

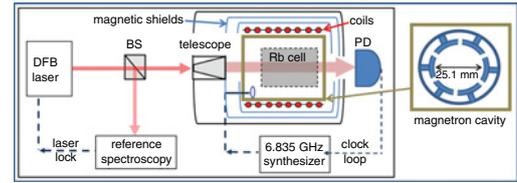
# High-performance laser-pumped rubidium frequency standard for satellite navigation

T. Bandi, C. Affolderbach, C.E. Calosso and G. Miletì

Presented is a double-resonance continuous-wave laser-pumped rubidium (Rb) atomic clock with a short-term stability of  $4 \times 10^{-13} \tau^{-1/2}$  for integration times  $1 \text{ s} \leq \tau \leq 1000 \text{ s}$ , and a medium- to long-term stability reaching the  $1 \times 10^{-14}$  level at  $10^4 \text{ s}$ . The clock uses an Rb vapour cell with increased diameter of 25 mm, accommodated inside a newly developed compact magnetron-type microwave cavity. This results in a bigger signal with reduced linewidth, and thus improved short-term stability from a clock with  $1 \text{ dm}^3$  physics package volume only. The medium- to long-term clock stability is achieved by minimising the effects of light-shift and temperature coefficient on the atoms. Potential applications of the clock are discussed.

**Motivation:** Portable and compact atomic clocks are today indispensable for many aspects of human civilisation [1], with increasing demand for better clock precision and stability [2, 3]. Application examples of such frequency standards include precise navigation, telecommunication, and space science [1, 3–5]. Laboratory clocks like primary caesium (Cs) fountains and optical clocks exhibit excellent stabilities of  $\sigma_y(\tau) \leq 1 \times 10^{-13} \tau^{-1/2}$ , but are bulky and expensive. Even cold atom clocks or optical clocks proposed for space applications target outlines of  $1 \text{ m}^3$  volume, 230 kg mass, and 450 W power consumption [5]; hence a trade-off must be made between stability and portability. Recently developed portable standards, such as the passive hydrogen maser (SPHM) [4] or laser-pumped Cs beam clocks (LPCs) [6], exhibit a reasonable trade-off with volume ( $13 < V < 28 \text{ dm}^3$ ), mass ( $8 < m < 18 \text{ kg}$ ), power consumption ( $30 < P < 80 \text{ W}$ ) and stability ( $7 \times 10^{-13} < \sigma_y(1 \text{ s}) < 1.5 \times 10^{-12}$  and  $1 \times 10^{-14} < \sigma_y(10^4 \text{ s}) < 3 \times 10^{-14}$ ). Here we show that our simple and compact, continuous-wave (CW) laser-pumped double-resonance (DR) Rb clock stability outperforms that of LPCs standards up to 1000 s, and is comparable to cold-atom portable clocks [3] or the SPHM, but from a physics package (PP) with volume of  $< 1 \text{ dm}^3$  only in our case. A previous laser-pumped Rb clock based on a magnetron-type cavity had a stability of  $\sigma_y \approx 3 \times 10^{-12} \tau^{-1/2}$  [7]. By increasing the cell diameter to 25 mm and redesign of the magnetron cavity, we improve on this clock stability while maintaining a very compact volume of the magnetron-type resonator. This clock can have applications in, e.g., next generation satellite navigation systems like GALILEO. In particular, a short-term stability of  $6 \times 10^{-13} \tau^{-1/2}$  allows reaching the  $1 \times 10^{-14}$  level already at timescales of 3600 s, well before the 6000 s relevant for clock error prediction and synchronisation.

**Clock setup:** The main components of our DR clock are shown in Fig. 1. A DFB laser diode emitting at  $\lambda = 780 \text{ nm}$  (Rb D2 transition) acts as light source. Measured parameters are a linewidth  $\approx 4.5 \text{ MHz}$ , relative intensity noise (RIN)  $7 \times 10^{-14} \text{ Hz}^{-1}$  and FM noise of  $4 \text{ kHz}/\sqrt{\text{Hz}}$  (both at 300 Hz). The laser is mounted in a stabilised laser head (PP  $V \leq 0.5 \text{ dm}^3$ ) that also includes an evacuated reference Rb cell. The laser is locked to the  $F_g = 1$  to  $F_g = 0-1$  cross-over sub-Doppler saturated-absorption line obtained from this cell, by FM modulation techniques. The clock PP is composed of a glass cell (25 mm diameter and length) filled with  $^{87}\text{Rb}$  and a mixture of Ar + N<sub>2</sub> as buffer gases. The cell is fixed inside a compact magnetron-type microwave cavity, which resonates at the  $^{87}\text{Rb}$  hyperfine ground-state splitting of  $\approx 6.835 \text{ GHz}$ . The electrode arrangement inside the cavity allows reaching this resonance frequency from a reduced overall cavity volume of  $\approx 45 \text{ cm}^3$  only, compared to  $\approx 140 \text{ cm}^3$  for a fundamental-mode cavity. A magnetic field applied to the cell lifts the Zeeman degeneracy and isolates the clock transition ( $5^2S_{1/2}|F_g = 1, 0\rangle \rightarrow |F_g = 2, 0\rangle$ ). This assembly is surrounded by two magnetic shields (longitudinal shielding factor  $> 3000$ ) to suppress fluctuations in the ambient magnetic field. At the entrance of the PP, a telescope expands the laser beam to the cell diameter, in order to sample a maximum number of atoms at low light intensity, for an optimised DR signal. The PP control electronics include the cell heater thermostats, current sources, and a local oscillator (LO) microwave synthesiser generating the 6.835 GHz used to interrogate the atoms. The LO phase-noise at 6.8 GHz, relevant for the clock's short-term stability, is  $-112 \text{ dBc/Hz}$  at 300 Hz (6.8 GHz carrier). The microwave frequency is locked to the centre of the DR line using a digital lock-in and loop filter implemented in the FPGA technique [8].

