Laser-pumped high-performance compact gas-cell Rb standard with < $3\times10^{-13}\ \tau^{-1/2}$ stability

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Abstract **— We demonstrate a high-performance laser-pumped rubidium-cell atomic frequency standard exhibiting a short-term stability of < $3\times10^{-13}\ \tau^{-1/2}$. 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 < $7\times10^{-13}\ \tau^{-1/2}$ and reaching the 1×10^{-14} level at 1-day timescale. State-of-the-art lamp-pumped space Rb standards (RAFS) exhibit $\approx 2\times10^{-12}$ at $\tau = 1$ s, reaching $\leq 4\times10^{-14}$ 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 < $6\times10^{-13}\ \tau^{-1/2}$ and < $1.6\times10^{-13}\ \tau^{-1/2}$, respectively.

In this work, we aim to develop a laser-pumped Rb standard that can reach stabilities of < $6\times10^{-13}\ \tau^{-1/2}$ (1 s < τ < 10'000 s) and < 1×10^{-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].

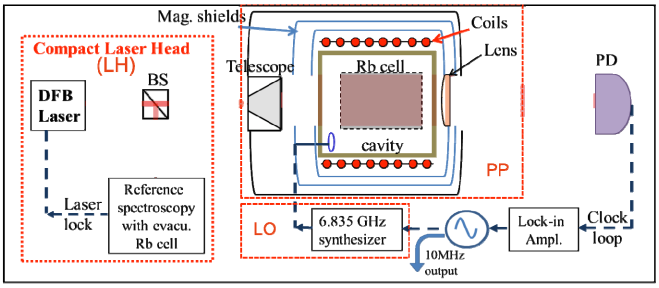

Figure 1. Schematics of the double-resonance (DR) clock setup. PD: photo detector; BS: beam splitter.

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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 $S_\varphi < -108$ dBrad^2/Hz. From this value, the LO contribution to the clock instability via the intermodulation effect is calculated as ≈ 8×10^{-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 µA at FWHM corresponds to a shot-noise limited frequency stability of $5.5\times10^{-14}\ \tau^{-1/2}$ [1]. However, presently the estimated signal-to-noise (S/N) stability of our clock is limited to $2.4\times10^{-13}\ \tau^{-1/2}$, mainly due to FM-to-AM noise conversion of laser FM noise in the atomic vapor [11].

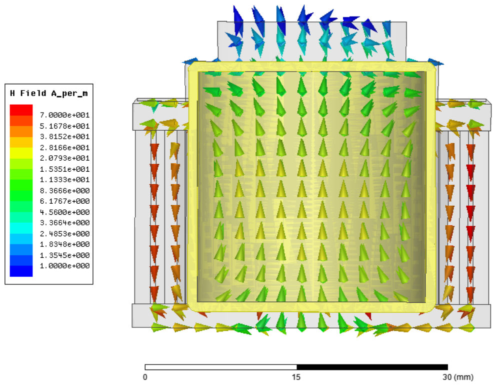

Figure 2. Microwave field simulations showing the TE_{011}-like resonant mode [9].

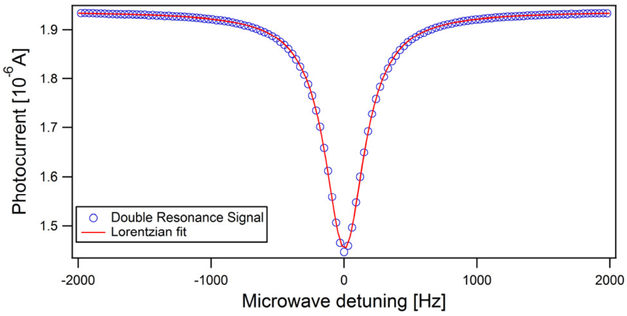

Figure 3. measured DR clock signal, showing a linewidth of 361 Hz and a contrast of 25%.

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 $2.4\times10^{-13}\ \tau^{-1/2}$ (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.

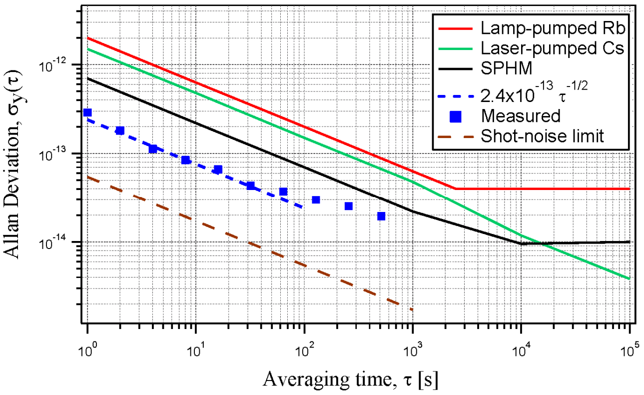

Figure 4. Measured clock short-term stability (blue squares) compared to other clocks.

IV. CONCLUSIONS

We have demonstrated a conceptually simple and compact continuous-wave laser-pumped DR clock, showing a short-term frequency stability of $2.4\times10^{-13}\ \tau^{-1/2}$ when operated in laboratory conditions. This clock has a fundamental shot-noise limit of $5.5\times10^{-14}\ \tau^{-1/2}$ 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 $1\text{x}10^{-14}$ at 10^4s 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.

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