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► **To cite this version:**

Fabiola Camargo, Paul Dumont, Iryna Ghozyk, Gaëlle Lucas-Leclin, Patrick Georges, et al.. Two-cross-polarized-frequency VECSEL at 852nm for CPT-based Cs clocks. *Advanced Solid State Lasers* (ASSL 2013), Oct 2013, Paris, France. 2013. <hal-00926268>

**HAL Id: hal-00926268**

**<https://hal-iogs.archives-ouvertes.fr/hal-00926268>**

Submitted on 9 Jan 2014

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# Two-cross-polarized-frequency VECSEL at 852nm for CPT-based Cs clocks

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**Abstract:** We demonstrate a tunable high-purity microwave signal generation from a cross-polarized dual-frequency diode-pumped vertical external-cavity semiconductor laser operating at 852 nm for the coherent population trapping of cesium atoms in compact atomic frequency references.

**OCIS codes:** (140.7260) Vertical cavity surface emitting lasers; (270.2500) Fluctuations, relaxations, and noise.

## 1. Introduction

Among the different kind of compact atomic clocks, those using the technique of coherent population trapping (CPT) to interrogate the atoms could achieve significantly better performance than the conventional double-resonance clocks [1]. In an atomic clock based on CPT, the microwave interrogation between two atomic levels is caused by two coherent, in-phase, laser fields resonant with a common excited state, the frequency difference of the two laser fields corresponding exactly to the frequency microwave clock. The atoms are trapped in a superposition of states decoupled from the laser fields, called a "dark" state, and stop interacting with the laser light. With <sup>133</sup>Cs atoms, the pair of laser fields has to be tuned either at the D1 (894 nm) or D2 (852 nm) optical transition line, and the hyperfine frequency splitting in the microwave range is equal to 9.192631770 Hz. It corresponds to a narrow transmission line in the Cs absorption spectrum, which is used as a frequency reference. The common solutions for the realization of the coherent pair of laser beams are sideband generation by microwave modulation of a single-frequency diode laser [2] and optical phase-locking of two independent lasers [3]. The latter configuration is ideal as regards the atomic signal and it is commonly used nowadays in atomic clock experiments; however it requires a complex and costly wideband phase-locked electronics loop. Dual-frequency operation of an optically-pumped vertical external cavity semiconductor laser (VECSEL) has been proposed as a simple and compact solution for CPT clocks [4] and it presents many advantages. First, this configuration takes benefit of the intrinsically strong correlation between the two laser lines which share the same cavity; second, the frequency difference, which is proportional to the intracavity phase anisotropy, may be tunable from few tens of MHz to a few THz. Finally, a high-cavity-finesse VECSEL exhibits a class-A dynamical behavior, which results in a flat, shot-noise limited, intensity noise spectrum on a wide frequency range, and so for the phase noise; this should provide a high-purity RF signal.

## 2. Description of the dual-frequency laser

The semiconductor active chip has been grown by metal-organic chemical-vapor deposition on a 350  $\mu\text{m}$  thick GaAs substrate and is designed for emission at  $\lambda = 852$  nm under barrier-pumping at  $\lambda \leq 700$  nm. The  $30\lambda/4$ -thick active region is composed of seven 8-nm thick GaAs quantum wells, embedded between  $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$  barriers. The active structure is resonant at the design wavelength, which increases its effective optical gain [5]. The bottom Distributed Bragg Reflector (DBR) consists of 32.5 pairs of  $\text{AlAs}/\text{Al}_{0.225}\text{Ga}_{0.775}\text{As}$   $\lambda/4$ -thick layers, and its reflectivity is evaluated to  $R > 99.95\%$  at 852 nm. As no anti-reflection coating is deposited on the top surface of the structure,  $\sim 30\%$  of the incident pump beam is reflected on the surface.

The laser cavity is composed by the semiconductor chip and a 15 mm concave output mirror with a transmission of 0.5% at 852 nm. The cavity length is 10 mm, resulting in a laser beam diameter of 70  $\mu\text{m}$  in the structure. The pump source is a 1.6 W-broad-area laser diode emitting at 670 nm coupled into a 100  $\mu\text{m}$  diameter,  $\text{NA} = 0.22$ , multimode fiber. This source delivers almost 1 W at the fiber end and is focused on the semiconductor chip with two doublets of  $f_1 = 25$  mm and  $f_2 = 19$  mm under a  $50^\circ$  angle, yielding a  $70 \mu\text{m} \times 110 \mu\text{m}$ -elliptical spot on the structure.