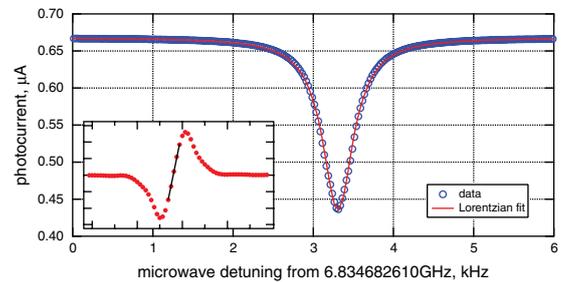


**Fig. 1 Schematic of DR clock setup**

BS: beam splitter; PD: photodetector  
 Inset: cross-section of new magnetron-type cavity

**DR signal and clock stability:** Fig. 2 shows the DR clock signal, with a signal contrast of 35% and a narrow linewidth of 467 Hz. The 3.3 kHz frequency shift of the line from the unperturbed Rb ground-state splitting is due to the buffer-gas inside the cell. From this data, the clock's short-term stability can be estimated using (1):

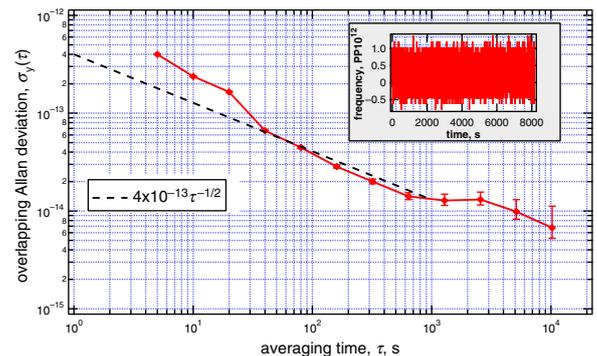
$$\sigma_y = \frac{N_{PSD}}{\sqrt{2} \cdot D \cdot \nu_0} \tau^{-1/2} \quad (1)$$



**Fig. 2 Double-resonance clock signal**

Inset: error signal at lock-in output, giving discriminator slope

where  $N_{PSD} = 0.8 \text{ pA}/\sqrt{\text{Hz}}$  is the total noise on the photodetector,  $D = 0.34 \text{ nA/Hz}$  is the discriminator slope of the error signal (Fig. 2 inset), and  $\nu_0$  is the Rb ground-state splitting. The estimated signal-to-noise limit is  $\sigma_y(\tau) \approx 3 \times 10^{-13} \tau^{-1/2}$ , and the shot-noise limit is  $\approx 1 \times 10^{-13} \tau^{-1/2}$ . The measured clock stability shown in Fig. 3 (in terms of Allan deviation) is  $\sigma_y(\tau) = 4 \times 10^{-13} \tau^{-1/2}$  up to 1000 s, in reasonable agreement with the signal-to-noise limit.



**Fig. 3 Measured clock stability**

Data up to 20 s integration time is degraded by noise of measurement system  
 Inset: raw frequency data measured over period of 8000 s

We measured an intensity-light-shift (LS) coefficient of  $\alpha = -1.9 \times 10^{-12}/\%$ ; frequency-LS coefficient of  $\beta = 2.2 \times 10^{-17}/\text{Hz}$ , and temperature coefficient (TC)  $< 6.6 \times 10^{-12}/\text{K}$ , which result in a clock instability estimation of  $< 1 \times 10^{-14}$  at  $\tau > 10^4 \text{ s}$ . The measured clock stability meets this value. The frequency drift is  $1 \times 10^{-14}/\text{hour}$ .

**Conclusion:** We have demonstrated a compact Rb clock with a short-term stability of  $4 \times 10^{-13} \tau^{-1/2}$  and medium-term stability  $< 1 \times 10^{-14}$  at  $10^4 \text{ s}$ . This is comparable to stabilities of bigger clocks previously demonstrated [3, 4, 6], but from a much more compact PP

and with a simple scheme using CW operation with one single laser frequency only. The demonstrated clock also widely relies on refined implementation of technologies already qualified for space applications, which is relevant in view of future clocks for space navigation and telecommunication. It also can be used as a compact LO reference in portable optical frequency combs (optical synthesizers).

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