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## COMPACT AND ROBUST SINGLE-FREQUENCY DIODE-PUMPED VECSEL AT THE CESIUM D<sub>2</sub> LINE FOR ATOMIC CLOCKS

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### ABSTRACT

This work reports on an optically-pumped vertical external-cavity surface-emitting laser emitting around 852 nm dedicated to atomic physics experiments with cold Cs atoms. The design of the semiconductor active structure has been optimized to provide a low threshold. A low-power diode-pumped compact prototype has been developed with improved stability. With this setup, we obtained a 17-mW single frequency emission exhibiting large tunability around the Cesium D<sub>2</sub> line. The laser linewidth has been measured to less than 500 kHz on a 10 ms time.

### 1. INTRODUCTION

In atomic physics experiments, complex laser benches are used to perform trapping, cooling, manipulation and optical detection of atoms [1]. Actually the different stages of these cold-atom experiments have distinct constraints on laser sources, such as high output power (> 200 mW) for efficient atom cooling or stimulated-Raman transitions, but narrow-linewidth emission (< 500 kHz) for optical detection. In any case, stable single-frequency operation and fine tunability over some GHz around the atomic transitions are requested. Currently, available laser sources show intrinsic limitations in fulfilling all the required properties. Consequently, several lasers are used simultaneously to provide different optical features, while a single laser source would greatly improve the compactness, the efficiency and the simplicity of these set-ups.

Optically-pumped Vertical External-Cavity Surface-Emitting Lasers (VECSELs) combine the approach of diode-pumped solid-state lasers and engineered semiconductor lasers, generating both circular diffraction limited output beams and high powers [2]. These lasers benefit from the knowledge in semiconductor fabrication. The power scaling possibilities of these semiconductor thin disks to obtain multi-watts output powers have already been demonstrated [3,4]. Furthermore the utilization of a resonant periodic gain design ensures a spatially and

spectrally-homogeneous gain, which is favourable for single-frequency operation [5]. VECSELs appear then to be an interesting way to achieve compact and efficient tunable single-frequency sources for metrology and spectroscopy.

In this paper we present the design of a specific laser structure emitting near 852 nm - corresponding to the Cs D<sub>2</sub> line. In a very simple and compact laser cavity setup, we have obtained a single-frequency line tunable around the Cesium D<sub>2</sub> line. The frequency stabilization on an atomic line has been performed, and the laser linewidth has been characterized through a beat note with a reference laser.

### 2. DESIGN OF THE SEMICONDUCTOR ACTIVE STRUCTURE

The active region of the semiconductor structure has been specifically designed for laser emission around 852 nm. It is optically-pumped in the quantum-well (QW) barriers, which prescribes a pump wavelength below 720 nm. Since red laser sources are neither as efficient nor as powerful in that spectral range than in the infrared, the active structure has been carefully designed with the aim to reach a low laser threshold while keeping an optical gain high enough to compensate for cavity losses. Seven QWs correspond to an optimum which minimizes the pump intensity at threshold for an output coupler which transmission T is about a few percents. Further increase of the QWs number would result in a higher threshold intensity.

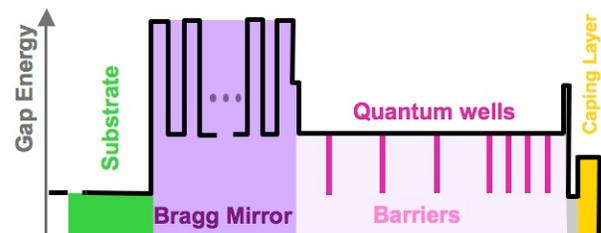


Fig.1 : Active structure design

The semiconductor chip has been grown by metal-organic chemical-vapor deposition (MOCVD) on a 350- $\mu$ m thick (100) GaAs substrate. It contains a multilayer

Distributed Bragg Reflector (DBR) which consists of 32.5 pairs of AlAs/Al<sub>0.225</sub>Ga<sub>0.775</sub>As quarter-wave layers resulting in a 99.95 %-reflectivity 70-nm-wide stop-band centered on 852 nm. The active layer consists of seven 8-nm thick quantum wells (QWs) between Al<sub>0.225</sub>Ga<sub>0.775</sub>As barriers which are distributed among the optical standing-wave antinodes position with a repartition which has been calculated in order that the excited carrier density remains constant in all QWs. The top of the structure is protected a 20 nm-thick In<sub>0.48</sub>Ga<sub>0.52</sub>P capping layer against oxidation of the Al-rich barrier layers. Finally, the wafer is anti-reflection coated at 852 nm with a  $\lambda/4$  Si<sub>3</sub>N<sub>4</sub> layer to maximize the transmission of the incident pump laser and to reduce any intracavity etalon effect at the laser wavelength.