The dual frequency emission is obtained by introducing a birefringent element in the laser cavity, which controls the phase anisotropy inside the cavity and results in the emission of two cross-polarized lines. We use a 500  $\mu\text{m}$ -thick antireflection coated  $\text{YVO}_4$  plate cut at  $45^\circ$  to its optic axis, which induces a spatial separation of

50  $\mu\text{m}$  between the extraordinary and ordinary beams in the structure in the longer axis of the pump ellipse (Figure 1 left). This spatial separation of the two polarized beams reduces the nonlinear coupling between them and is thus necessary to ensure a stable dual frequency emission [6]; nevertheless it is small enough to maintain a good overlap between the pump beam and the two laser spots. The birefringence introduced in the laser cavity results in slightly different optical paths for each polarization, which produce two combs of longitudinal modes distanced by  $\Delta\nu$ . This frequency difference between the two polarizations is adjusted by a 1 mm-long MgO:SLT electro-optic modulator (Figure 1 right), whose birefringence changes with both the temperature and the applied voltage [7]. A coarse tunability of the frequency difference  $\Delta\nu$  is possible by changing the temperature of the crystal thanks to the high rate of 1.25 GHz/K. And the fine tunability of  $\Delta\nu$  is obtained with the voltage applied to the crystal, with a rate of 1.59 MHz/V; it allows to achieve the exact microwave transition of Cs atoms, and to compensate for the residual  $\Delta\nu$  fluctuations on a wide frequency range.

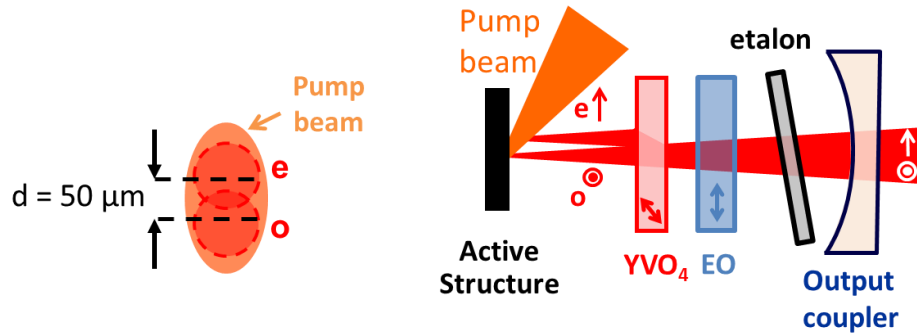


Figure 1: Experimental setup for the OP-VECSEL (right) and the laser and pump beam overlap on the chip surface (left).

The laser cavity design has focused on compactness, mechanical and thermal stabilities. The pump optics, the semiconductor chip and the laser cavity elements are integrated in a compact 90 mm  $\times$  90 mm  $\times$  40 mm casing [7]. This limits mechanical and acoustic vibrations as well as air temperature fluctuations inside the external cavity. The temperature of the whole setup is stabilized to 24° C. The temperature of the semiconductor chip is controlled at 16° C using a Peltier element. The output coupler is glued on a piezo-electric transducer (PZT) for the fine adjustment of the cavity length. In these conditions the laser delivers around 10 mW per polarization at 852 nm.

### 3. Laser stabilization and noise

A small portion (less than 0.5 mW) of the ordinary-polarized laser line is used to lock the laser frequency at the top of a Doppler-free transition ( $F = 4 - F' = 4'/5'$ ) of the Cs D<sub>2</sub> line at 852 nm using a pump-probe saturated absorption technique, as shown in Figure 2. An acousto-optic crystal is used to modulate the so-called pump beam at 100 kHz to generate the error signal. This method avoids the direct modulation of the pump diode current, which would simultaneously introduce a modulation of the laser intensity. The error signal is used to compensate for the low-frequency fluctuations of the laser cavity length through a 2-integration stage servo loop on the piezoelectric transducer glued to the output coupler. The power spectral density of the frequency noise is measured from the error signal with a Fast Fourier Transform analyzer (Figure 3 left). The servo loop gain reaches 60 dB at low frequencies and its bandwidth is around 600 Hz, limited by the piezoelectric bandwidth.

