Invited Paper

Atomic clock based on a coherent population trapping resonance in ^{87}Rb with improved high-frequency modulation parameters

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ABSTRACT

This work reports for the first time development and experimental study of a laboratory prototype of an atomic clock with stability of $2\times10^{-11}\tau^{-1/2}$ (Allan deviation) over time 1 s < τ < 1000 s (7×10^{-13} over 1000 s) on the basis of a coherent population trapping (CPT) resonance in ^{87}Rb in a compact spherical cell having 1.3-cm diameter and without any buffer gas. Demonstrated are dependencies of the width of the studied CPT resonance upon the amplitude and modulation frequency of optical frequency difference (3.417 GHz) of a bichromatic circularly polarised pump field. For the first time, a considerable non-linearity was discovered in the dependence upon the reference difference frequency of the spectral position of the CPT resonance when the modulation frequency of the optical frequency difference is varied within a broad range.

Keywords: atomic clock, coherent population trapping resonance, Rb, rubidium cell

1. INTRODUCTION

Frequency standards relying on atomic CPT resonances [1, 2] in alkali metal vapours [3-5] feature relatively high short-term stability and are used in high-data-rate communication systems, high-precision geo-location, and in many other high-technology applications. During the last few decades, considerable scientific and technical advances have not only led to better stability of frequency standards, but also reduced their physical dimensions and energy consumption [6–8]. The principle of operation of these devices is based on stabilisation of a quartz oscillator frequency (10 MHz) to the frequency of a quantum discriminator, a CPT resonance determined by the structure of the specific atoms used in it. Quality of the quantum discriminator in this case is governed by the parameters of the CPT resonance which, in their turn, depend on the conditions of its excitation (i.e. depending on the parameters of the exciting radiation, absorption cell, and on those of the electronic control and measurement system). Therefore, key properties of a CPT resonance crucially depend on numerous parameters of the system, in which it is excited.

In this work, we focused our efforts on identification of dependencies of the width of the studied CPT resonance and its spectral position upon the key parameters of the experimental system. Subsequent optimisation of the experimental prototype of the atomic clock resulted in frequency stability of 7×10^{-13} over 1000 s (Allan deviation), which is close to the theoretical limit [9] for a cell with an anti-relaxation coating [10-12] of relatively small size used in these experiments.

2. EXPERIMENTAL SETUP

To stabilise the quartz oscillator (TCVCXO, IQD FOQ GmbH), we used a CPT resonance on the D_1 line of ^{87}Rb (Fig. 1 (a)). The experimental installation is schematically shown in Fig. 1 (b). The output wavelength of a single-frequency semiconductor laser (VCSEL, Oclaro Inc.) was tuned to the rubidium D_1 line by simultaneous adjustment of the injection current and the laser diode temperature within their working ranges.

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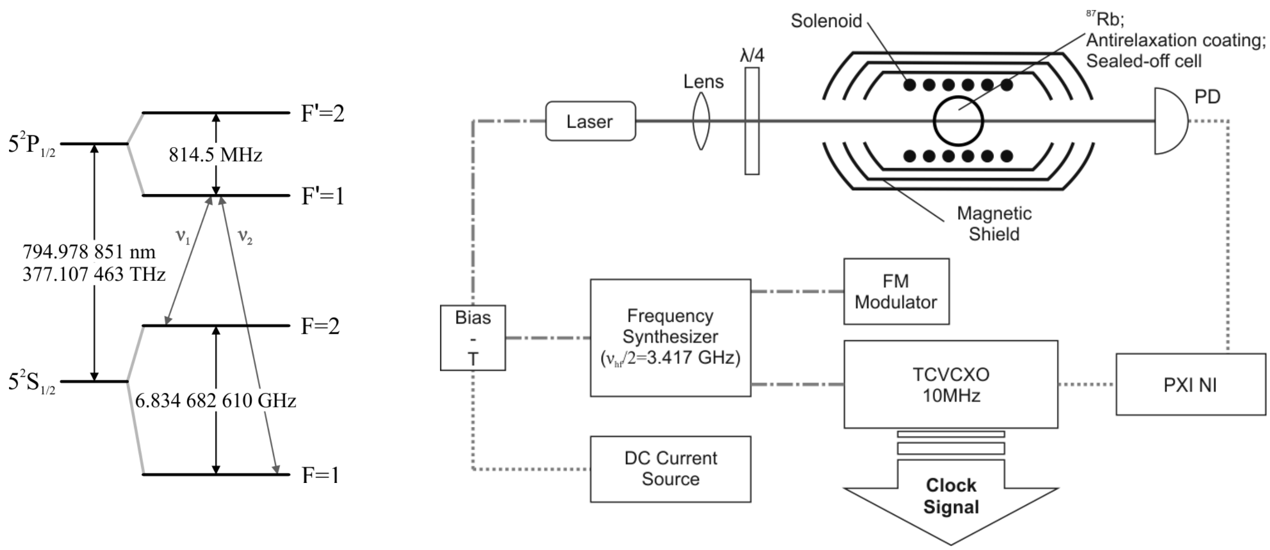
Injection current of the laser was modulated at the frequency of 3.417 GHz (RF-signal) produced with a Phase Matrix 10-GHz signal generator and a reference 10-MHz TCVCXO, which gave rise to side-bands in the laser diode output spectrum (Fig. 2). The most powerful spectral side-band components were spaced ± 3.417 GHz apart from the central frequency and these components were used to create a CPT resonance. Difference between these side frequencies was equal to 6.835 GHz, corresponding to the transition frequency between the levels of hyperfine splitting of ^{87}Rb ground state. Intensity of the RF signal at 3.417 GHz was chosen to produce the largest side-band signal and amounted to 6 dBm.



