

Study of laser-pumped double-resonance clock signals using a microfabricated cell

M Pellaton¹, C Affolderbach¹, Y Pétremand², N de Rooij² and G Miletì¹

¹ Laboratoire Temps-Fréquence (LTF), Institut de Physique, Université de Neuchâtel, Neuchâtel, Switzerland

² Ecole Polytechnique Fédérale de Lausanne (EPFL) IMT-NE SAMLAB, Neuchâtel, Switzerland

E-mail: gaetano.mileti@unine.ch

Abstract

We present our microwave spectroscopic studies on laser–microwave double-resonance (DR) signals obtained from a micro-fabricated Rb vapor cell. This study focuses on the characteristics and systematic shifts of the ground-state ‘clock transition’ in ⁸⁷Rb ($|F_g = 1, m_F = 0\rangle \rightarrow |F_g = 2, m_F = 0\rangle$) used in Rb atomic clocks, and represents a first step toward a miniature atomic clock based on the DR scheme. A short-term clock instability below $2 \times 10^{11} \tau^{-1/2}$ is demonstrated, staying below 10^{-11} up to $\tau = 10^4$ s.

PACS numbers: 06.20.fb, 06.30.Ft, 33.40.Fi, 32.70.Jz, 42.62.Fi

1. Introduction

The demonstration of coherent population trapping (CPT) spectroscopy using VCSEL diode lasers [1] has opened up the way toward significantly reducing the size, power and complexity of atomic clocks [2], and many studies have been carried out on the miniaturization of CPT-based atomic clocks [3]. Nevertheless, this interrogation principle has some drawbacks, such as a non-negligible light background to the clock signal (due to non-resonant laser modulation sidebands) and the difficulty of controlling precisely the spectrum of the multi-frequency light field used. Microwave power requirements are another issue; in recent papers, about -3 dBm [4] and -14 dBm [5] of RF power are required for a CPT clock, while the need for only -30 dBm has been reported for a double-resonance (DR) clock using a resonant microwave cavity [6]. In addition, it has also been shown that DR allows for roughly five times better short-term instability compared to a CPT clock using the same cell [7]. All this motivated our present studies aimed at realizing a miniature Rb clock based on the DR scheme [8], which could use either a laser or potentially a micro-fabricated spectral lamp [9, 10] as the pump-light source.

Here we report on our experimental results obtained with a table-top laser–microwave DR atomic clock using a micro-fabricated buffer gas (BG) Rb cell as a clock cell. The

two main frequency shifts known to significantly degrade the medium- and long-term stabilities of an atomic clock (ac Stark shift and temperature shift) are measured. Finally, we present a stability measurement of a DR clock using this micro-fabricated cell as a frequency reference.

2. Cell fabrication

The micro-fabricated Rb vapor cell is realized by following the main technology steps described in figure 1, similar to previously reported methods [11]. First, a silicon wafer is prepared for cavity etching by photolithography. For this step, silicon dioxide is grown on the surface. The wafer is then etched by deep reactive ion etching (DRIE) in order to obtain through holes of the desired dimensions. The obtained wafer is then bonded to a glass wafer by anodic bonding. This wafer stack is diced to obtain preforms. In parallel, a glass wafer is diced to form glass lids of the same dimension as the preforms. From this point, the fabrication is continued at chip level.

The obtained chips (preform and lid) are placed into a dedicated dispensing and bonding machine, and then pumped to high vacuum. A small droplet of Rb (natural isotope mixture) is dispensed into the preform using a commercially available Rb dispenser (from SAES Getters, Italy). Once the desired amount of Rb is in the cavity, the chamber of the

"

"

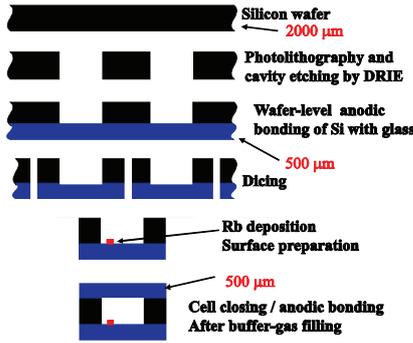


Figure 1. Cell fabrication process flow (cross-sectional view).

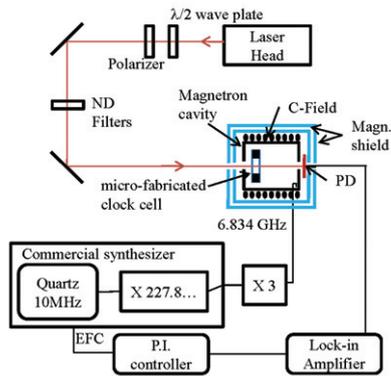


Figure 2. Block diagram of the experimental setup.

machine is filled with the appropriate pressure and mixture of BG (Ar–N₂). The cavity is finally closed with a glass lid by anodic bonding to seal hermetically the alkali cell. Due to the presence of BG, the last bonding step has to be performed at a limited voltage (dependent on gas pressure) to prevent corona discharges in the chamber. Final cell external dimensions used here are 10 × 10 mm² and 3 mm thickness, with an internal cell volume of 5 mm diameter by 2 mm height occupied by the Rb atomic vapor.

