# High-purity microwave signal from a dual-frequency semiconductor laser for CPT atomic clocks (poster)

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# High-purity microwave signal from a dual-frequency semiconductor laser for CPT atomic clocks

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***Abstract*— Coherent population trapping (CPT) of metal-alkali atoms is an interesting technique for the development of compact atomic frequency references; it relies on the excitation of the atoms by two phase-coherent laser fields. We describe the design and operation of an innovating dual-frequency laser source dedicated to Cs CPT atomic clocks, based on the direct dual-frequency and dual-polarization operation of an optically-pumped semiconductor laser at 852 nm. The phase noise of beatnote generated by the laser source is at maximum of -90 dBrad²/Hz with active stabilization, and the relative intensity noise (RIN) has been measured at -115 dB/Hz. It would potentially results in a clock frequency stability of 1.6 .$10^{-12}$ at 1 second, limited by the laser RIN. With proper adjustments in the laser and clock set-up, we target a stability of 3.$10^{-13}$ at 1 second.**

***Keywords—Atomic clocks, Coherent population trapping, Vertical external cavity surface emitting lasers, Dual-frequency lasers, Phase noise.***

## I. Introduction

Atomic frequency references provide high-precision stable signals, which are crucial in the most demanding applications as satellite positioning, high bitrate communication networks, or high-end inertial navigation. Because of their potential for size reduction, atomic clocks based on the coherent population trapping (CPT) of $^{133}$Cs atoms have raised a considerable interest within the last decade in the scientific and industrial community [1], [2]. In a CPT-based Cs atomic clock, the microwave interrogation at 9.192 GHz is induced by two phase-coherent laser fields at resonance with a common excited state. In this work, we are interested in an optical configuration which combines a cross-polarized excitation scheme and a temporal Ramsey-like pulsed interrogation. Highly contrasted and narrow-linewidth CPT resonances have already been demonstrated, resulting in a short-term frequency stability of a few $10^{-13}$ at one second [3]

We propose here a new laser source for such CPT clocks, consisting in a unique dual-frequency laser emitting simultaneously two cross-polarized longitudinal modes inside the same laser cavity [4]. As the noise properties of theoretically-carried microwave signal impact the clock signal, we describe the thorough evaluation of the intensity, frequency and phase noise of our laser. Eventually we theoretically estimate the short-term stability of the CPT atomic clock based on the experimental characterization of the laser noise.

## II. Description & evaluation of the laser source

### A. Laser source architecture

The laser architecture is a Vertical External Cavity Semiconductor Laser (VECSEL), also known as a semiconductor disk laser (SDL). It consists in a semiconductor gain medium grown onto a Bragg mirror, pumped by a high-power fiber-coupled laser diode at 670 nm. The semiconductor chip is designed to ensure efficient pump absorption and light emission at wavelengths close to 852 nm, corresponding to the $D_2$ line of $^{133}$Cs [5]. The laser cavity is simply closed by a low-transmission (T = 0.5%) concave output coupler. The laser emission properties are controlled by adding free-space intracavity elements: a 50 µm-thick Fabry-Perot etalon forces the single-mode emission at the desired wavelength; the fine tuning of the laser wavelength is obtained using a piezo-transducer glued on the output coupler. A birefringent plate induces a lateral separation of 50 µm in the gain medium between the ordinary and extraordinary polarized beams; a MgO-SLT electro-optical crystal allows the fine adjustment through temperature and voltage, of the frequency difference $\Delta\nu$ between the two cross-polarized lines. With all the intra-cavity elements, the free spectral range of the laser cavity is 12 GHz, higher than the targeted frequency difference $\nu_{Cs}$ = 9.192 GHz, and corresponding to an optical cavity length $L_{cav}$ = 12.5 mm. The pump optics, the semiconductor chip and the intra-cavity elements are integrated in a compact (90 mm × 90 mm × 40 mm) thermo-regulated casing.