a

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Fig. 1. (a) Energy level diagram of ^{87}Rb; (b) Experimental set-up.

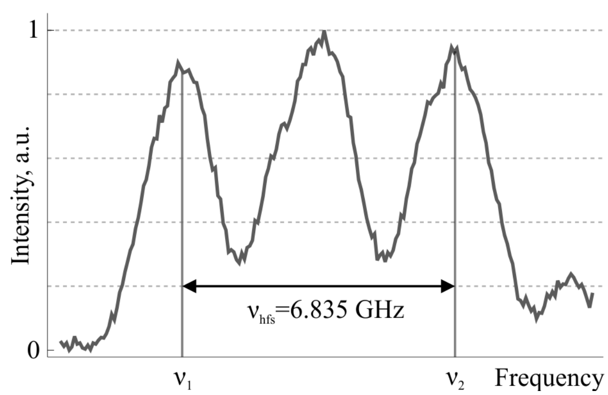


Fig. 2. Output spectrum of the laser diode when its injection current was modulated at 3.417 GHz.

Difference between frequencies of these side bands was modulated at f_{mod}=200 Hz around the central value of Δν with modulation depth of $f_{md} \approx \pm$ 2.5 kHz. The laser output was guided into a spherical sealed-off optical cell containing ^{87}Rb vapour and with anti-relaxation coatings on the walls. Both the semiconductor laser and the optical cell were temperature-stabilised (temperature instability not exceeding 1 mK). Intensity of laser light passed through the optical cell was registered by a photo-detector phase-locked at f_{mod}, the signal from which was used for frequency locking of the reference 10-MHz generator. Active stabilisation of the reference quartz generator to the CPT resonance allowed significant improvement of its frequency stability.

Overall control of components of the experimental installation was done with a PXI system by National Instruments. For example, a module with highly stable current output allowed us to directly feed the pumping laser diode, avoiding additional complexity of wavelength stabilisation systems, such as DAVLL [13, 14]. Removal of residual long-term drift of the laser diode output wavelength was done via automatic locking of the laser's output wavelength to the center of the absorption line of ^{87}Rb.

Fig. 3 demonstrates the measured CPT resonance, a peak in the amount of radiation from the pump laser diode passing through the optical cell as a function of detuning of the difference between optical frequencies of the bichromatic field from ground-state hyperfine splitting frequency 6.835 GHz (two-photon detuning). This dependence was registered in slow two-photon detuning mode, in which data collection time exceeded 1 s. CPT resonance width measured 450 Hz at less than 1% contrast.

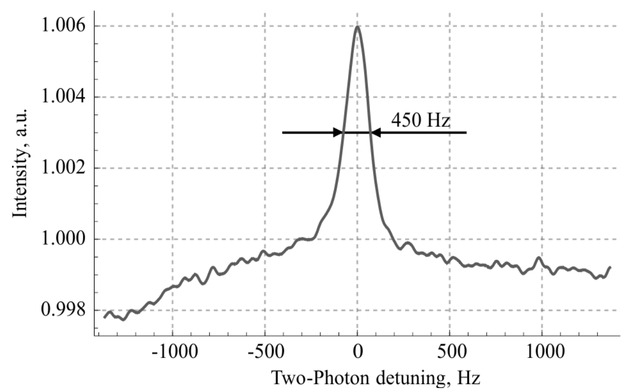


Fig. 3. Coherent population trapping resonance.