3. Experimental setup

The experimental clock setup is presented in figure 2. The pump light is generated by a compact, frequency-stabilized laser head [12] that can be frequency-stabilized to any of the different optical transitions of the ⁸⁷Rb D1 line, obtained by saturated-absorption spectroscopy of an evacuated glass blown reference cell containing enriched ⁸⁷Rb. Optics elements serve to control light polarization and intensity sent to the micro-fabricated clock cell. The micro-fabricated clock cell is placed in a compact magnetron-type cavity [13] sustaining a microwave field at the 6.834 GHz frequency of the ⁸⁷Rb ground-state hyperfine splitting. The cavity is surrounded by a solenoid used to produce a dc magnetic field to isolate the $|F_g = 1; m_F = 0\rangle \rightarrow |F_g = 2; m_F = 0\rangle$ clock transition. The 6.834 GHz microwave radiation is produced from the 2.278 GHz output of a commercial synthesizer, via a frequency tripler. This radiation is frequency modulated at 187 Hz in order to generate an error signal by phase-sensitive detection, which can be used either as spectroscopic signal or for stabilizing the microwave frequency to the clock

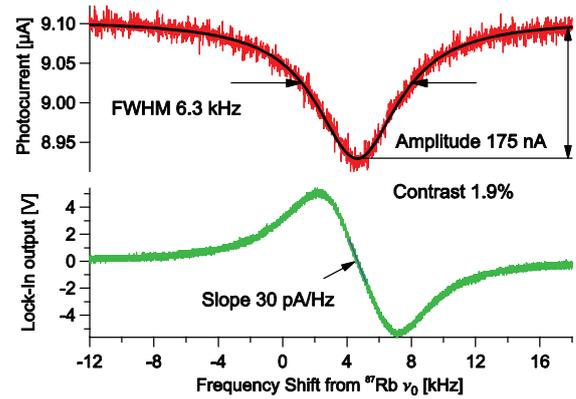


Figure 3. Clock signal and its corresponding error signal obtained by phase-sensitive detection.

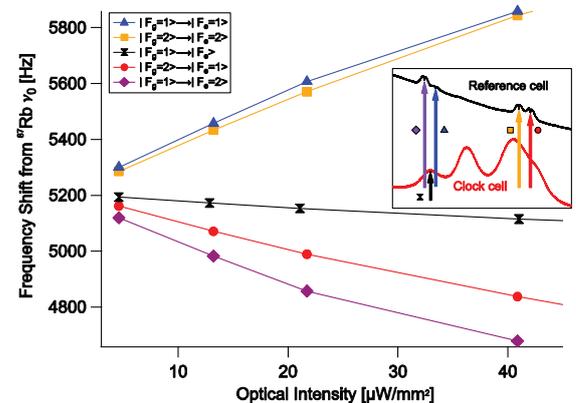


Figure 4. Light shift measured with the laser frequency referenced to the different possible transitions on the D1 line. The inset shows the laser absorption in the clock cell (lower trace) and saturated absorption in the reference cell inside the laser head (upper trace).

transition. For the clock application, the error signal is sent to a Proportional/Integrator (P.I.) controller, which in turn is applied to the Electronic Frequency Control (EFC) input of the microwave synthesizer.

4. Experimental results

Figure 3 shows a typical DR clock signal, obtained using the micro-fabricated cell (laser frequency stabilized to the $|5^2S_{1/2}; F_g = 2\rangle \rightarrow |5^2P_{1/2}; F_e = 1\rangle$ transition). It has a full-width at half-maximum (FWHM) of 6.3 kHz and a contrast (amplitude over background level) around 2%. The corresponding error signal has a discriminator slope of $D = 30 \text{ pA Hz}^{-1}$. The laser intensity incident on the cell is $50.9 \mu\text{W mm}^{-2}$ and the cell temperature is 373 K. The observed frequency shift of the clock signal corresponds to the mixture and pressure of the BG. The intrinsic linewidth of the clock signal (at zero light intensity and microwave power) is 2.2 kHz, in reasonable agreement with the linewidth calculated for this BG cell [2, pp 404–9]. The shifts in the clock signal's center frequency due to laser power variations are shown in figure 4 for different laser frequencies (i.e. different laser lock points), and the linearized intensity light-shift coefficients α are obtained from the slopes of these curves. In our experimental clock conditions (laser frequency referenced to the $|F_g = 2\rangle \rightarrow |F_e = 1\rangle$ transition of the reference cell), the light-shift