The laser threshold is reached at 0.35 W of incident pump power. At the maximum pump power of 1 W, the optical power is 13 mW on each cross-polarized laser line. The frequency difference $\Delta\nu$ between the two laser frequencies is tunable with the electro-optic temperature (1.3 GHz/K) and the voltage (1.6 MHz/V); this allows the fine tuning of $\Delta\nu$ at the Cs reference frequency at 9.192 GHz. Under free-running operation of the laser source, the linewidth of the RF beatnote spectrum is 500 kHz at -3 dB on a 300 ms measurement time - limited by residual uncorrelated mechanical and thermal fluctuations.

### B. *Stabilization of the dual-frequency VECSEL*

The laser frequencies are stabilized with two different servo-loops: on one hand, the ordinary-polarized laser frequency is locked onto a Doppler-free transition in a Cs cell at room temperature, through feedback to the piezo-electric transducer glued to the output coupler. On the other hand, the frequency difference $\Delta\nu = (\nu_e - \nu_o)$ between the two laser modes is locked onto a commercial RF local oscillator (LO) using an optical-phase lock loop; the correction is applied to the intracavity electro-optic crystal through a 1 MHz-bandwidth proportional-integrator servo (Fig 1). The beatnote spectrum is then strongly narrowed, below the resolution of our RF analyzer (<30 Hz). The signal-to-noise ratio, measured between the peak maximum and its minimum close to the frequency carrier, is 95 dB/Hz at 100 kHz from the carrier frequency.

### C. *Laser noise*

The noise properties of the stabilized laser emission are investigated in order to evaluate the contribution of the dual-frequency VECSEL to the performance of a CPT-Ramsey atomic clock. We study three main noise sources: the laser intensity noise, the laser frequency noise and the beatnote phase noise.

The relative intensity noises (RIN) of the two cross-polarized lines are identical, and exhibit a white noise floor at -115 dB/Hz up to 100 kHz (Fig. 2). They are limited by the pump intensity noise, with a +5 dB conversion factor within the bandwidth of the pump-to-laser $RIN$ transfer – estimated at 90 MHz [6]. A lower $RIN$ of the dual-frequency laser should thus be achievable by using a low-noise single-mode

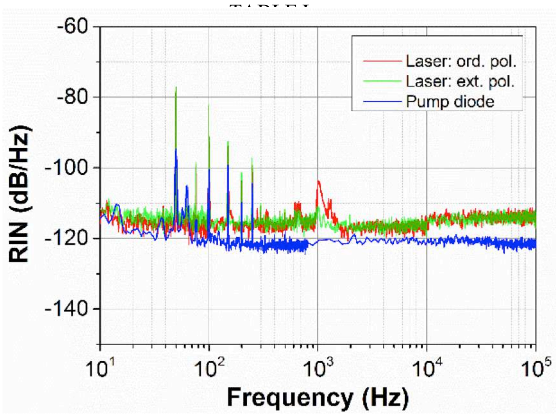


Fig. 2. Spectral density of the laser relative intensity noise for each polarization, and of the pump relative intensity noise. The measurements show a 5 dB difference between pump and laser RIN, consistent with a pump to laser RIN transfer [6].

pump source.

The laser (in-loop) frequency noise $S_{\nu_{opt}}(f)$, which reveals the fluctuations of the optical frequency, is measured from the error signal of the wavelength stabilization loop. It is mostly limited in the low frequency range by thermal and mechanical fluctuations of the laser cavity. The contribution of the pump-induced thermal fluctuations inside the semiconductor chip - converted into a frequency noise through changes of the optical cavity length - is estimated at $6 \times 10^5$ Hz²/Hz theoretically and $2 \times 10^6$ Hz²/Hz experimentally, in the bandwidth of the thermal effects [7]. We believe this contribution to prevail for frequencies above 3 kHz (Fig. 3). In locked operation, the frequency noise is suppressed on a bandwidth of 600 Hz limited by the piezo-transducer resonance. Since the measurement is realized within the servo-loop, the noise issued from the loop components themselves is not revealed. The actual noise floor coming from the conversion of the laser $RIN$ into frequency noise through the servo-loop, is estimated at $2.0 \times 10^3$ Hz²/Hz.