At shorter periods or CPT resonance measurement (higher frequency of modulation of the difference between optical frequencies of the bichromatic pump field), its width and contrast varied considerably (Fig. 4 (a)). In Fig. 4 (b), we traced the dependence of CPT resonance width upon the modulation frequency of the frequency difference between the optical components of the bichromatic pump field, where it can be seen that in the modulation frequency range of 10 - 150 Hz, the resonance width grows from 400 Hz to over 3000 Hz. Significant broadening of the CPT resonance results from a relatively long relaxation time of the atomic polarisation in the used cell with an anti-relaxation coating [15].

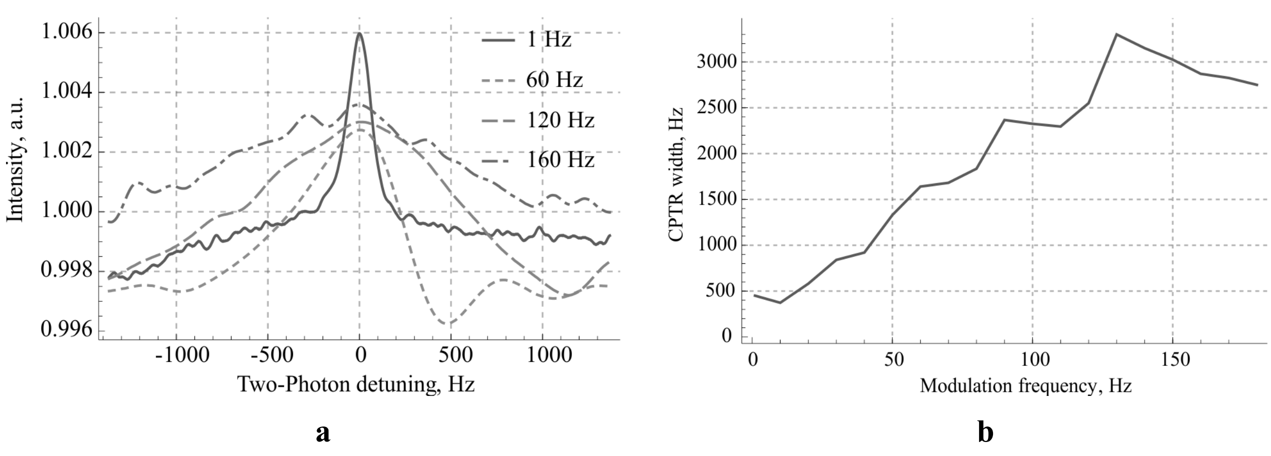


Fig. 4: (a) CPT resonance registered at different modulation frequencies of the frequency difference between the optical components of the bichromatic pump field; (b) CPT resonance width vs. frequency of modulation of the frequency difference between optical components of the bichromatic pump field.

Another salient feature of the studied experimental configuration is the identified significant non-linearity of the dependence of the CPT resonance spectral position upon the base frequency difference as the modulation of the optical frequency difference is varied. At low modulation frequencies (1–30 Hz), the shift of the CPT resonance spectral position corresponded to that of the base difference frequency, whereas at higher modulation frequencies, the CPT resonance spectral shift was substantially larger than the corresponding variation of the base difference frequency. The measured dependence of the ratio of the spectral shift of the CPT resonance and the corresponding shift of the base difference frequency upon the frequency of modulation of the optical frequency difference is presented in Fig. 5.

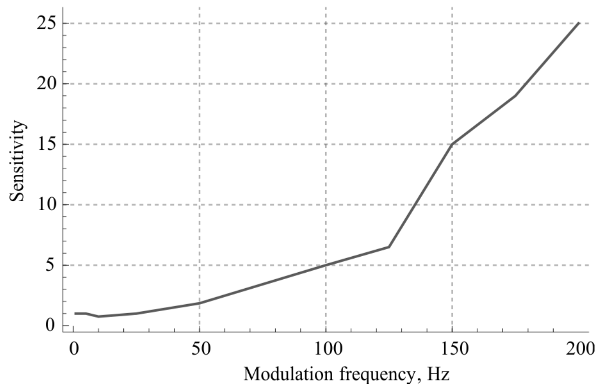


Fig. 5. Dependence of the CPT spectral shift upon the corresponding variation of the base difference frequency at different frequencies of modulation of the optical frequency difference.

As it is obvious from Fig. 5, sensitivity of the CPT resonance spectral position to variations of the base difference frequency grows by a factor of 25 when the frequency of modulation of the optical frequency difference is adjusted from 1 to 200 Hz.

CPT resonance spectral position and width are affected not only by the parameters of modulation of the optical frequency difference of the bichromatic pump field. Optical (light) shift of the CPT resonance is also proportional to the intensity of the optical pump field. Earlier on (for example, in [16–18]) it was shown that when the CPT resonance is formed by the radiation of a laser diode whose injection current is modulated, the amount of the field shift may be considerably reduced by appropriate selection of the amplitude of the injection current modulation. Such optimisation was also carried out during the present work. We measured the CPT resonance shift dependence on the intensity of the laser diode injection current modulation (around 6–7 dBm) at two different levels of optical radiation power, 50 and 100 μW (Fig. 6).