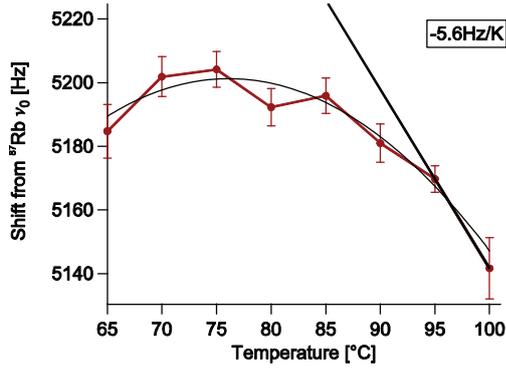


Figure 5. Temperature shift measured. An inversion temperature is observed at 75 °C.

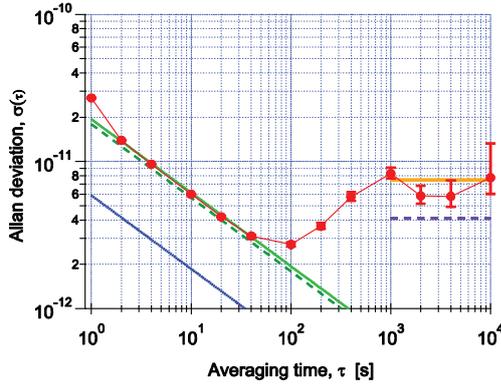


Figure 6. Measured clock instability in terms of Allan deviation. The experimental data (solid red circles), signal-to-noise limit (dashed green) and shot-noise limit (dotted blue) are shown. Stability limitations at $\tau \geq 10^3$ s: temperature shift (dashed purple) and light shift (solid orange).

coefficient was measured to be $\alpha = 1.5 \times 10^{-9} \text{ mm}^2 \mu\text{W}^{-1}$. The temperature shifts are shown in figure 5. The first-order temperature coefficient was measured to be $8.2 \times 10^{-10} \text{ K}^{-1}$ at 373 K, consistent with the predictions [14].

The short-term instability of a clock based on this cell can be estimated using the following formula [15]:

$$\sigma_y(\tau) = \frac{N}{\sqrt{2Df_0}} \tau^{-1/2} \quad (1)$$

where N is the total detection noise, D the discriminator slope and f_0 the frequency of the microwave transition. With $N = 5.14 \text{ pA}/\sqrt{\text{Hz}}$ of measured noise, a signal-to-noise limit of $\sigma_y(\tau) = 1.8 \times 10^{11} \tau^{-1/2}$ is calculated. The shot-noise limit is $6 \times 10^{-12} \tau^{-1/2}$. The medium- and long-term instabilities are estimated using the coefficients previously measured. Although the cell temperature is stabilized, fluctuations of about 5 mK result in an instability of 4.1×10^{-12} at $\tau > 1000$ s. By optimizing the ratio of the BG mixture [2, pp 1306–10], the temperature coefficient can be reduced by two orders of magnitude. Relative light intensity fluctuations are measured to be of the order of 10^{-4} , resulting in a clock instability of 8×10^{-12} at 1000 s. Figure 6 shows our clock's frequency instability measured in comparison to a hydrogen maser. The laser frequency is referenced to the $|5^2\text{S}_{1/2}; F_g = 2\rangle \rightarrow |5^2\text{P}_{1/2}; F_c = 1\rangle$ transition. A clock instability of $1.9 \times 10^{-11} \tau^{-1/2}$ is achieved for $\tau < 100$ s, in good agreement

with the calculated signal-to-noise limit. The instability stays below 1×10^{-11} up to 10^4 s averaging time, mainly limited by the light shift. Referencing the laser on the Doppler-broadened line $|5^2\text{S}_{1/2}; F_g = 1\rangle \rightarrow |5^2\text{P}_{1/2}\rangle$ obtained from the clock cell reduces this intensity light shift by a factor of four, but a significantly reduced signal-to-noise ratio is observed, and degrades the clock in the short term ($6 \times 10^{-11} \tau^{-1/2}$ recorded instability).

5. Conclusions

We have presented our studies of DR signals obtained from a micro-fabricated Rb vapor cell. An inversion of the temperature coefficient is observed in the expected range of temperature. The measured short-term clock instability below $2 \times 10^{-11} \tau^{-1/2}$ demonstrates that the DR in micro-fabricated cells is of interest for a future miniature atomic clock, as an alternative to the widely pursued CPT clock scheme. The next important steps will include the development of a more radically miniaturized microwave cavity (similar to, e.g., [8, 16, 17]) in order to open the way toward a novel miniature atomic DR clock with competitive frequency stability.