Finally, we have measured the phase noise of the RF signal, resulting from the beatnote of the two laser lines; we have been more specifically interested in the additive contribution

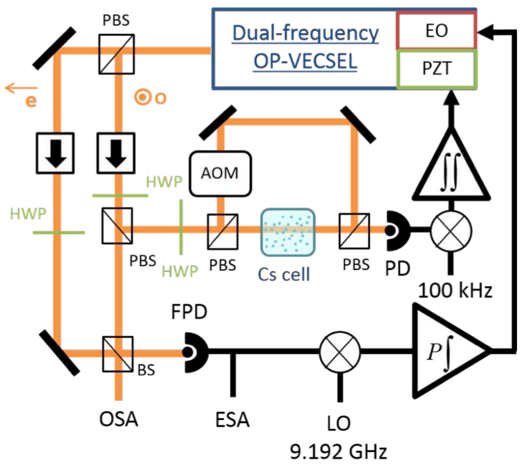


Fig. 1. Laser stabilization set-up. EO: electro-optic crystal, PZT: piezo-electric transducer, BS: beam splitter, PBS: polarization beam splitter, HWP: half-wave plate, AOM: acousto-optic modulator, PD: photodiode, FPD: fast photodiode, LO: local oscillator, P∫: proportional integrator corrector, ∬: double-integrator corrector, OSA: optical spectrum analyzer, ESA: electrical spectrum analyzer.

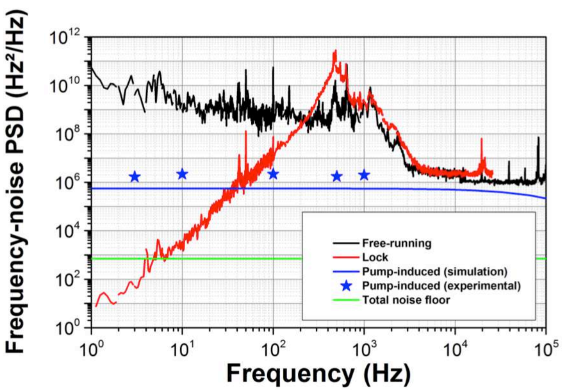


Fig. 3. Power spectrum density of the frequency noise of the ordinary polarized mode, under free-running operation (black line) and under locked operation (red line). The bleu curve is a simulation of the frequency noise induced by the pump RIN through thermal effects inside the semiconductor structure. Total noise floor originating from the $RIN$ conversion into the servo loop is represented in the green line.

$S_{\Phi_{Add}}(f)$ resulting from the electrical-to-optical conversion through the phase-lock loop on the RF reference at 9.2 GHz and the laser itself. Under free-running operation, $S_{\Phi_{Add}}(f)$ reflects the pump-induced thermal fluctuations of the semiconductor structure [8]. When the RF beatnote is locked to the local oscillator, the additive phase-noise is reduced to -105 dBrad²/Hz on the 100 Hz - 5 kHz frequency range, and remains below -90 dBrad²/Hz up to 1 MHz (Fig 4).

## III. IMPACT ON THE SHORT-TERM CLOCK STABILITY

We consider in the following the clock architecture developed at Observatoire de Paris - SYRTE, based on a temporal Ramsey-like pulsed interrogation [3]. In this configuration, the dual-frequency laser beam which illuminates the Cs cell is pulsed using an external acousto-optic modulator, in a time sequence of duration $T_c$ = 6 ms, composed of one pump pulse $\tau_p$ = 2 ms, a free-evolution time $T_R$ = 4 ms and a very short detection pulse $\tau_d$ = 25 µs, during which the power transmitted by the Cs cell is measured. The dual-frequency laser noise directly impacts the frequency stability of the CPT atomic clock by causing random fluctuations of the CPT signal. Three contributions are taken into account, which result from the laser intensity noise (IN), the laser frequency noise (FN) and the beatnote phase noise (PN) which includes the LO intrinsic phase noise and the additive phase noise of the laser source $S_{\Phi_{Add}}(f)$ (see II-C). The Allan standard deviation $\sigma_y(\tau)$ is then the quadratic sum:

