

## High performance vapour-cell frequency standards

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 J. Phys.: Conf. Ser. 723 012006

(<http://iopscience.iop.org/1742-6596/723/1/012006>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 130.125.30.139

This content was downloaded on 14/12/2016 at 12:40

Please note that [terms and conditions apply](#).

You may also be interested in:

[Observation of single neutral atoms in a large-magnetic-gradient vapour-cell magneto-optical trap](#)

Wang Jing, He Jun, Qiu Ying et al.

[Continuously transferring cold atoms in caesium double magneto-optical trap](#)

Yan Shu-Bin, Geng Tao, Zhang Tian-Cai et al.

[ac Stark shift in double resonance and coherent population trapping in a wall-coated cell for compact Rb atomic clocks](#)

Danijela Miletic, Thejesh Bandi, Christoph Affolderbach et al.

[Microfabricated rubidium vapour cell with a thick glass core for small-scale atomic clock applications](#)

Y Pétremand, C Affolderbach, R Straessle et al.

[Radiation trapping in atomic vapours in finite-cylinder vapour cells excited by a laser beam](#)

A F Molisch, B P Oehry, W Schupita et al.

[Multi-sensor magnetoencephalography with atomic magnetometers](#)

Cort N Johnson, P D D Schwindt and M Weisend

[Metrological characterization of the pulsed Rb clock with optical detection](#)

S Micalizio, C E Calosso, A Godone et al.

# High performance vapour-cell frequency standards

**M Gharavipour, C Affolderbach, S Kang, T Bandi, F Gruet, M Pellaton and G Mileti**

Laboratoire Temps-Fréquence, Institut de Physique,  
Université de Neuchâtel, Switzerland

Email: gaetano.mileti@unine.ch

**Abstract.** We report our investigations on a compact high-performance rubidium (Rb) vapour-cell clock based on microwave-optical double-resonance (DR). These studies are done in both DR continuous-wave (CW) and Ramsey schemes using the same Physics Package (PP), with the same Rb vapour cell and a magnetron-type cavity with only 45 cm<sup>3</sup> external volume. In the CW-DR scheme, we demonstrate a DR signal with a contrast of 26% and a linewidth of 334 Hz; in Ramsey-DR mode Ramsey signals with higher contrast up to 35% and a linewidth of 160 Hz have been demonstrated. Short-term stabilities of  $1.4 \times 10^{-13} \tau^{-1/2}$  and  $2.4 \times 10^{-13} \tau^{-1/2}$  are measured for CW-DR and Ramsey-DR schemes, respectively. In the Ramsey-DR operation, thanks to the separation of light and microwave interactions in time, the light-shift effect has been suppressed which allows improving the long-term clock stability as compared to CW-DR operation. Implementations in miniature atomic clocks are considered.

## 1. Introduction

Since the first invention of lamp-pumped rubidium (Rb) clocks in the 1960's [1,2], the demand for a stable, reliable, and compact Rb frequency standard with low power consumption has been growing, for various applications fields such as industry, telecommunication, navigation, space applications (e.g. GPS [3], GALILEO [4] and COMPASS [5]). Recently, thanks to the semiconductor laser technology, laser-pumped Rb clocks have been considered in several studies, for their better optical pumping efficiency results in short-term frequency stabilities at least one order of magnitude better than their lamp-pumped counterparts [6-9]. This opened up also several new schemes for vapour-cell atomic clocks, such as the continuous-wave (CW) Rb clock [9], coherent population trapping (CPT) Cs clock [10] and pulsed optical pumping (POP) Rb clock [11]. In this paper we report our studies on high-performance Rb frequency standards based on the laser-microwave double-resonance (DR) scheme, using both CW and Ramsey interrogation. Both CW-DR and Ramsey-DR schemes require two resonant electromagnetic fields of light and microwave. In the case of CW-DR, the laser optically pumps the vapour of the Rb atoms by creating a polarization of the atomic ground-state; simultaneously the microwave field, generated from a quartz oscillator and is near-resonant with the <sup>87</sup>Rb hyperfine clock transition (energy levels  $5^2S_{1/2} |F_g=1, m_F=0\rangle \leftrightarrow |F_g=2, m_F=0\rangle$ ), is applied. The opacity of the Rb vapour to the transmitted light signal as a function of microwave frequency is a measure of the atomic ground state polarization known as CW-DR signal [9]. In CW-DR, the steps of optical pumping, microwave interrogation and optical detection are applied simultaneously (figure 1(b)). In the case of Ramsey-DR, these three sequences are separated in time, see figure 1(c): first, during optical pumping a strong laser pulse creates a significant atom population imbalance between





