Atomic clock on the basis of the CPT effect in counter-propagating circularly polarised waves

D. Radnatarov*, S. Kobtsev, I. Gromov, P. Kozmina, M. Basalaev, V. Yudin
Novosibirsk State University, Pirogova str., 2, Novosibirsk, Russia 630090

ABSTRACT

This study explores a Rb CPT atomic clock using two counter-propagating waves with orthogonal circular polarisation. By suppressing the optical pumping effect, the clock demonstrates substantial (several times) improvement in CPT contrast compared to the conventional single circularly polarised wave configuration. The use of two counter-propagating beams also allows for positive interference between two photon transitions excited by anti-parallel waves. A double-pass optical layout improves short-term stability by 1.5 times, achieving a result of 4.5×10^{-11} over 1 second using a 5-mm long optical cell.

Keywords: CPT atomic clock, quantum states interference, rubidium atomic clock.

1. INTRODUCTION

Atomic frequency standards play a significant role in modern technology, fundamental research, and navigation. They ensure accuracy and stability of time measurements (and, by extension, also of space) indispensable in many applications such as telecommunications, navigation, and astronomy. Over the recent decades, major effort was directed into development and improvement of miniaturised atomic frequency references for use in mobile and wearable equipment[1]. At the core of these reference devices lies the effect of coherent population trapping (CPT) that occurs when a resonant bi-chromatic laser field interacts with atomic vapour of an alkali metal, which allows observation (and practical application) of a narrow resonant transmission peak as the frequency difference of the field comes close to that of the hyper-fine splitting of the ground state[2].

One of the factors limiting short-term stability of CPT-based atomic clocks is redistribution of a part of the atomic ensemble onto the outermost magnetic sub-level of the ground state under the action of optical pumping[3]. Atoms in this state do not interact with the field and hence do not participate in formation of the reference resonance, thus resulting in its reduced contrast. This effect may be suppressed by restoration of the initial atomic distribution over sub-levels if the CPT resonance is excited with the field of two counter-propagating radiation beams with orthogonal circular polarisations (so-called $\sigma+$-$\sigma-$ field configuration). Compared to the conventional configurations, the CPT resonance contrast may be improved in this case due to two factors: first of all, greater number of atoms that participate in formation of the resonance, and secondly, the effect of interference between CPT states excited by the counter-propagating waves in each atom. Earlier, this approach was explored in [4] where a theoretical possibility of many-fold CPT resonance improvement was presented, and also in [5] where an improvement of CPT resonance contrast was demonstrated by excitation of cold atoms. This work for the first time experimentally studies application of the mentioned-above approach for improvement of CPT resonance contrast in a gas cell with rubidium vapour, and also demonstrates the possibility of improved metrological parameters of atomic clocks.

*d.radnatarov@nsu.ru

Quantum and Nonlinear Optics X, edited by Qiongyi He, Dai-Sik Kim,
Chuan-Feng Li, Proc. of SPIE Vol. 12775, 127751G · © 2023 SPIE
0277-786X · doi: 10.1117/12.2687435

2. EXPERIMENTAL SETUP

Experimental studies were performed on the installation shown in Fig. 1. Essentially, this set-up is an implementation of an atomic frequency standard based on the CPT effect[6] with addition of two optical elements: a quarter-wave plate and a partially reflective mirror inserted between the optical cell and the photo-detector. An acousto-optical modulator was used to control the radiation intensity. We also added a radiation amplitude modulator. The output of a diode laser (VCSEL) emitting at 794.7 nm—which corresponds to the D1 absorption line in rubidium—was collimated with a lens into a beam with a diameter of approximately 1 mm and then passed through the acousto-optical amplitude modulator and the phase plate, acquiring circular polarisation. Further on, this radiation passed through the optical cell with rubidium vapour and a buffer gas, then through the second quarter-wave plate, partially reflected off the mirror and passed again through the wave plate and the optical cell. The radiation transmitted through the mirror was registered with the photo-detector. As a result of the wave plates, the laser beams counter-propagating within the cell had the orthogonal circular polarisation. The cylindrical rubidium cell had the internal volume length of 5 mm and diameter of 4 mm. This cell contained a mix of argon and nitrogen at the pressure of 80 Torr and partial pressure ratio of $PAr/PN_2 \sim 1.47$. The Helmholtz coils created an axial magnetic field along the laser beam for splitting of Seeman sub-levels. The cell was protected from the external magnetic fields with a three-ply μ-metal shield. The highest radiation power at the cell input was 40 μW. The injection current of the diode laser was modulated at the frequency of ~ 3.417 GHz, thus leading to emergence in the laser's output spectrum of equidistant frequency components. For CPT resonance excitation, we used the first +1 and –1 spectral components with a frequency difference of ~ 6.835 GHz corresponding to the hyper-fine splitting frequency of the ground state in rubidium-87. The optical cell assembly with the heater and the magnetic shield could be freely shifted along the laser beam in order to modify the distance from the mirror to the cell centre and hence to control the relative phase of the difference frequency (6.8 GHz) of the reflected radiation passing through the cell.

