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An innovative laser bench for a high performance compact cesium CPT clock

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ABSTRACT

We developed and implemented a miniature electro-optical bench for the stabilization of a dual-frequency laser beam for high-contrast CPT interrogation of cesium. Preliminary results of optical intensity and wavelength simultaneous stabilizations give respective noise reduction of 15 dB and 60 dB at low frequencies. These performances are in line with targeted clock stability of 5×10^{-13} at 1 s. For longer time scales, a study of the optical power stability shows a drastic reduction of power fluctuations and highlights the temperature sensitivity of the optical components.

Keywords: Cesium CPT clock, intensity noise, frequency noise.

1. INTRODUCTION

High performance and compact atomic clocks are needed for on-board applications such as Galileo next generation systems. Recent studies focused their work on Coherent Population Trapping (CPT) of cesium, showing impressive frequency stability at both short and long time scales[1].

We propose to implement a highly compact set-up for a CPT clock based on a miniature electro-optical bench and a disruptive dual-frequency dual-polarization Vertical External Cavity Surface Emitting Laser (DF-VECSEL) that generates directly two eigenmodes at 852 nm separated by 9.192 GHz[2] with perpendicular polarizations needed for Lin per Lin interrogation[3]. The targeted relative frequency stability at 1 s of integration time is below 5×10^{-13}, averaging down below 10^{-14} at 1 h. Extensive studies of the power stabilization function of the bench has been done for both short and long time scales and interactions with a dual-frequency laser beam were described[4,5]. Here we present and discuss preliminary characterizations of simultaneous optical power stabilization and optical frequency locking of the laser within the complete miniature electro-optical bench.

2. MINIATURE ELECTRO-OPTICAL BENCH

The miniature electro-optical bench, designed and developed with the French company Kylia, provides all the functions needed for the laser beam stabilization within a low volume. The whole set-up is protected from external perturbations by a rigid box of dimensions 9.5×25×43 for a total volume of just above 10 L (Figure 1).

First, the laser is protected from back reflections with a single dual-polarization optical isolator. Second, the optical power stabilization is done by adjusting the transmission of an acousto-optic modulator (AOM) as described in reference[6]. Third, saturated absorption spectroscopy using a shielded cesium gas cell generates an error signal[7] to lock the wavelength of the laser onto the D_2 line. Forth, a fast photodetector converts down the optical beat note at 9.2 GHz between the two polarization modes into the radiofrequency domain for comparison to the local oscillator. Last, a third AOM pulses the laser intensity for Raman-Ramsey interrogation and the beam is extended to match the diameter of the Cs cell.

These functions are implemented on a single silica board with free-space miniature optical components. Optical alignments and adjustments have been carefully optimized and fixed with robust and space-qualified bonding technics to guarantee a high mechanical stability.

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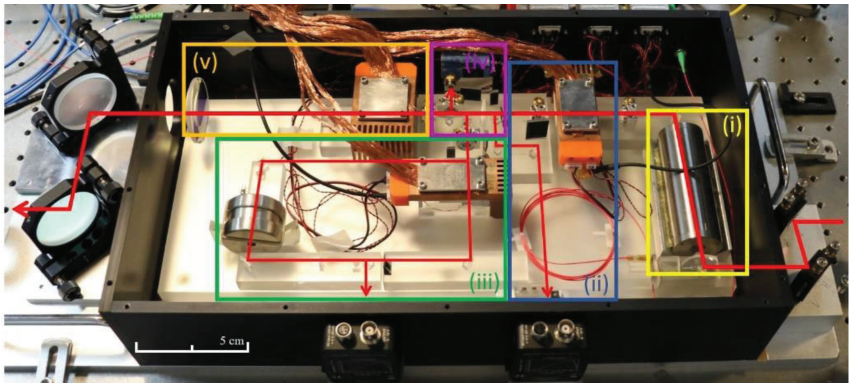

Figure 1. Miniature electro-optical breadboard. The power consumption of each AOM is 1 W. The dimensions are 9.5×25×43 cm^3.

As a first step and before integrating the dual-frequency laser, preliminary characterizations of the stabilization loops performances are conducted using a monomode distributed feedback (DFB) laser source providing few milliwatts of optical power (Figure 2).

