LINEWIDTH

In the following experiments, we demonstrate that the VeCSEL is a highly coherent light source. It exhibits a fundamental (lorentzian) linewidth limit lower than 40 Hz, i.e. typically five orders of magnitude smaller than conventional micro-cavity laser diodes [9,10]. Nevertheless, any laser linewidth is time dependent because of 1/f or technical fluctuations. We observed linewidth values as narrow as 250 Hz for 5µs time delay and 1.2kHz for 125 µs, two order of magnitude narrower than commercial External-Cavity Laser Diodes for similar integration times. For much longer durations (10ms), we obtained a 200 kHz RMS frequency fluctuation.

5.1 Self-Homodyne Technique

In a first step, the linewidth properties are obtained with a delayed self-homodyne technique, using two fiber time delays τ=5µs and 125µs between the two paths. The photo-detected signal is then Fourier-transformed by a FFT Analyser. For the longest delay the linewidth exhibits a 1.2kHz technical FM-noise (frequency noise)induced broadening @ -3 dB for 125µs measuring time (*fig. 13, inset a)*, two order of magnitude narrower than commercial External-Cavity Laser Diodes.

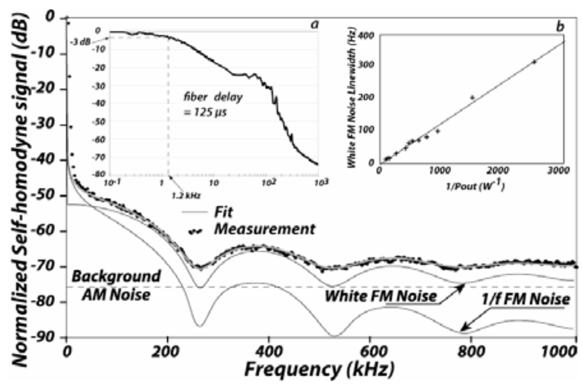

Figure 13 : Fitted and measured self-homodyne signal @ τ=5µs. - (inset a) : Self-homodyne τ=125 µs - (inset b) : White FM noise linewidth versus 1/Pout.

For the shortest delay (*fig. 13)* the measurements are fitted with an FFT-transformed autocorrelation function taking into account mechanical, white and 1/f FM noise contributions [8,9]. This treatment leads to a classical behavior for the white FM noise originated linewidth with a 0.04 Hz.W slope and a 3 Hz limit at 10 mW emitted power (*fig. 13, inset b)*. An optical power independent 1/f FM noise contribution (2.10^5 Hz^2/Hz at 1Hz) is also observed. All these parameters are 5 to 6 orders of magnitude smaller than usual values for conventional integrated semi-conductor lasers [9].

5.2 Frequency Discrimination Technique

Because of the ultra high coherence of the VeCSEL, the self-homodyne technique may require much longer delays to reach long-term linewith values. Such delays are not accessible due to the fibre optics attenuation and dispersion over long lengths.

Moreover, fitting the self-homodyne spectrum leads to almost inaccurate values owing to the large amount of needed free parameters to take into account all the noise contributions (mechanics, 1/f and white noise). This technique nevertheless allows reaching good orders of magnitude.

We thus performed direct frequency noise measurements at low to medium frequencies, using a home-made stable plano-concave Fabry-Perot interferometer (40cm long, 33 finesse) as frequency discriminator. The results (fig. 14) exhibit less than 10 Hz^2/Hz fundamental white noise limit, leading to a linewidth limit below 40 Hz. Moreover, the RMS frequency fluctuation of the VeCSEL over integration times as long as 10 ms is ~ 200 kHz, limited by low frequency technical noise (acoustic, thermal). Thus, a laser linewidth lower than 100Hz could be easily reached, by balancing technical noise with a simple low frequency feedback loop on the PZT.

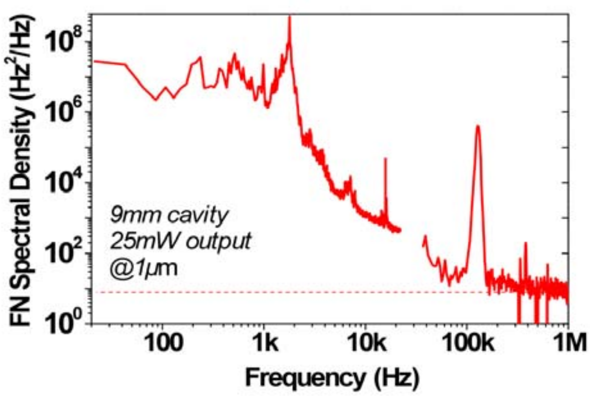

Figure 14: Low to medium frequencies FM noise spectrum: technical noise before 200 kHz and 10 Hz^2/Hz white noise limit close to the fundamental limit.

6. CONCLSUION

We demonstrated an ultra low noise single frequency semiconductor laser at high power level with a circular low divergent TEM_{00} beam. It is based on a compact external cavity VCSEL device, diode pumped by a commercial GaAs diode laser. The laser frequency is broadly continuously tunable and shows a linewidth below 1kHz in free running operation.

The laser noise or coherence properties demonstrated here are quasi-wavelength independent, as more related to the high finesse semiconductor laser geometry, the pump system and the mechanical environment. Thus similar VeCSEL properties could be obtained in the wavelength range 0.8-2.5µm where this laser device technology is already mature exploiting III-V materials [1,2,7].

All the noise values measured are 5 to 6 orders of magnitude smaller than usual values for conventional integrated semi-conductor lasers [8,10].

ACKNOWLEDGEMENTS

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REFERENCES

1. A. Garnache, *et al.*, Proc. SPIE Semiconductor Lasers and Laser Dynamics, Vol. 6184, 61840N (2006)
2. M. Jacquemet, *et al.*, Appl. Phys. B, 86 (3) (2006) p 503-510
3. A. Mignot, *et al.* Optics Lett., In press (2008)
4. M. Kuznetsov, *et al.* IEEE J.Selec.Topics in Quantum Electron. 5, 561 (1999)
5. M. Triki *et al.*, IEEE Photon. Techn. Lett., in press (2008)
6. A. Garnache, *et al*., Optics Express, vol. 15, p. 9403, 2007.
7. A. Ouvrard, *et al*., IEEE Photon. Tech. Lett., vol. 17 (2005), p. 2020.
8. J.P. Tourrenc et al., IEEE J. Quantum Electron, vol. 41(2005), p. 549.
9. M. Myara et al., Proc. Of Unsolved Problems on Noise, (2008), p. 106
10. P. Signoret et al., IEEE Photonics Technology Letters, vol. 25(2004), n. 7, p. 1429-1431