$$\sigma_y^2(\tau) = \sigma_{IN}^2 + \sigma_{FN}^2 + \sigma_{PN}^2 \quad (4)$$

The laser power fluctuations (IN) generate an amplitude noise on the CPT signal $S(t)$ which is then injected in the feedback-loop. The atomic clock is sensitive to IN on a bandwidth corresponding to $1/\tau_d$ = 40 kHz. On the other hand, the laser frequency noise $S_{\nu_{opt}}(f)$ impacts the clock frequency stability during the pumping pulse duration $\tau_p$. Indeed it causes fluctuations of the atom population trapped in the dark-state and thus of the CPT signal amplitude. In our conditions, the bandwidth of this effect is about 700 Hz. And the beatnote

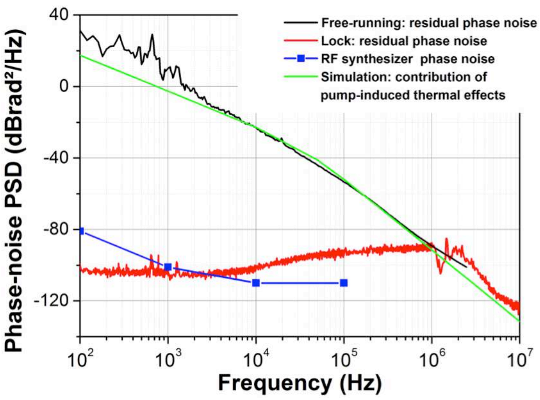


Fig. 4. Power spectrum density of the beatnote phase noise due to the laser and the optical phase-lock loop contribution (residual phase noise) under free-running operation (black line) and under locked operation (red line, LO frequency: 9.6 GHz) compared to the standard phase noise of the LO used (blue curve). The green line is a simulation of the phase noise induced by the pump RIN through thermal effects inside the semiconductor structure.

phase noise contributes to the frequency stability through the Dick effect, which arises from the lack of information on the optically-carried RF frequency during the optical pumping of the Cs atoms [9]. The bandwidth of this effect includes all frequencies above the clock interrogation frequency $1/T_c$ = 160 Hz. The beatnote phase noise includes two contributions: the LO intrinsic phase noise and the additive phase noise, as defined in II-C.

Each laser contribution to the Allan standard deviation is estimated following the approach described in [10] (Table 1). For the sake of simplicity, the laser noise contributions are described as white noise with spectral densities at their measured maximum levels. The commercial RF synthesizer used as the LO also contributes to $5 \times 10^{-13}\,\tau^{-1/2}$ to the clock stability. From these calculations, we estimate a clock stability of $\sigma_y(\tau) = 1.6 \times 10^{-12}.\tau^{-1/2}$, limited mainly by the laser intensity noise. Though this value is higher than the state-of-the-art CPT-Ramsey atomic clock, it is not a fundamental limit of the atomic clock and simple solutions can be implemented to limit the impact of the IN as for example: an increase of the detection time; a normalization of the CPT signal[10]; or a power stabilization of the pump source. We could thus reasonably reduce the IN contribution below the beatnote additive phase noise one. In addition, with a change of our current LO for an ultra-low noise microwave chain (frequency stability $\sigma_y(\tau) = 2.7 \times 10^{-13}.\tau^{-1/2}$ [3]), we target a clock frequency stability of $3 \times 10^{-13}.\tau^{-1/2}$.

## IV. CONCLUSION

We have described the dual-frequency / dual-polarization emission of an optically-pumped semiconductor laser at 852 nm, with a frequency difference of 9.2 GHz. It is based on the introduction of a controlled birefringence within the laser cavity, which results in two cross-polarized lasers lines. A compact prototype has been designed, which allows a fine tunability of the laser optical frequencies. The laser dual-frequency emission is stabilized by means of two servo-loops, on a Cs atomic transition in a saturated-absorption setup and on a stable RF oscillator. Under this working operation, the laser noise properties have been carefully investigated. Measurements show a maximum noise level of -115 dB/Hz for the laser relative intensity noise and -90 dBrad²/Hz for the additive phase noise.