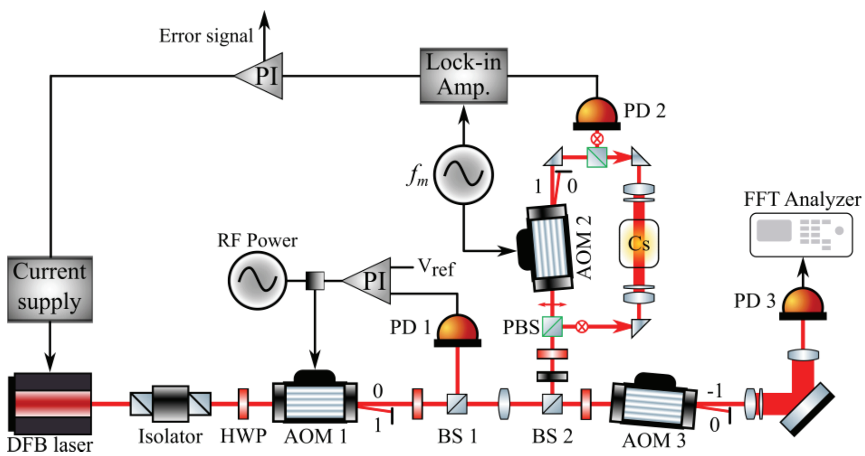

Figure 2. Intensity stabilization and frequency locking set-up. AOM: acousto-optic modulator; HWP: half-wave plate; PD: photodiode; BS: beam splitter; PBS: polarization beam splitter.

3. REDUCTION OF FREQUENCY AND INTENSITY NOISES

3.1 Optical frequency-lock loop

The saturated absorption spectroscopy signal is modulated by the AOM 2 at a frequency $f_m = 600$ kHz. The photodetected signal generated by PD 2 is then sent to a lock-in amplifier that demodulates the error signal used for the locking loop. The optical frequency of the laser is stabilized on one of the saturated peaks of Cs D_2 line by applying a correction signal to the laser current supply.

The frequency noise is measured through the power spectral density of the error signal of the servo loop (Figure 3). A drastic reduction of 60 dB is observed for low offset frequencies when the loop is closed, down to a noise floor of 40 dBHz^2/Hz. For offset frequency above 500 Hz, the noise increases and an excess of noise appears at 30 kHz, the cut-off frequency of the servo loop. Peaks between 50 Hz and 1 kHz are attributed to the laser current supply and can be filtered.

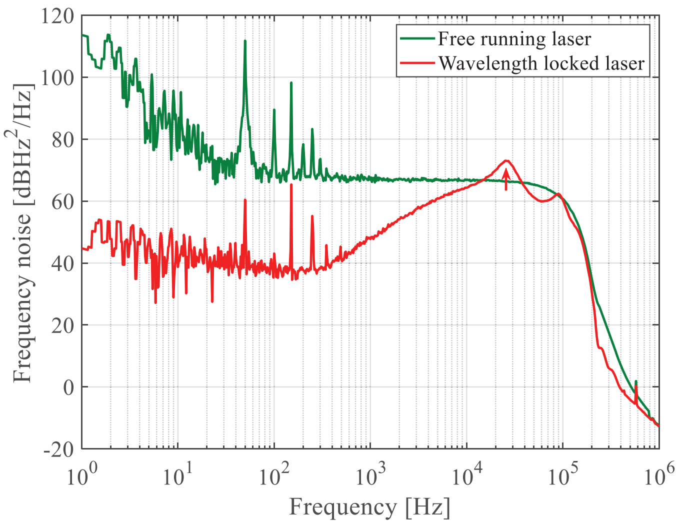

Figure 3. Frequency noise of the laser when the wavelength locking is applied: in free running regime (green) and in locked regime (red).

3.2 Simultaneous locking of optical power and frequency

To stabilize the optical power, a locking loop adjust the RF power driving the AOM 1 to keep the photodetected signal generated by PD 1 at the level of a reference voltage (V_{ref}). The optical power stabilization and frequency locking were operated simultaneously. Figure 4 presents the relative intensity noise (RIN) measured in the loop with PD 1 and out of the loop, at the position of the atomic resonator, with PD 3.