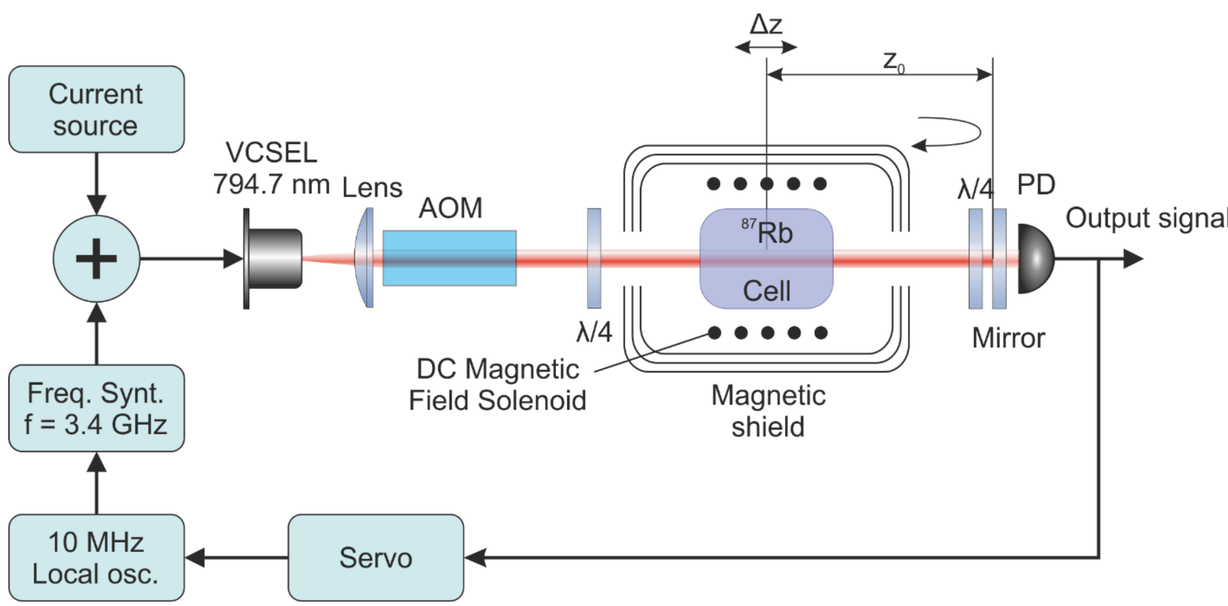

Figure 1. Diagram of the experimental installation. AOM – acousto-optical modulator, VCSEL – vertical-cavity surface-emitting laser, PD – photodetector.

Two mirrors were used in this work: one with a transmittance of 1.5% and the other, 10%. At first, the mirror with the 1.5% transmittance was installed. Such a mirror reflects almost the totality of the incident radiation and therefore the intensity of the counter-propagating beams is almost equal. There is, however, a drawback: the transmitted radiation had low intensity resulting in low signal-to-noise ratio in the feed-back system and thus, high instability of the frequency reference. This is why in subsequent experiments, the mirror with a 10% transmittance was used, instead. In this case, the intensity of the reflected beam did not change significantly, but the level of transmitted signal was almost 6 times as high. This was sufficient for high stability of the frequency reference

3. RESULTS

The first experiments were focused on study of the interference effect of two-photon transitions excited with counter-propagating waves. In order to ensure constructive interference and CPT resonance contrast improvement, it is required that the distance from the centre of the optical cell to the mirror be equal to an odd number of half-waves at the frequency of hyper-fine splitting. For rubidium-87, the difference between maxima was ~22 mm. Fig. 2 presents the contrast dependence vs the mirror displacement. The measured results are in general agreement with the theory: the dependence is periodic with the period length close to the calculated. The highest measured contrast was 2.8%, while in the absence of the mirror, it did not exceed 1.4%. Therefore, the addition of a counter-propagating beam improved the resonance contrast by a factor of two.