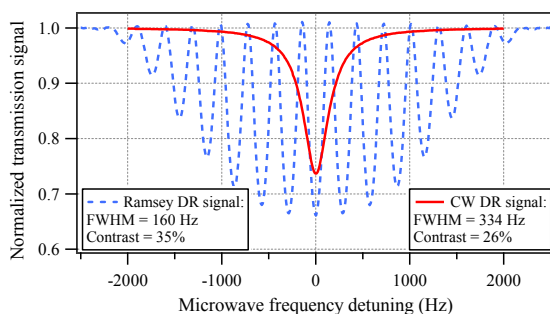
atoms experienced well approximated  $\pi/2$ -pulses [15]. A C-field coil around the resonator generates a static magnetic field (typical amplitude  $\approx 40$  mG) oriented parallel to the laser propagation vector (z direction). This static field is required to lift the degeneracy of  $^{87}\text{Rb}$  hyperfine ground states into their respective Zeeman levels. A two-layer magnetic shield surrounds the whole system to prevent the external magnetic field fluctuations. The photodetector collects the detection signal after the cell. The LO consists of an oven controlled crystal oscillator (OCXO), the microwave synthesizer to generate the  $\approx 6.835$  GHz radiation for  $^{87}\text{Rb}$  clock transition interrogation and the servo loop [19].

### 3. Experimental Results

#### 3.1. DR and Ramsey signals

As explained in the previous section, in the case of the CW-DR scheme both resonant optical and microwave fields act simultaneously (figure 1(b)). The light power transmitted through the cell (as function of the microwave frequency) constitutes the clock signal used to adjust the frequency of the LO. For this scheme the optimized DR signal is shown by the solid red line in figure 2. Here, the laser intensity is  $0.46 \mu\text{W}/\text{mm}^2$  and the microwave input power is  $-34$  dBm. The signal can be well fitted by a Lorentzian line shape with a full width at half maximum (FWHM)  $\Delta\nu_{1/2}=334$  Hz, which is limited by optical and microwave power broadening, and a contrast of  $C=26\%$  [9].

The pulse sequences for the case of the Ramsey-DR scheme are shown in figure 1(c), using the following parameters: 1) optical pumping pulse time  $T_p=0.4$  ms with a laser power of about 15 mW, 2) two  $\pi/2$  microwave pulses with the duration of  $T_1=0.4$  ms and input power (to the cavity) of  $-20$  dBm, 3) Ramsey time  $T_{\text{Ramsey}}=3$  ms, and 4) optical detection pulse time of  $T_d=0.7$  ms with a laser power of about 0.1 mW. The Ramsey pattern obtained in this situation is given by the dashed blue line in figure 2. Its central fringe has a contrast of  $C=35\%$  and a linewidth of  $\Delta\nu_{1/2}=160$  Hz, consistent with the theoretical prediction of  $\Delta\nu_{1/2}=1/(2 \cdot T_{\text{Ramsey}})$  [15].



**Figure 2.** Double resonance signal in the case of the CW-DR scheme (solid red line) compared to Ramsey fringes in the case of Ramsey-DR (dashed blue line) [9, 15]. (colour online)

#### 3.2. Short-term clock stability

The signal-to-noise ratio (S/N) limits the short-term stability (at  $\tau=1$  to 100 s) of a passive Rb clock and can be estimated by [9]:

$$\sigma_{S/N}(\tau) = \frac{N_{psd}}{\sqrt{2} \cdot D \cdot \nu_{Rb}} \tau^{-1/2}, \quad (1)$$

where  $N_{psd}$  is the power-spectral density of the detection noise when microwave and pump laser are switched on (in closed-loop condition) and  $D$  is the discriminator slope of the error signal. Here,  $N_{psd}$  includes shot-noise, laser's amplitude-modulation (AM) noise and FM-to-AM noise conversion in the vapour cell [20]. Moreover, in the case of the Ramsey-DR scheme, contributions of AOM's additional noises are also added [15]. For the CW-DR scheme the clock's shot-noise limit is estimated as  $4.9 \times 10^{-14} \tau^{-1/2}$ , by replacing  $N_{psd}$  in (1) with the shot-noise level. In the Ramsey-DR scheme with optical detection the shot-noise limit can be estimated by [11]:

$$\sigma_{sn}(\tau) = \frac{I}{\pi Q_a R_{sn}} \sqrt{\frac{T_c}{\tau}}, \quad (2)$$

where  $Q_a \approx 4.3 \times 10^7$  is the quality factor of the clock transition and  $T_c = 4.95$  ms is the cycle time of the pulse sequence. The signal-to-noise ratio  $R_{sn}$  for our clock is at the level of 30000 [14] and the final expected shot-noise stability limit is  $\sigma_{sn}(\tau) \approx 1.7 \times 10^{-14} \tau^{-1/2}$ .