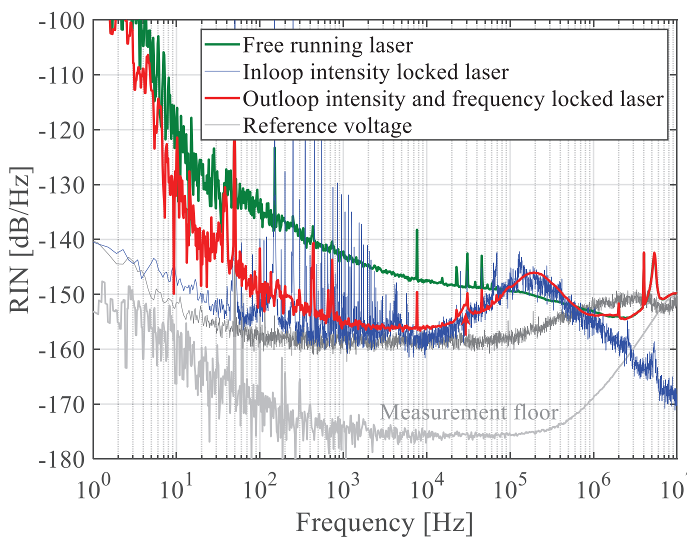

Figure 4. Relative intensity noise of the DFB laser when both intensity and wavelength stabilizations are applied: in free running regime (green), in locked regime in the loop (blue) and out of the loop (red). The reference voltage noise is given in dark grey. The frequency-lock loop noise contribution is represented with a red arrow.

In the loop, the (RIN) of the laser naturally reproduces the reference voltage RIN across the full bandwidth of the servo loop, down to a noise floor of -158 dB/Hz. For offset frequencies above 20 kHz, the stabilization loop cut-off generates an excess of noise with a peak at 200 kHz. Spurs appear due to electronics perturbations when measuring the signal used for the locking loop. These parasitic peaks only appears when measurement is done in the loop and shall not degrade the optical signal sent through the atomic resonator, as described in the next paragraph.

Out of the loop, when the optical power stabilization loop is closed, a reduction of the RIN of 15 dB is measured at an offset frequency of 100 Hz. The noise then reaches a floor of -156 dB/Hz between 1 kHz and 10 kHz, close to the noise of the reference voltage. The outloop signal is measured after AOM 3, on the diffracted beam of order -1. This leads to a high degradation of the RIN of the laser beam below Fourier frequencies of 100 Hz, preventing the transfer of the reference voltage stability out of the loop. The simultaneous operation of the wavelength locking generates a 3 dB bump at its cut-off frequency (30 kHz), where the gain of the power stabilization loop lacks gain. Few parasitic peaks appears and are due to the current supply of the laser. Filtering these peaks will be part of future works.

3.3 Estimation of clock instabilities

Contributions of the laser intensity noise and frequency noise to the clock frequency Allan deviation $\sigma_y(\tau)$ can be estimated through AM to FM (amplitude modulation to frequency modulation) and FM to FM (frequency modulation to frequency modulation) processes. The expression of RIN contribution to clock instability is:

$$\sigma_{y,RIN}(\tau) = \frac{2}{\pi}\frac{\Delta\nu}{\nu_0}\frac{\sigma_{RIN}}{C}\sqrt{\frac{T_c}{\tau}}, \tag{1}$$

where of the atomic signal, ν_0 is the clock frequency (9.192 GHz for cesium), C and $\Delta\nu$ are respectively the linewidth and the contrast of the atomic signal, T_c is the cycle time of the clock and σ_{RIN} is the deviation of the RIN averaged over the clock pulsed sequence:

$$\sigma_{RIN}^2 = 2\int_0^\infty \mathrm{sinc}^2(\pi\tau_m f)[1-\cos(2\pi f T_C)\,\mathrm{RIN}(f)df\ , \tag{2}$$

where τ_m is the measurement time during the sequence. The atomic interrogation pulsed sequence is especially sensitive to noises at Fourier frequencies between 100 Hz and 10 kHz.In the same way, we can define the deviation of the frequency noise of the laser σ_f. Knowing the clock frequency sensitivity to optical frequency variations of the laser (4 Hz/GHz), the contribution of this noise is defined as:

$$\sigma_{y,f}(\tau) = 4\times10^{-9}\frac{\sigma_f}{\nu_0}\sqrt{\frac{T_c}{\tau}}. \tag{1}$$

The calculations of both contributions are reported in Table 1 for integration time of 1 s.

Table 1. Estimation of the laser noises contributions to Allan deviation of the clock.