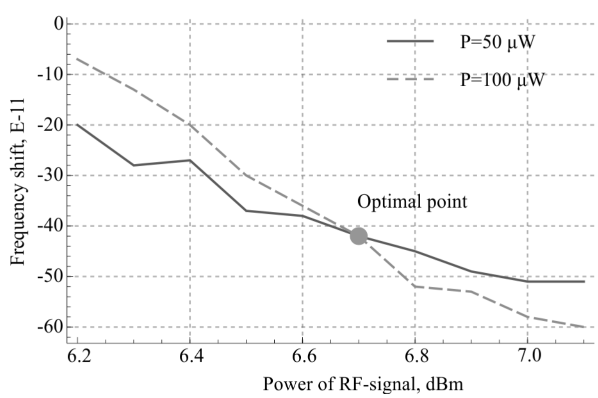


Fig. 6. CPT resonance shift vs. power of RF-signal; the optimal point corresponds to the intensity of the laser diode injection current modulation at which the light shift is minimal.

To measure the pump radiation power, we used an optical filter installed in front of the optical cell. The value of intensity of the laser diode injection current modulation at the point where two recorded dependences intersect corresponds to the optimal value of the intensity of the injection current modulation, at which the field shift of the CPT resonance reaches its minimum.

After our studies and parameter optimisation, we measured the Allan deviation value over the time periods 1–1000 s at the frequency of modulation of the optical frequency difference of the bichromatic pump field equal to 200 Hz (Fig. 7). There it can be seen that the instability of studied the atomic clock is the worst over short periods (up to 10 s), which is related to the effect of low-frequency noise. Raising the modulation frequency to 2 kHz considerably improved stability of the proposed atomic clock (Fig. 8).

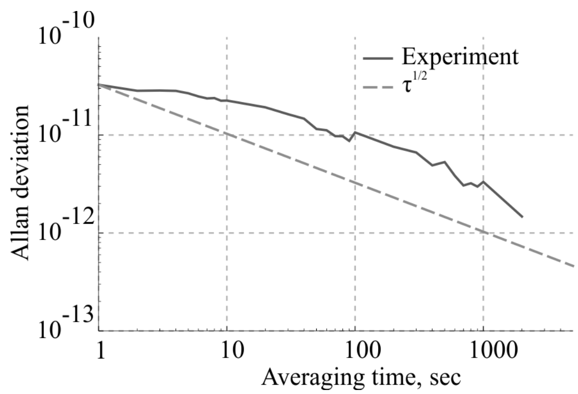
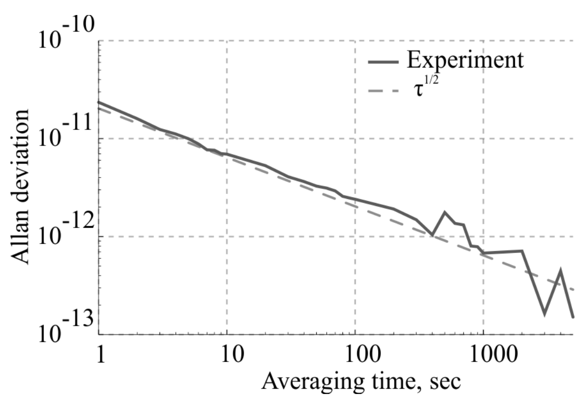


Fig. 7. Allan deviation at the modulation frequency $f_{mod} = 200$ Hz.



Pic. 8. Allan deviation at the modulation frequency $f_{mod} = 2$ кHz.

4. CONCLUSION

The developed laboratory prototype of an atomic clock based on a CPT resonance in ^{87}Rb and a compact spherical cell with the diameter 1.3 cm and containing no buffer gas demonstrated frequency stability of 7×10^{-13} (Allan deviation) over 1000 s, which is a value close to the best theoretically achievable for an anti-relaxation-coated cell of relatively small size used in our experiments. A substantial CPT resonance broadening (from 400 Hz to 3000 Hz) was discovered, which was caused by adjustment in the range of 1–200 Hz of the frequency of modulation of the difference between the optical frequencies of the bichromatic circularly polarised pump field. A significant (by a factor of 25) variation in sensitivity of the CPT resonance spectral position to a corresponding variation of the base difference frequency was identified as the frequency of modulation of the optical frequency difference was adjusted in the range of 1 to 200 Hz.

ACKNOWLEDGMENTS

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