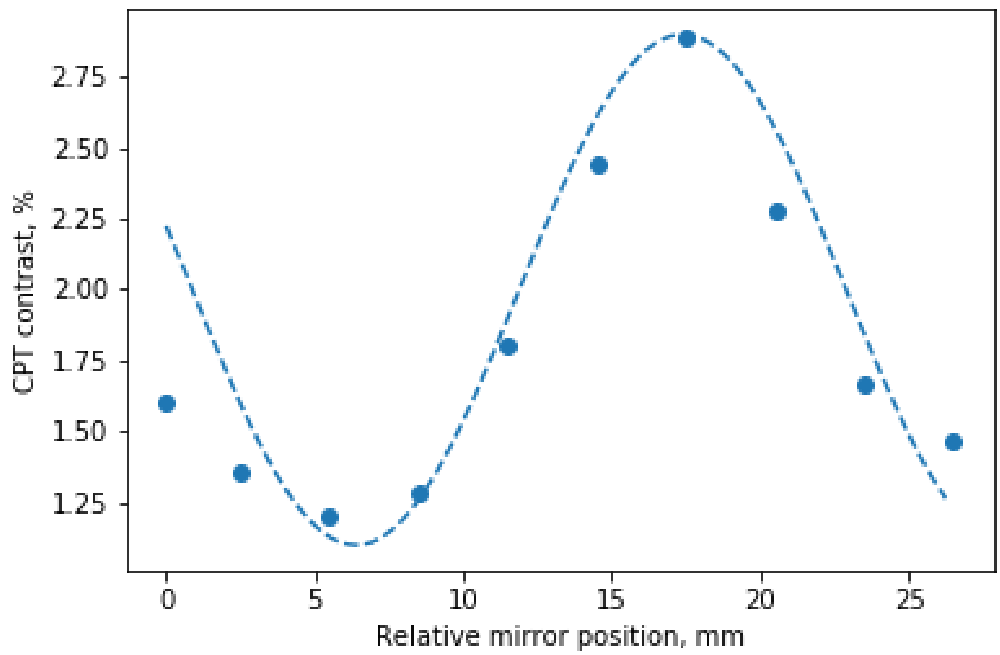

Figure 2. Dependence of the resonance contrast upon Δz (displacement of the optical cell relative to the mirror.

Further on, the dependence of the resonance contrast upon the radiation intensity was also studied. The result is shown in Fig. 3. Our measurements indicate that implementation of a double-pass configuration leads to improvement of the resonance contrast by a factor of 2–4 depending on the intensity. Furthermore, when mirrors are added, the power point at which the best contrast is achieved also shifts higher. In the single-pass configuration, the best contrast was observed at 10 μW, whereas in the double-pass one, the optimal power is in the range of 30–40 μW. The results also demonstrate that the contrast is practically independent of the mirror transmittance. Aside from higher contrast, the presence of the reflected beam also leads to resonance broadening approximately by a factor of 1.5 (see Fig. 4).

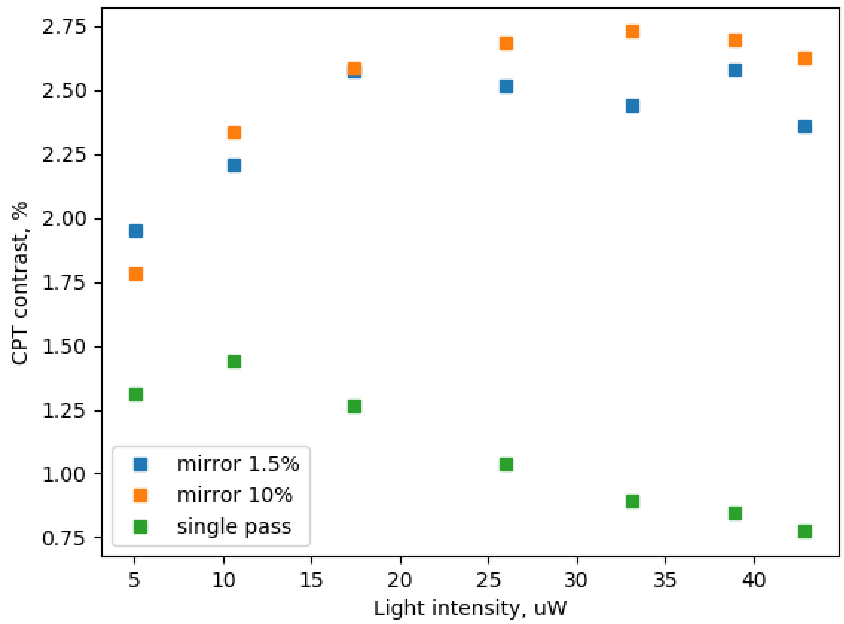

Figure 3. Dependence of the resonance contrast upon the incident radiation power in different conditions.