The total short-term clock stability of  $\sigma_y(\tau)$  includes, in addition to the S/N limit, the contributions from the LO's phase noise through the Dick effect [21] and from laser intensity and frequency fluctuations via the light-shifts (LS), and can be expressed as [7]:

$$\sigma_y(\tau) = \sqrt{\sigma_{S/N}^2(\tau) + \sigma_{Dick}^2(\tau) + \sigma_{LS}^2(\tau)}. \quad (3)$$

Table 1 shows the measured short-term instability budget for both CW-DR and Ramsey-DR schemes. The dominant source for this stability is the optical detection noise which mainly originates from the technical laser noise and FM-to-AM noise conversion in the cell [15, 18].

**Table 1.** Short-term instability budget comparison for both CW-DR and Ramsey-DR Rb clocks.

Instability	Shot-noise limit ( $\tau^{-1/2}$ )	Signal-to-noise $\sigma_{S/N}$ ( $\tau^{-1/2}$ )	Dick effect ( $\tau^{-1/2}$ )	Light Shift ( $\tau^{-1/2}$ )	Total ( $\tau^{-1/2}$ ) (theory)	Total ( $\tau^{-1/2}$ ) (measured)
<b>CW-DR</b> [9]	<b><math>4.9 \times 10^{-14}</math></b>	$1.2 \times 10^{-13}$	$7.5 \times 10^{-14}$	$4 \times 10^{-14}$	<b><math>1.4 \times 10^{-13}</math></b>	<b><math>1.4 \times 10^{-13}</math></b>
<b>Ramsey-DR</b> [17]	<b><math>1.7 \times 10^{-14}</math></b>	$2.0 \times 10^{-13}$	$\leq 1 \times 10^{-13}$	$3 \times 10^{-15}$	<b><math>2.2 \times 10^{-13}</math></b>	<b><math>2.4 \times 10^{-13}</math></b>

### 3.3. Light shifts (LS)

Light shifts (or AC Stark shifts) are the shifts of the atomic energy levels arising when a near-resonant optical field interacts with an atom [22, 23]. With the clock frequency  $\nu_{clock}$ , we define the intensity LS coefficient  $\alpha = \delta\nu_{clock}/\delta I_L$  (at fixed laser frequency  $\nu_L$ ) and the frequency LS coefficient  $\beta = \delta\nu_{clock}/\delta\nu_L$  (at fixed laser intensity  $I_L$ ). Measured LS coefficients in the CW-DR scheme are  $\alpha = 1.0 \times 10^{-12}$  /% and  $\beta = 1.2 \times 10^{-11}$  /MHz [9], more than one order of magnitude higher than  $\alpha = -2.1 \times 10^{-14}$  /% and  $\beta = 4.6 \times 10^{-13}$  /MHz in the Ramsey-DR case [17]. In principle, LS can be fully suppressed in a Ramsey scheme. The residual LSs found in Ramsey-DR mode might be due to the position shift effect (non-uniform spatial distribution of microwave field and laser absorption rate) [12], residual coherence at the beginning of the first Ramsey pulse [24] and residual non-zero light power during the Ramsey phase.

### 3.4. Microwave power shift (PS)

In both cases of optical-microwave DR interrogation schemes, the spatial inhomogeneity of the optical and microwave fields as well as the residual gradients of the static magnetic field can cause a position dependent inhomogeneous shift on the clock hyperfine frequency. This depends on the microwave power and is called microwave power shift [25]. The microwave power shift coefficients for CW-DR and Ramsey-DR are measured  $2.2 \times 10^{-12}$  / $\mu$ W and  $1.8 \times 10^{-12}$  / $\mu$ W, respectively [9, 17].

### 3.5. Systematic shifts and long-term clock stability

We evaluate the limitations on the medium- to long term frequency stability of our Rb clocks arising from systematic shifts. The contributions from the main physical perturbations such as intensity and frequency LS, microwave power shift, vapour cell and stem temperature coefficients (TC) are measured. Table 2 summarizes and compares the long-term instability budgets for our CW and Ramsey DR clocks, at  $\tau = 10^4$  s. Measurements of the long-term frequency stability show that in the case of our current vapour cell with a long stem (25 mm), in both CW and Ramsey schemes the total clock instabilities are limited to  $\approx 6 \times 10^{-14}$ , mainly because of the stem temperature coefficient (TC), although in Ramsey-DR scheme the instability contributions due to LS are reduced by more than one

