

Laser-pumped high-performance compact gas-cell Rb standard with $< 3 \times 10^{-13} \tau^{-1/2}$ stability

Thejesh Bandi, Christoph Affolderbach,
and Gaetano Mileti

Laboratoire Temps – Fréquence (LTF)
Institut de Physique, Université de Neuchâtel
Neuchâtel, Switzerland
Email: thejesh.band@unine.ch

Camillo Stefanucci, Francesco Merli,
and Anja K. Skrivervik

Laboratoire d'Electromagnétisme et d'Acoustique (LEMA),
École Polytechnique Fédérale de Lausanne (EPFL),
Lausanne, Switzerland

Claudio E. Calosso

Optics division
Istituto Nazionale di Ricerca Metrologica (INRIM)
Torino, Italy

Abstract — We demonstrate a high-performance laser-pumped rubidium-cell atomic frequency standard exhibiting a short-term stability of $< 3 \times 10^{-13} \tau^{-1/2}$. The key components of this standard are a Rb vapor cell of 25mm diameter and a newly developed compact microwave resonator cavity. The overall volume of the clock's physics package – including the frequency-stabilized laser head and physics package – is < 3 liters, which shows the potential of this compact clock for future portable applications.

I. MOTIVATION

There is an increasing interest in improving the performances of portable atomic frequency standards, e.g. in view of next generation GNSS applications [1]. Presently, the best clock onboard GNSS navigation systems is the Passive Hydrogen Maser (PHM) with a short-term stability $< 7 \times 10^{-13} \tau^{-1/2}$ and reaching the 1×10^{-14} level at 1-day timescale. State-of-the-art lamp-pumped space Rb standards (RAFS) exhibit $\approx 2 \times 10^{-12}$ at $\tau = 1$ s, reaching $\leq 4 \times 10^{-14}$ over one day [2,3]. However, the superior stability of the PHM comes with a compromise on the mass, volume, and power consumption of the clock, key figures that exceed the values for a Rb standard by a factor of 5.5, 11, and 4.5, respectively. Recent works on laser-pumped Rb atomic clocks using noise-cancellation in 14mm-size cells [4] and Pulsed Optical Pumping (POP) [5] approaches have demonstrated short-term clock stabilities of $< 6 \times 10^{-13} \tau^{-1/2}$ and $< 1.6 \times 10^{-13} \tau^{-1/2}$, respectively.

In this work, we aim to develop a laser-pumped Rb standard that can reach stabilities of $< 6 \times 10^{-13} \tau^{-1/2}$ ($1 \text{ s} < \tau < 10^5 \text{ s}$) and $< 1 \times 10^{-14}$ over one day. This clock uses an enlarged Rb cell (25mm diameter and 25mm length) placed inside a newly developed compact magnetron-type microwave

cavity. Thanks to this new cavity, the clock can maintain the compact volume, low mass, and low power consumption of a conventional lamp-pumped RAFS.

II. EXPERIMENTAL SETUP AND CLOCK COMPONENTS

Figure 1 shows the schematics of our experimental clock setup. This setup consists of three main parts: the frequency stabilized Laser Head (LH), the Physics Package (PP), and the microwave synthesizer (Local Oscillator, LO).

The laser head is based on a distributed feed-back (DFB) diode laser emitting at 780nm (Rb D2 transition). The LH also contains an evacuated Rb reference cell. Narrow sub-Doppler saturated-absorption spectroscopy lines obtained from this reference cell are used for frequency stabilization of the laser light. The overall volume and mass of the laser head are 0.9 liters and 0.6 kg, respectively. Further details on the laser head were reported in [6-8].

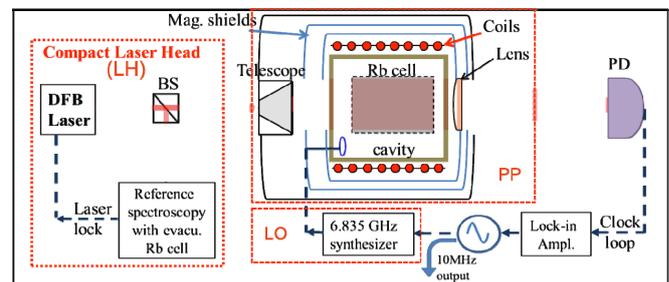


Figure 1. Schematics of the double-resonance (DR) clock setup. PD: photo detector; BS: beam splitter.