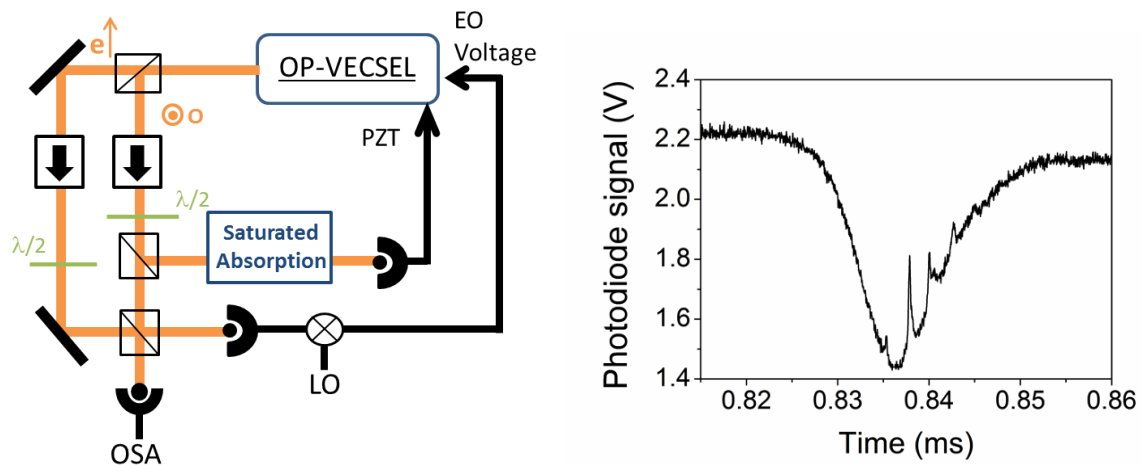


Figure 2: Experimental set-up of two the servo-loops use to lock the laser frequency at the Cs transition and the frequency difference at a RF reference (left). Doppler-free Cs absorption (right).

The frequency difference between the two laser lines has been locked to a local oscillator (LO) which produces a stable RF reference (Figure 2). The polarization of the extraordinary line is rotated with a  $\lambda/2$  plate and both lines are superimposed on a fast photodiode (bandwidth  $> 12.5$  GHz). The subsequent beatnote signal is amplified and mixed with the RF reference to generate the error signal, which is amplified. The error signal is applied to the electro-optic crystal to compensate for the frequency-difference fluctuations.

Figure 3 compares the beat-note spectra of the free-running laser with the one of the laser when the frequency difference between the two laser lines is locked to the RF reference at 9.2 GHz. The servo loop bandwidth is about 1 MHz, which depends on the proportional gain as well as on the electro-optic crystal response. The signal-to-noise ratio is 60 dB and the RF beat note linewidth is less than 30 Hz, limited by the analyzer resolution. The two servo-loops – of the absolute frequency difference on a Cs atomic transition and of the frequency difference on a microwave local oscillator – operate together without perturbing each other. Eventually the beatnote phase noise has been measured with both servo-loops operating. In the frequency range from 100 Hz to 10 kHz, the phase noise is lower than  $-100$  dBrad<sup>2</sup>/Hz. For frequencies higher than 10 kHz, the phase noise increases to  $-90$  dBrad<sup>2</sup>/Hz. Using the formalism of the Dick effect [8], the frequency stability of a pulsed CPT atomic clock based on this laser source is estimated as low as  $3.10^{-13}\tau^{-1/2}$ .

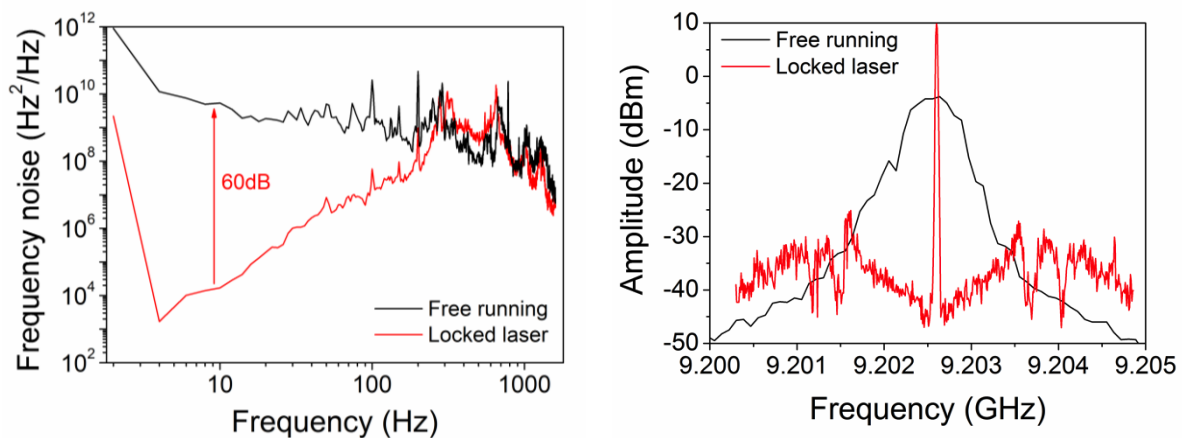


Figure 3: Spectral density of the frequency noise of the free running laser and of the laser frequency locked at the Cs transition (left). Beat note of the free-running laser and with the frequency difference locked at the RF reference at 9.2GHz.

We have described the design and operation of a new laser source based on the dual-frequency operation of an OP-VECSEL. The performance of the laser source has been assessed with regards to the requirements for the interrogation of Cs atoms in a compact atomic clock experiment. The phase noise level of the 2-frequency 2-polarization laser source demonstrated here is already suitable for the realization of a Cs atomic clock with a stability of  $3.10^{-13}\tau^{-1/2}$ .

**Acknowledgments :** This work was supported by the French Agence Nationale de la Recherche (ANR-07-BLAN-0320-03) and the french RENATECH network. F. Camargo was funded by RTRA/Triangle de la Physique (2010-089T).

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