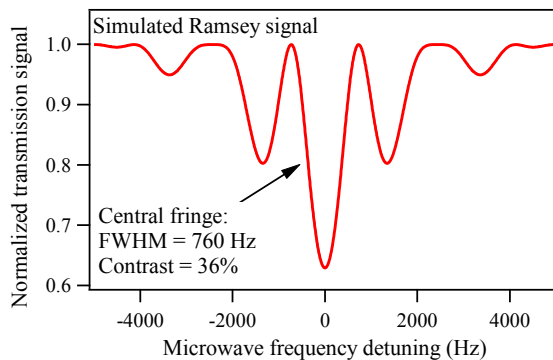
order of magnitude compared to the CW-DR scheme (from  $3.8 \times 10^{-14}$  to  $2.3 \times 10^{-15}$ ). Therefore a new vapour cell with ten times smaller stem volume was designed, resulting in its potential instability contribution reduced to  $5.5 \times 10^{-15}$ . With this cell, we expect our Ramsey-DR clock to reach  $7.2 \times 10^{-15}$  at  $\tau = 10^4$  s.

**Table 2.** Comparison of clock stability limitations at  $\tau = 10^4$  s, calculated from the main systematic shift coefficients and parameters instabilities.

Effect or source	CW-DR		Ramsey-DR	
	Long stem [9]	Short stem	Long stem [17]	Short stem
Intensity LS		$9.9 \times 10^{-15}$		$1.1 \times 10^{-15}$
Frequency LS		$3.7 \times 10^{-14}$		$2 \times 10^{-15}$
Cell TC		$\leq 3.5 \times 10^{-15}$		$\leq 3.5 \times 10^{-15}$
Microwave PS		$8.9 \times 10^{-16}$		$1.9 \times 10^{-15}$
Stem TC	$5.6 \times 10^{-14}$	$5.5 \times 10^{-15}$	$5.6 \times 10^{-14}$	$5.5 \times 10^{-15}$
<b>Total <math>\sigma_{\text{tot}} = [\sum_i \sigma_i^2]^{1/2}</math></b>	<b><math>6.8 \times 10^{-14}</math></b>	<b><math>3.9 \times 10^{-14}</math></b>	<b><math>5.6 \times 10^{-14}</math></b>	<b><math>7.2 \times 10^{-15}</math></b>
<b>Total (measured)</b>	<b><math>6 \times 10^{-14}</math></b>	----	<b><math>6 \times 10^{-14}</math></b>	----

#### 4. Applications in miniature DR clocks

The suppression of light-shift effects in the Ramsey-DR scheme could also be beneficial for improving the long-term stability of miniature or chip-scale atomic clocks [26]. We therefore investigate on the approach of Ramsey-mode operation of a miniature DR clock as e.g. described in [27], based on a 50 mm<sup>3</sup> internal volume microfabricated Rb cell and a micro-loop-gap resonator, by numerical simulations using the model described in [15]. First results show that Ramsey signals with a narrow central fringe (760 Hz FWHM) and > 30% contrast may be expected. Such a miniature Ramsey DR clock could be a good candidate for achieving short-term stabilities of  $\leq 1 \times 10^{-11} \tau^{-1/2}$  and  $< 1 \times 10^{-12}$  at one day, for e.g. applications such as in smart grids.



**Figure 3:** Ramsey DR signal simulated for a micro-fabricated Rb vapour cell such as used in [27].  $T_{\text{Ramsey}} = 0.2$  ms and  $T_1 = 0.4$  ms. (colour online)

#### 5. Conclusion

We have studied compact Rb atomic clocks based on both CW-DR and Ramsey-DR schemes, using the same clock setup with a clock resonator Physics Package of only 0.8 litres overall volume. CW-DR and Ramsey signals with contrasts of 26% and 35%, and FWHMs of 334 Hz and 160 Hz, respectively, are shown. The measured short-term clock stabilities are  $\approx 2 \times 10^{-13} \tau^{-1/2}$  (at  $\tau = 1$  to 100 s) in both schemes, with optical detection noise being the main limitation. On medium- to long-term scales ( $\tau \approx 10^4$  s) the main limiting effects in the CW-DR scheme are the LS and stem TC, which can be reduced by about one order of magnitude by passing to the Ramsey-DR scheme and implementing a new cell design, respectively. A final clock stability of  $< 1 \times 10^{-14}$  at  $10^4$  s up to 1 day is expected.