Finally, we have theoretically evaluated the impact of the residual noise of our dual-frequency laser source on the short-term frequency stability of a CPT-Ramsey atomic clock. We demonstrate that a clock stability of $1.6 \times 10^{-12}.\tau^{-1/2}$ should be achieved, and would be limited by the laser intensity noise contribution. The latter might be reduced by changing either the laser or the clock set-up; the impact of these changes will have to be investigated through an exhaustive study of the total signal-to-noise ratio of the CPT signal. Eventually we expect that the laser contribution to clock frequency stability would be limited by the Dick effect below $3 \times 10^{-13}\,\tau^{-1/2}$, paving the way for future compact atomic clocks with $1 \times 10^{-13}\,\tau^{-1/2}$ frequency stability level.

## REFERENCES


[1] J. Vanier, "Atomic clocks based on coherent population trapping: a review," *Appl. Phys. B*, vol. 81, no. 4, pp. 421–442, Jul. 2005.

[2] S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L.-A. Liew, and J. Moreland, "A microfabricated atomic clock," *Appl. Phys. Lett.*, vol. 85, no. 9, pp. 1460–1462, 2004.

[3] J. Danet, M. Lours, S. Guérandel, and E. de Clercq, "Dick effect in a pulsed atomic clock using coherent population trapping," *IEEE Ultrason. Ferroelectr. Freq.*, 2014.

[4] G. Baili, L. Morvan, M. Alouini, D. Dolfi, F. Bretenaker, I. Sagnes, and A. Garnache, "Experimental demonstration of a tunable dual-frequency semiconductor laser free of relaxation oscillations.," *Opt. Lett.*, vol. 34, no. 21, pp. 3421–3, Nov. 2009.

[5] F. A. Camargo, J. Barrientos, G. Baili, L. Morvan, D. Dolfi, D. Holleville, S. Guerandel, I. Sagnes, P. Georges, and G. Lucas-leclin, "Coherent Dual-Frequency Emission of a Vertical External-Cavity Semiconductor Laser at the Cesium D2 Line," *IEEE Photonics Technol. Lett.*, vol. 24, no. 14, pp. 1218–1220, 2012.

[6] G. Baili, F. Bretenaker, M. Alouini, L. L. Morvan, D. Dolfi, and I. Sagnes, "Experimental Investigation and Analytical Modeling of Excess Intensity Noise in Semiconductor Class-A Lasers," *J. Light. Technol.*, vol. 26, no. 8, pp. 952–961, 2008.

[7] A. Laurain, M. Myara, G. Beaudoin, I. Sagnes, and A. Garnache, "Multiwatt-power highly-coherent compact single-frequency tunable vertical-external-cavity-surface-emitting-semiconductor-laser.," *Opt. Express*, vol. 18, no. 14, pp. 14627–36, Jul. 2010.

[8] S. De, A. El Amili, I. Fsaifes, G. Pillet, G. Baili, F. Goldfarb, M. Alouini, I. Sagnes, and F. Bretenaker, "Phase Noise of the Radio Frequency (RF) Beatnote Generated by a Dual-Frequency VECSEL," *J. Light. Technol.*, vol. 32, no. 7, pp. 1307–1316, Apr. 2014.

[9] G. J. Dick, "Local oscillator induced instabilities in trapped ion frequency standards," in *Proc. 19th Precise Time and Time Interval (PPTI) Applications and Planning Meeting*, 1987, pp. 133–147.

[10] J. Danet, O. Koslova, P. Yun, S. Guérandel, and E. de Clercq, "Compact atomic clock prototype based on coherent population trapping," *Eur. Phys. Journal, Web Conf.*, 2014.