Laser noise	**Allan deviation at 1 s ($\times10^{13}$)**
Intensity noise	0.70
Frequency noise	0.13

The intensity noise of the laser contributes to 0.7×10^{-13}. For comparison, contribution in free running regime is twice higher, reaching a level of 1.4×10^{-13}. The optical frequency noise only contributes to 0.13×10^{-13}. When the laser is stabilized, these contributions are one order of magnitude smaller than targeted stability of 5×10^{-13} at 1 s.

4. LONG-TERM OPTICAL POWER STABILITY

Due to light shift effects[8], the power instability tends to be the limiting parameter for long-term CPT clock frequency stability. We measured the optical power of the laser over long periods of time (tens of hours), out of the loop as well as in the loop. The results, presented as relative fluctuations σ_P/P, are given in Figure 5.

For short integration times (below 30 s), the resolution of the data logger used for the measurement generates a white noise, the quantification noise. This noise is on the order of few 10^{-6} and averages down as $\tau^{-1/2}$. It limits the measure of low optical power fluctuations.

In the loop, the fluctuations are close to the voltage fluctuations of the reference of few 10^{-7}. We find a high correlation between the fluctuations of the electronics temperature and the power in the loop (Figure 6a). These fluctuations however only limit the stability after 1 000 s of integration time and are not detrimental yet for the aimed clock performances.

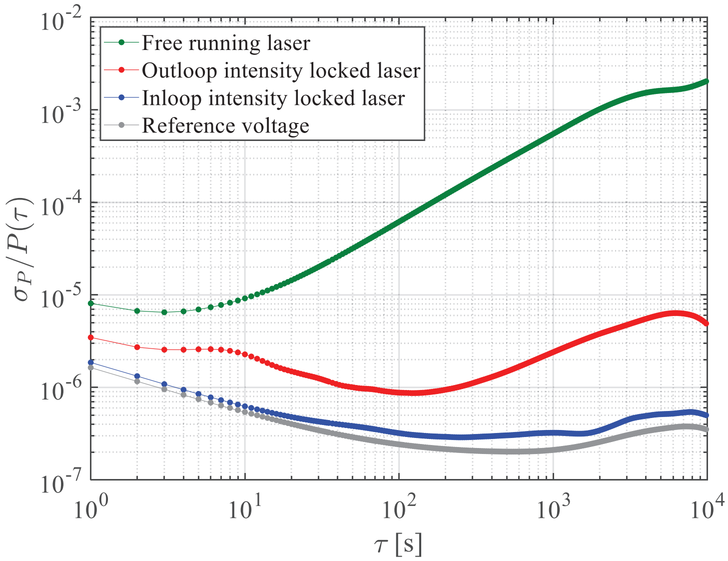

Figure 5. Relative power fluctuations of the laser: in free running regime (green), in locked regime in the loop (blue) and out of the loop (red). The reference voltage fluctuations are given in dark grey.