### 3. DESCRIPTION OF THE LASER SOURCE

With the aim to develop a low-power single-frequency source dedicated to the detection of Cesium atoms, a compact monolithic external cavity with improved thermal and mechanical stability has been designed. We chose a single-transverse-mode laser diode as the pump source in order to limit intensity noise transfer from the pump to the laser emission. The pump was thus a Mitsubishi red laser diode delivering up to 150 mW at 658 nm for an operating current of 245 mA. The pump beam was focused on a 20  $\mu$ m radius spot with a pair of aspheric lenses, at the incidence angle of 70° relatively to the structure, which circularizes the elliptic shape of the incident pump beam on the semiconductor chip. The external cavity was formed by a 12 mm-concave mirror R = 99 % at 852 nm mounted on a piezo-electric transducer (PZT) (see Fig. 2). The laser cavity length was carefully adjusted in order to optimize the overlap between the cavity mode and the pump one. The pump system, the semiconductor chip and the external mirror have been integrated on the same mount. The overall setup fitted within a 52×52×58 mm<sup>3</sup> cube. The temperature of the laser cavity was stabilized with a thermoelectric cooler, and the semiconductor device was thermally regulated with an independent controller. The whole set-up was protected by Dural® and acoustic isolant coatings to improve both its thermal and acoustic isolation. Then the laser remains running for weeks without needs for re-alignment.

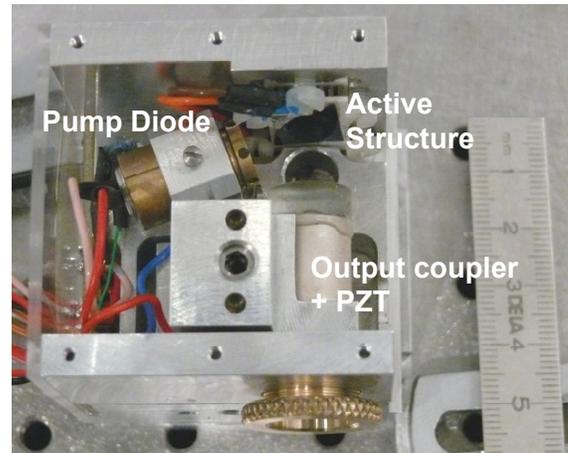


Fig. 2 : Laser prototype

### 4. LASER OPERATION

#### 4.1. Without any spectrally selective element

In this compact prototype, the laser output power is limited by the available pump power to 17 mW (Fig. 3) at an active structure temperature of 10° C. The threshold was reached for an incident pump power of 52 mW, and the slope efficiency was 17% (with regard to incident pump power) without any evidence of thermal roll-over up to the maximum 150-mW pump power. The emission was linearly polarized, and the beam was diffraction-limited with a quality factor  $M^2 < 1.1$ . The emitted wavelength shifted from 850.5 nm at threshold to 852.2 nm at maximum pump power.

Without any frequency-selective intracavity element, we observed a stable single-frequency operation within a large range of operating conditions of the substrate temperature and pump current, with a side-mode suppression ratio higher than 25 dB (measurement-limited). This was checked with a high finesse (F=130) scanning Fabry Perot with a free-spectral range (FSR) of 37.5 GHz larger than the FSR of the laser cavity. This single-frequency operation is attributed to the nearly-ideal gain homogeneity of VECSELs sources which has been extensively studied in [6]. Actually the characteristic time needed for the laser spectrum to collapse to a single-mode is about 1 ms in our experimental conditions, faster than acoustic and thermal fluctuations in our laser set-up.

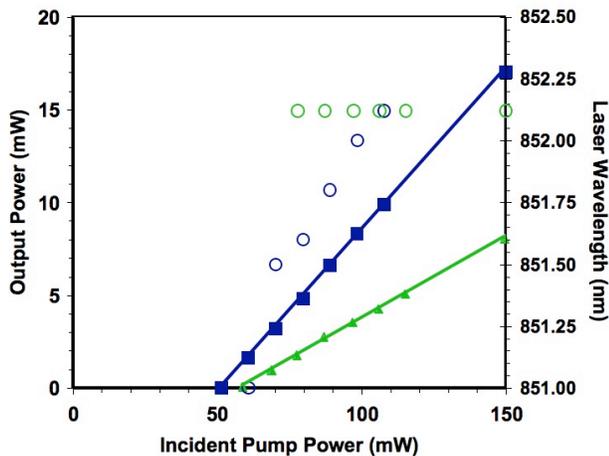


Fig. 3 : Output power (full symbols, left axis) and wavelength (circles, right axis) of the VECSEL source with (green) and without (blue) intracavity etalon.