The Physics Package is similar to the one presented in [7], except for the Rb cell and the magnetron-type cavity. At the heart of the PP is a 25mm-diameter Rb cell filled with atomic Rb and a mixture of buffer gases. A novel magnetron-type microwave cavity was designed to surround the cell. This design exploits electrodes placed inside the cavity in order to make it resonate at the ^{87}Rb clock transition of ≈ 6.835 GHz, and sustain a TE_{011} -like mode structure of the microwave magnetic field. A microwave field simulation of this resonant TE_{011} -like mode is shown in Fig. 2. Based on these simulations and design, a microwave resonator was fabricated and characterized (for further details see [9]). Thanks to the magnetron-type cavity design, the overall volume of the cavity is < 0.04 liters (outer cavity dimensions), which is much smaller than for a fundamental-mode resonator with comparable mode structure (≈ 0.14 liters). The complete Physics Package (including heaters and magnetic shields) has a total volume of < 0.8 liters, and a mass of < 1.4 kg.

The microwave source (LO) and the digital lock-in and clock loop electronics were realized at INRIM and are described in detail in [10]. The phase noise of this LO at 6.835 GHz carrier is measured to be $S_{\phi} < -108$ dB rad^2/Hz . From this value, the LO contribution to the clock instability via the intermodulation effect is calculated as $\approx 8 \times 10^{-14}$ at 1s integration time.

We used in-house made temperature control modules based on digital electronics for the PP and the laser head, and a low-noise current driver and lock-in loop for operation of the DFB laser head.

III. DOUBLE RESONANCE (DR) SIGNAL AND CLOCK STABILITY

A. Double resonance signal and stability prediction

Figure 3 shows our typical measured double resonance signal, with a linewidth of 361 Hz (FWHM) and a signal contrast of 25%. Here contrast is defined as the DR line peak amplitude divided by the background level outside the microwave resonance condition. The photocurrent of $1.7 \mu\text{A}$ at FWHM corresponds to a shot-noise limited frequency

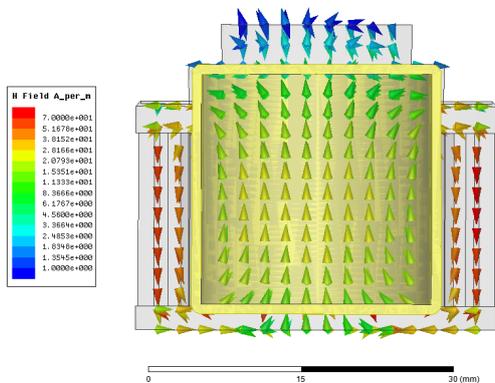


Figure 2. Microwave field simulations showing the TE_{011} -like resonant mode [9].

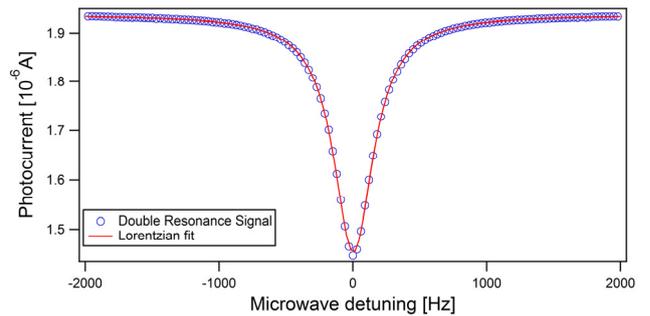


Figure 3. measured DR clock signal, showing a linewidth of 361 Hz and a contrast of 25%.

stability of $5.5 \times 10^{-14} \tau^{-1/2}$ [1]. However, presently the estimated signal-to-noise (S/N) stability of our clock is limited to $2.4 \times 10^{-13} \tau^{-1/2}$, mainly due to FM-to-AM noise conversion of laser FM noise in the atomic vapor [11].

B. Measured clock stability

The output frequency of the microwave LO is locked to the center of the DR signal using a clock loop as shown in Fig. 1, and the 10 MHz output of the VCXO quartz oscillator is compared to the reference signal from an active Hydrogen Maser. The measured stability of our clock is $2.4 \times 10^{-13} \tau^{-1/2}$ (see Fig. 4), which is in excellent agreement with the predicted S/N limit. For this result, the clock was operated in standard laboratory conditions (no vacuum enclosure or thermal chambers used). The clock stability at longer time-scales ($\tau \geq 1000$ s) remains to be studied.

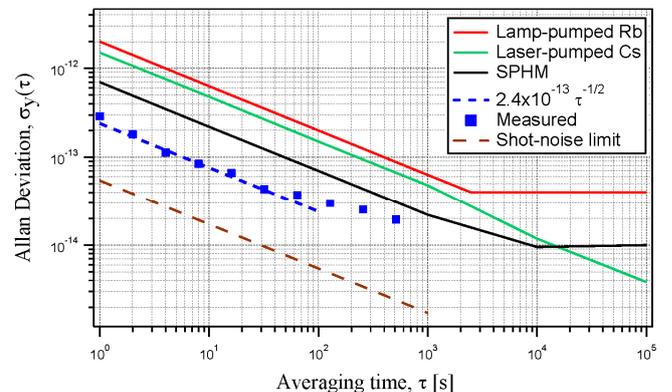


Figure 4. Measured clock short-term stability (blue squares) compared to other clocks.