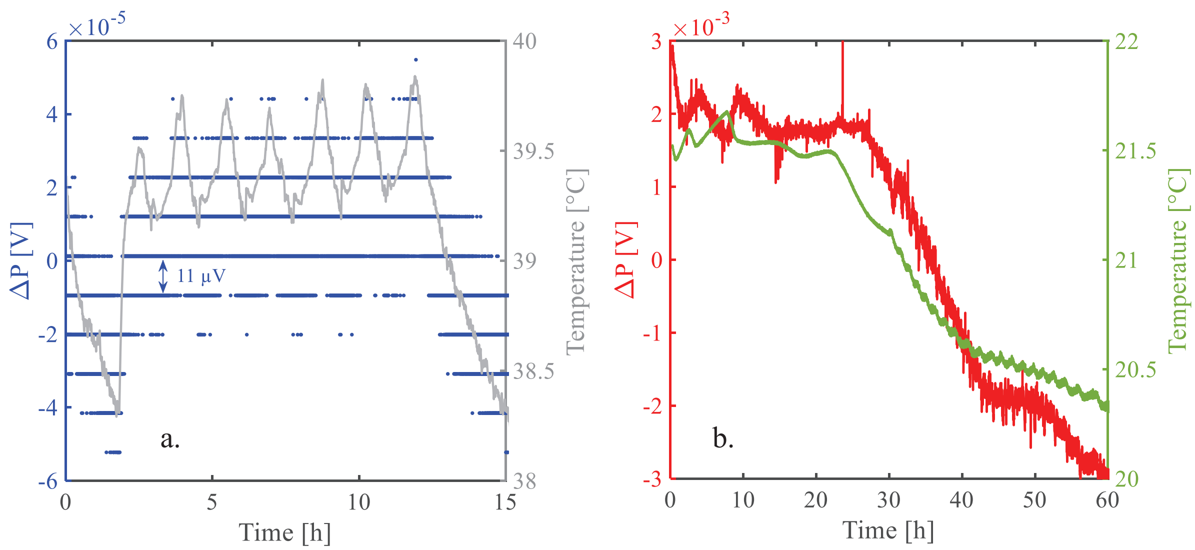

Figure 6. a. Evolution of the optical power fluctuation in the loop (blue) and of the reference voltage electronics temperature (dark grey). b. Evolution of the optical power fluctuation out of the loop (red) and of the temperature of optical components (light green).

Out of the loop, the optical power fluctuations are greatly reduced in comparison to the free running regime. A reduction of more than two orders of magnitude is measured at 10 000 s. However the level of the inloop fluctuations is not reached. By monitoring the temperature of the optical components of the set-up, we found a high correlation between the temperatures fluctuation of the PBS used for the separation of inloop and outloop paths (Figure 6b). We attribute this effect to the temperature sensitivity of the PBS transmission and reflection coefficients. A much lower temperature sensitivity of the photodiode has also been observed.

These levels of optical power stability are just enough to stay below 10^{-14} for the clock relative frequency Allan deviation at 10 000 s. Methods to further mitigates light shift effect, such as autobalanced Ramsey spectroscopy, have also been successfully implemented on CPT clocks[1] and could be used on our system to reach even lower level of clock stability.

5. CONCLUSION

We developed a miniature electro-optical bench for the stabilization of a laser beam for CPT interrogation of Cs atoms. We demonstrated the simultaneous locking of both the optical power and the optical wavelength of a monomode DFB laser with performances comparable to noise reduction obtained in state-of-the-art clock laboratory set-ups. Optical power stability has also been studied over long periods of time. Sensitivity to temperature fluctuations of optical components were highlighted, especially of the PBS.

These promising results are all in line with the aimed clock frequency stability and paves the way to the implementation of a complete highly compact clock system. Further works have now to be done to implement the DF-VECSEL source for the generation of the dual-frequency electromagnetic field need for the CPT interrogation.

REFERENCES

[1] Abdel Hafiz, M.; Coget, G.; Petersen, M.; Rocher, C.; Guérandel, S.; Zanon-Willette, T.; de Clercq, E. & Boudot, R., “Toward a high-stability coherent population trapping Cs vapor-cell atomic clock using autobalanced Ramsey spectroscopy”, Physical Review Applied, 9, 064002 (2018),

[2] Dumont, P.; Camargo, F.; Danet, J.-M.; Holleville, D.; Guerandel, S.; Pillet, G.; Baili, G.; Morvan, L.; Dolfi, D.; Gozhyk, I. et al., “Low-noise dual-frequency laser for compact Cs atomic clocks”, Journal of Lightwave Technology, 32, 3817-3823 (2014).

[3] Zanon, T.; Guerandel, S.; De Clercq, E.; Holleville, D.; Dimarcq, N. & Clairon A., “High contrast Ramsey fringes with coherent-population-trapping pulses in a double lambda atomic system”, Physical review letters, 94, 193002 (2005).

[4] Gredat, G.; Liu, H.; Cotxet, J.; Tricot, F.; Baili, G.; Gutty, F.; Goldfarb, F.; Sagnes, I. & Bretenaker, F., “Optimization of laser dynamics for active stabilization of DF-VECSELs dedicated to cesium CPT clocks”, JOSA B, 37, 1196-1207 (2020).

[5] Cotxet, J. et al., “Progress on a Highly Compact Cesium CPT Clock Based on a Dual-Frequency VECSEL”, conference paper, IEEE EFTF-IFCS 2021 (2021).

[6] Tricot, F.; Phung, D.; Lours, M.; Guérandel, S. & De Clercq, E., “Power stabilization of a diode laser with an acousto-optic modulator”, Review of Scientific Instruments, 89, 113112 (2018).

[7] McCarron, D.; King, S. & Cornish, S., “Modulation transfer spectroscopy in atomic rubidium”, Measurement science and technology, 19, 105601 (2008).

[8] Arditi, M. & Carver, T., “Pressure, light, and temperature shifts in optical detection of 0-0 hyperfine resonance of alkali metals”, Physical Review, 124, 800, (1961).