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

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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 ^{87}Rb ($|F_g = 1, m_F = 0\rangle \rightarrow | F_g = 2, m_F = 0\rangle$) 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.

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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 th

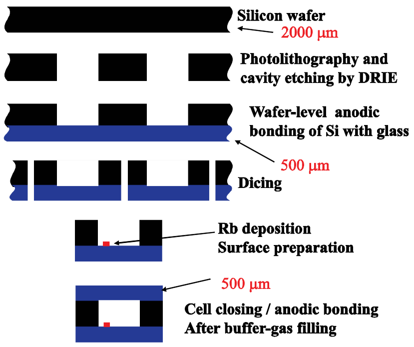

Figure 1. Cell fabrication process flow (cross-sectional view).

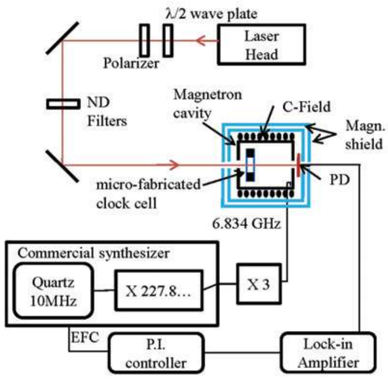

Figure 2. Block diagram of the experimental setup.

machine is filled with the appropriate pressure and mixture of BG (Ar–N_2). 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 $10 \times 10\,\text{mm}^2$ 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 ^{87}Rb D1 line, obtained by saturated-absorption spectroscopy of an evacuated glass blown reference cell containing enriched ^{87}Rb. 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 ^{87}Rb 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

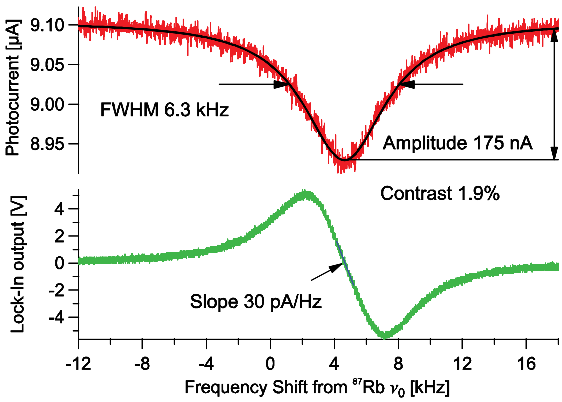

Figure 3. Clock signal and its corresponding error signal obtained by phase-sensitive detection.

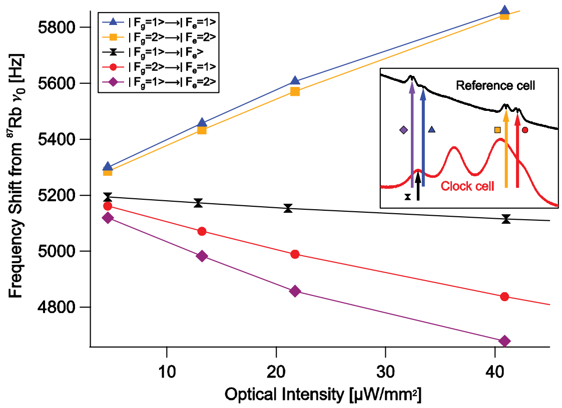

Figure 4. Light shift measured with the laser frequency referenced to the different possible transitions on the D1 line. The inset shows the laser absorption in the clock cell (lower trace) and saturated absorption in the reference cell inside the laser head (upper trace).

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 $D = 30\,\text{pA}\,\text{Hz}^{-1}$. The laser intensity incident on the cell is $50.9\,\mu\text{W}\,\text{mm}^{-2}$ 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

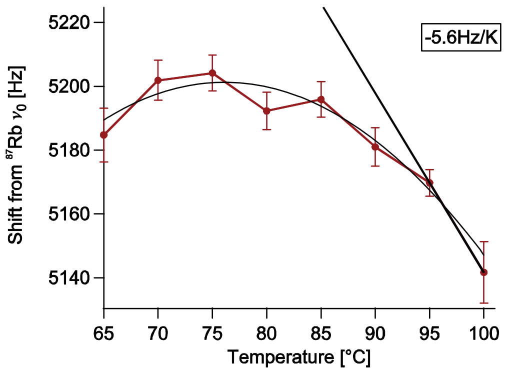

Figure 5. Temperature shift measured. An inversion temperature is observed at 75 °C.

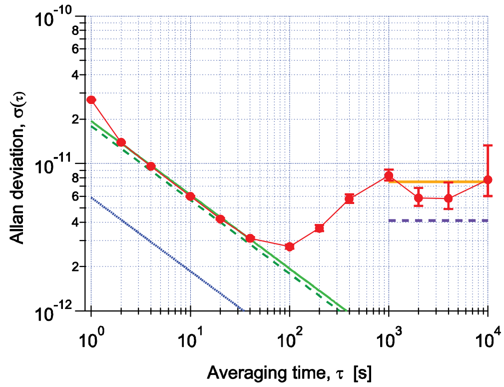

Figure 6. Measured clock instability in terms of Allan deviation. The experimental data (solid red circles), signal-to-noise limit (dashed green) and shot-noise limit (dotted blue) are shown. Stability limitations at $\tau \geqslant 10^3$ s: temperature shift (dashed purple) and light shift (solid orange).

coefficient was measured to be $\alpha = 1.5 \times 10^{-9}$ mm^2 μW^{-1}. The temperature shifts are shown in figure 5. The first-order temperature coefficient was measured to be 8.2×10^{-10} 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]:

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

where N is the total detection noise, D the discriminator slope and f_0 the frequency of the microwave transition. With $N = 5.14$ pA/$\sqrt{}$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 $|5^2\mathrm{S}_{1/2}; F_\mathrm{g} = 2\rangle \rightarrow |5^2\mathrm{P}_{1/2}; F_\mathrm{e} = 1\rangle$ 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 $|5^2\mathrm{S}_{1/2}; \mathrm{F_g} = 1\rangle \rightarrow |5^2\mathrm{P}_{1/2}\rangle$ 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

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