IV. CONCLUSIONS

We have demonstrated a conceptually simple and compact continuous-wave laser-pumped DR clock, showing a short-term frequency stability of $2.4 \times 10^{-13} \tau^{-1/2}$ when operated in laboratory conditions. This clock has a fundamental shot-noise limit of $5.5 \times 10^{-14} \tau^{-1/2}$ that could be approached by noise-subtraction technique [4] or by using a laser source with reduced FM noise [12]. Studies on the medium- to long-term stability of the clock remain to be done by evaluating, for

instance, the impact of light-shifts, temperature shifts, and microwave power shifts. A previous clock realization with a similar physics package (but using a different cavity) has already reached the level of 1×10^{-14} at 10^4 s integration times [1].

This clock has the potential for future portable applications, such as in GNSS (satellite navigation), high-speed telecommunication, deep space missions, and as LO reference for portable optical synthesizers or optical frequency standards.

ACKNOWLEDGMENT

We thank F. Gruet, M. Pellaton, P. Scherler and M. Durrenberger (all at LTF-UniNe) for their contributions to this work.

REFERENCES

- [1] T. Bandi, C. Affolderbach, C. E. Calosso, and G. Mileti, "High-performance laser-pumped rubidium frequency standard for satellite navigation", *Electronics Letters*, vol. 47, no. 12, pp. 698-699 (2011).
- [2] P. Rochat et al., "The Onboard Galileo Rubidium and Passive Maser, Status & Performance", *Proc. IEEE Int. Freq. Control Symposium*, Vancouver, Canada, August 29-31 2005, pp. 26-32.
- [3] R. T. Dupuis, T. J. Lynch, J. R. Vaccaro, "Rubidium Frequency Standard for the GPS IIF Program and Modifications for the RAFSMOD Program", *Proc. joint IEEE Int. Freq. Control Symposium and European Frequency and Time Forum*, Toulouse, France, April 22-25 2008, pp.655-660.
- [4] C. Affolderbach, T. Bandi, R. Matthey, F. Gruet, M. Pellaton, G. Mileti, "Compact, High-Stability Rb Atomic Clocks for Space", *Proc. of the 3rd International Colloquium - Scientific and Fundamental Aspects of the Galileo Programme*, August 31st – September 2nd 2011, Copenhagen, Denmark. ESA proceedings WPP-326, paper 1400.
- [5] S. Micalizio, A. Godone, C. Calosso, F. Levi, C. Affolderbach and F. Gruet, "Pulsed Optically Pumped Rubidium Clock with High Frequency-Stability Performance", *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 3, pp.457-462 (2012).
- [6] C. Affolderbach, G. Mileti, "A compact laser head with high-frequency stability for Rb atomic clocks and optical instrumentation", *Review of Scientific Instruments*, Volume 76, 073108, (2005).
- [7] T. Bandi, F. Gruet, C. Affolderbach, C. E. Calosso and G. Mileti, "Investigations on Improved Rb cell standards", *Proc. of the Joint IEEE Int. Freq. Control and European Frequency and Time Forum*, San Francisco, California, USA, May 2-5 2011, no. 7254.
- [8] R. Matthey, C. Affolderbach, G. Mileti, "Methods and evaluation of frequency aging in DFB laser diodes for Rubidium atomic clocks", *Optics Letters*, Vol. 36, No. 17, p. 3311-3313, (2011).
- [9] C. Stefanucci, T. Bandi, F. Merli, M. Pellaton, C. Affolderbach, G. Mileti and A. K. Skrivervik, "Compact microwave resonator for high-performance rubidium frequency standards", submitted for publication (2012).
- [10] C. E. Calosso, S. Micalizio, A. Godone, E. K. Bertacco, and F. Levi, "Electronics for the pulsed rubidium clock: design and characterization", *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 54 (9), pp. 1731-40, 2007.
- [11] J. C. Camparo, "Conversion of laser phase noise to amplitude noise in an optically thick vapor," *J. Opt. Soc. Am. B*, vol. 15, pp. 1177-1186, 1998.
- [12] G. Mileti, J. Deng, F. L. Walls, D. A. Jennings, R. E. Drullinger, "Laser-Pumped Rubidium Frequency Standards: New Analysis and Progress", *J. Quantum Electronics*, Vol. 34, pp. 233-237, 1998.