## Acknowledgments

This work was supported by the Swiss National Science Foundation (SNSF grant no. 140712) and the European Metrology Research Programme (EMRP project IND55-Mclocks). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. We also acknowledge previous support from the European Space Agency (ESA) and the Swiss Space Office (Swiss Confederation). We thank A. K. Skrivervik, C. Stefanucci (both EPFL-LEMA) for their support on the microwave cavity, and C. Calosso (INRIM, Italy) for the microwave LO.

## References

- [1] Camparo J 2007 *Phys. Today*, **60** 33
- [2] Kastler A 1950 *J. Phys. Radium*, **11** 255
- [3] Dupuis R T, Lynch T J and Vaccaro J R 2008 *Proc. IEEE Int. Frequency Control Symposium* edited by Jadasliwer B. (*Honolulu, Hawaii, USA 19-21 May 2008*) pp. 655-660
- [4] Waller P, Gonzalez S, Binda S, Sesia I, Hidalgo I, Tobias G and Tavella P 2010 *IEEE Trans. Ultrason. Ferroelect. Freq. Control* **57** 738
- [5] Chunhao H, Zhiwu C, Yuting L, Li L, Shenghong X, Lingfeng Z and Xianglei W 2013, *Int. J. Navig. Observ.* **2013** 371450
- [6] Camparo J and Frueholz 1986 *J. Appl. Phys.* **59** 3313
- [7] Mileti G, Deng J, Walls F, Jennings D and Drullinger R 1998 *IEEE J. Quantum Electron.* **34** 233
- [8] Vanier J 2005 *Appl. Phys. B* **81** 421
- [9] Bandi T, Affolderbach C, Stefanucci C, Merli F, Skrivervik A K and Mileti G 2014 *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on* **61** 1769-1778
- [10] Danet J M, Kozlova O, Yun P, Guérandel S and De Clercq E 2014 *EPJ Web of Conf.* **77** 00017
- [11] Micalizio S, Calosso C E, Godone A and Levi F 2012, *Metrologia* **49** 425-436
- [12] Micalizio S, Godone A, Levi F and Calosso C 2009 *Phys. Rev. A.* **79** 013403
- [13] Godone A, Micalizio S, Levi F and Calosso C 2006 *Phys. Rev. A* **74** 043401
- [14] Kang S, Affolderbach C, Gruet F, Gharavipour M, Calosso C E and Mileti G 2014 *Proc. 26th European Frequency and Time Forum (EFTF) (Neuchatel, Switzerland, 23-26 June 2014)* pp. 544-547
- [15] Kang S, Gharavipour M, Affolderbach C, Gruet F and Mileti G 2015 *J. Appl. Phys.* **117** 104510
- [16] Gruet F, Pellaton M, Affolderbach C, Bandi T, Matthey R and Mileti G, 2012 *Proc. Int. Conf. on Space Optics (ICSO) (Ajaccio, Corsica, 9-12 October 2012)* no. 48
- [17] Kang S, Gharavipour M, Gruet F, Affolderbach C and Mileti G. 2015 *Proc. Joint Conf. IEEE Int. Frequency Control Symposium & European Frequency and Time Forum (EFTF) (Denver, Colorado, USA 12-16 April 2015)*, pp. 800-803
- [18] Stefanucci C, Bandi T, Merli F, Pellaton M, Affolderbach C, Mileti G and Skrivervik A K 2012 *Rev. Sci. Instrum.* **83** 104706
- [19] Calosso C E, Micalizio S, Godone A, Bertacco E K and Levi F 2007 *IEEE Trans. Ultrason., Ferroelectr., Freq. Control.* **54** 1731
- [20] Camparo J C 1998 *J. Opt. Soc. Am. B* **15** 1177-1186
- [21] Deng J Q, Mileti G, Drullinger R E, Jennings D A, and Walls F L 1999, *Phys. Rev. A* **59** 773
- [22] Cohen-Tannoudji C and Barrat J 1961 *P. J. Phys. Radium* **22** 329
- [23] Mathur B S, Tang H and Happer W 1968 *Phys. Rev.* **171** 11
- [24] Godone A, Micalizio S and Levi F 2004 *Phys. Rev. A* **70** 023409
- [25] Vanier J and Audoin C 1989 *The Quantum Physics of Atomic Frequency Standards* vol. 1, (Bristol, UK: Adam Hilger)
- [26] Knappe S 2008 MEMS atomic clocks, *Comprehensive Microsystems* (vol. 3) ed. Y B Gianchadani et al. (Amsterdam: Elsevier) pp.571-612
- [27] Violetti M, Pellaton M, Merli F, Zürcher J-F, Affolderbach C, Mileti G and Skrivervik A K 2014 *IEEE Journal of Sensors* **14** 3193