Acknowledgments

This work was supported by the Swiss National Science Foundation (Sinergia grant CRSI20-122693/1) and the European Space Agency. We thank F Gruet, P Scherler, M Durrenberger and the CSEM cleanroom staff for their contributions to this study.

References

- [1] Affolderbach C, Nagel A, Knappe S, Jung C, Wiedenmann D and Wynands R 2000 Nonlinear spectroscopy with a vertical-cavity surface-emitting laser (VCSEL) *Appl. Phys. B* **70** 407–13
- [2] Vanier J and Audoin C 1989 *The Quantum Physics of Atomic Frequency Standards* ed A E Bailey (Bristol: Adam Hilger) pp 1257–343
- [3] Knappe S 2007 MEMS atomic clocks *Comprehensive Microsystems* vol 3, ed Y B Gianchandani *et al* (Amsterdam: Elsevier) pp 571–612
- [4] Schori C, Mileti G, Leuenberger B and Rochat P 2010 CPT atomic clock based on rubidium 85 *Proc. 24th European Frequency and Time Forum (Nordwijk, 13–16 Apr. 2010)*
- [5] Knappe S, Schwindt P D D, Gerginov V, Shah V, Hollberg L, Kitching J, Liew L and Moreland J 2004 Microfabricated atomic clocks at NIST *Proc. 36th Annu. Precise Time and Time Interval (PTTI) Meeting (Washington, DC, 7–9 Dec. 2004)* pp 383–92
- [6] Bandi T, Affolderbach C and Mileti G 2010 Study of Rb 0–0 hyperfine double-resonance transition in a wall-coated cell *Proc. 24th European Frequency and Time Forum (Nordwijk, 13–16 Apr. 2010)*
- [7] Lutwak R, Emmons D, Riley W and Garvey R M 2002 The chip-scale atomic clock—coherent population trapping vs. conventional interrogation *Proc. 34th Annu. Precise Time and Time Interval (PTTI) Meeting (Reston, VA, 3–5 Dec. 2002)* pp 539–50
- [8] Braun A M 2007 RF-interrogated end-state chip-scale atomic clock *Proc. 39th Annu. Precise Time and Time Interval (PTTI) Meeting (Long Beach, CA, 26–29 Nov. 2007)* pp 233–48

- [9] Venkatraman V, Shea H, Petremand Y, de Rooij N, Affolderbach C and Mileti G 2011 Low-power chip-scale rubidium plasma light source for miniature atomic clocks *Proc. Joint Conf. of the IEEE Int. Frequency Control Symp. (IFCS) and European Frequency and Time Forum (EFTF) (San Francisco, CA, 2–5 May 2011)* pp 804–7
- [10] Wang S, Lin L and Guo H 2009 Analysis and design of a micromachined Rb-85 filter in passive rubidium atomic clock *Proc. 4th IEEE Int. Conf. on Nano/Micro Engineered and Molecular Systems (Shenzhen, China, 5–8 Jan. 2009)* pp 911–4
- [11] Liew L A, Knappe S, Moreland J, Robinson H, Hollberg L and Kitching J 2004 Microfabricated alkali atom vapor cells *Appl. Phys. Lett.* **84** 2694–6
- [12] Micalizio S, Godone A, Levi F, Bertacco E K, Calosso C, Gruet F, Pellaton M, Bandi T, Affolderbach C and Mileti G 2010 Pulsed optically pumped Rb clock with optical detection: first results *Proc. 24th European Frequency and Time Forum (Nordwijk, 13–16 Apr. 2010)*
- [13] Affolderbach C, Droz F and Mileti G 2006 Experimental demonstration of a compact and high-performance laser-pumped rubidium gas cell atomic frequency standard *IEEE Trans. Instrum. Meas.* **55** 429–35
- [14] Vanier J, Kunski R, Cyr N, Savard J Y and Têtu M 1982 On hyperfine frequency shifts caused by buffer gases: application to the optically pumped passive rubidium frequency standard *J. Appl. Phys.* **53** 5387–91
- [15] Mileti G 1995 Study of the S/N performance of passive atomic clocks using a laser pumped vapour *Proc. 9th European Frequency and Time Forum (Besançon, 8–10 Mar. 1995)* pp 271–6
- [16] Deng J 2001 Subminiature microwave cavity for atomic frequency standards *Proc. 2001 IEEE Int. Frequency Control Symp. and PDA Exhibition (Seattle, WA, 6–8 Jun. 2001)* pp 85–8
- [17] Guo-Bin L, Feng Z and Si-Hong G 2009 Study of a low power dissipation, miniature laser-pumped rubidium frequency standard *Chin. Phys. B* **18** 3839–43