#### 4.2. With an intracavity Fabry-Perot etalon

To force the laser wavelength independently of the operating conditions, we chose to insert a 26- $\mu\text{m}$  thick uncoated silica etalon inside the cavity. The laser wavelength is then only controlled by the etalon orientation over 9 nm, and does not change with either the temperature (over  $\Delta T = 30^\circ\text{C}$ ) or the available pump power. In the meantime the output power and the efficiency decreased respectively to 8 mW at the maximum available pump power and 12% with respect to the incident pump power; the threshold increased to 85 mW due to the extra losses introduced by the etalon. By tuning the external-cavity length with the piezoelectric ceramic, we achieved a continuous tunability over 15 GHz (0.03 nm) without any mode hop. This large continuous tunability of the laser frequency, owing to our short-length cavity, makes it possible to scan continuously the optical transitions of interest, distant from 9.192 GHz, corresponding to the hyperfine levels ( $6^2S_{1/2}, F = 3$ ) and ( $6^2S_{1/2}, F = 4$ ) of the  $^{133}\text{Cs}$ -atom ground state (Fig. 4).

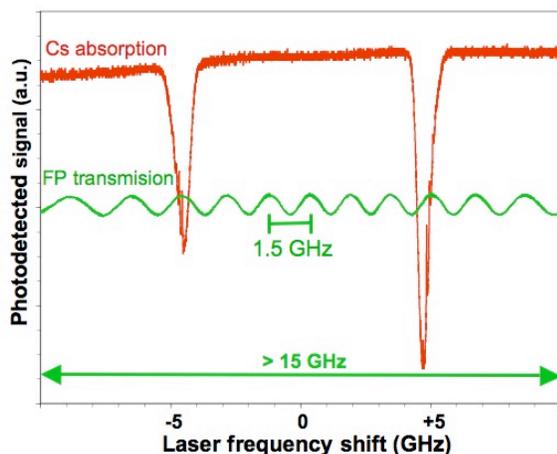


Fig. 4 : Continuous tunability of the laser frequency with PZT voltage; red curve : Cs absorption spectrum; green curve : transmission of a 1.5 GHz low-finesse etalon.

## 5. EVALUATION OF THE SPECTRAL PROPERTIES

With the etalon inside the cavity, the laser frequency has been locked at the side of a Doppler-free transition of the  $D_2$  line, through a low-frequency ( $f < 2$  kHz) 2-integration-stage servo loop on the piezoelectric ceramic. The laser linewidth of our source has been evaluated through the beat note measurement between our OP-VECSEL and an extended-cavity diode laser (ECDL) which linewidth has been evaluated to 130 kHz at -3 dB from previous measurements [7]. In order to suppress low-frequency drifts of the laser lines, the OP-VECSEL and the ECDL were locked to different sub-Doppler Cs lines. The heterodyne signal around  $F_0 = 135$  MHz was detected by a fast photodiode, then amplified and measured with a RF analyzer. The full width at half maximum of the beat note is 500 kHz, which is mainly attributed to the OP-VECSEL (see Fig. 5). The FWHM of the Lorentzian fit of the spectrum wings ( $|\nu - \nu_0| > 1$  MHz) is 70 kHz. These values are due to extra acoustic, thermal and electrical noises which are unavoidable under normal laboratory environment.

## 6. CONCLUSION AND OUTLOOK

From a low-power compact prototype we have obtained a pump-limited output power of 17 mW under single-frequency operation on the Cesium  $D_2$  transition. Our source was continuously tunable around the desired wavelength. Furthermore a beat-note experiment has established that the laser linewidth was about 500 kHz. These results demonstrate the potentialities of our source as an alternative in the optical benches of Cesium atomic clocks. Actually the VECSEL is already adequate for the detection of atoms in clock experiments.

Recently, preliminary experiments towards higher output power have already resulted in a 120-mW single-frequency emission of our VECSEL under 1-W diode pumping. The further increase of the laser power will require a reduction of the thermal resistance of the semiconductor chip in order to withstand high-power pumping. Standard solutions such as removing the GaAs substrate and soldering the structure onto a high-conductivity substrate or a heatsink are under investigation.

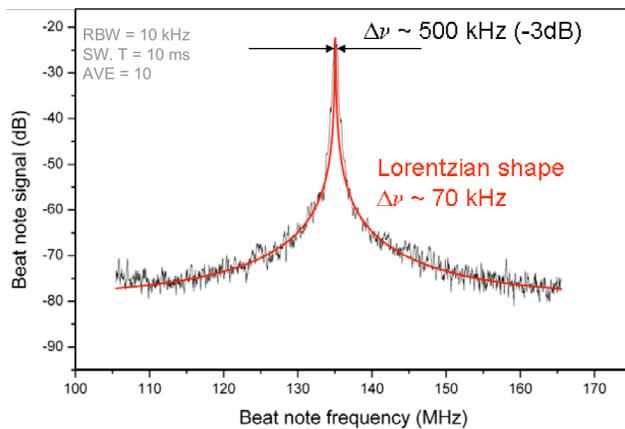


Fig. 5 : Beatnote spectrum, sweep time = 10 ms.

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