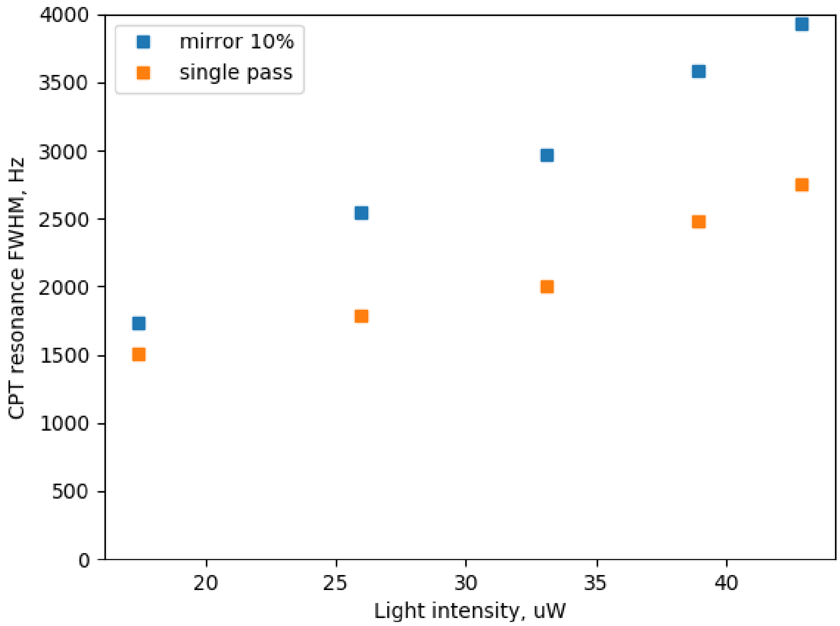

Figure 4. Dependence of the resonance width upon the input power for the mirror with a 10% transmittance and for the single-pass configuration.

Additionally, we measured the instability of the atomic clock in both single- and double-pass configurations (the latter with a 10% mirror). The measurements have shown that the double-pass configuration improved the instability figure over 1 second by a factor of 1.5. Nevertheless, over the averaging times of 10 seconds and longer, instability of the double-pass configuration was dropping slower than that of the single-pass one. We associate such a result with several factors. First of all, the depth of RF modulation was originally optimised for the single-pass version and produces the lowest light field shift [8, 9] specifically for this configuration. In the double-pass system, light field shifts may possibly be larger, as well as the field intensity is higher. Secondly, it is possible that the reflected beam could lead to fluctuations in the radiation parameters when entering the laser [10]. This is why in the future, we are planning to use an optical isolator so that this effect may be ruled out.

4. CONCLUSION

Significant improvement of the CPT resonance contrast is demonstrated in comparison with the conventional configuration having a single beam of pumping radiation. The effect of interference between two-photon transitions excited by counter-propagating waves is also observed. The conditions for constructive interference are defined. The measurements have shown that adoption of the double-pass configuration may improve the resonance contrast by a factor of 2–4 depending on the input radiation power. It was also established that the input power at which the best contrast is achieved shifts higher in the double-pass configuration. Whereas in the single-pass system the best contrast was observed at 10 μW, for the double-pass configuration, the optimal power is around 30–40 μW. Further on, instability of the developed atomic clock was measured both in the single- and in the double-pass (with a 10% mirror) versions. It was shown that the double-pass configuration led to a 1.5 times better short-term instability of the atomic clock and allowed reaching the level of 4.5×10^{-11} over 1 second.

5. ACKNOWLEDGEMENTS

The work was supported by the Russian Science Foundation (grant No. 22-72-10096). The work of D. Radnatarov and S. Kobtsev received support of the Ministry of Science and Higher Education of the Russian Federation (FSUS-2020-0036).

REFERENCES

[1] Kitching, J., “Chip-scale atomic devices,” Appl. Phys. Rev. **5**(3) (2018).

[2] Alzetta, G., Gozzini, A., Moi, L.., Orriols, G., “An experimental method for the observation of r.f. transitions and laser beat resonances in oriented Na vapour,” Nuovo Cim. B **36**(1), 5–20 (1976).

[3] Happer, W., “Optical Pumping,” Rev. Mod. Phys. **44**(2), 169–250 (1972).

[4] Taichenachev, A. V., Yudin, V. I., Velichansky, V. L., Kargapoltsev, S. V., Wynands, R., Kitching, J.., Hollberg, L., “High-contrast dark resonances on the D1 line of alkali metals in the field of counterpropagating waves,” J. Exp. Theor. Phys. Lett. **80**(4), 236–240 (2004).

[5] Liu, X., Yudin, V. I., Taichenachev, A. V., Kitching, J.., Donley, E. A., “High contrast dark resonances in a cold-atom clock probed with counterpropagating circularly polarized beams,” Appl. Phys. Lett. **111**(22), 1–6 (2017).

[6] Khripunov, S., Radnatarov, D.., Kobtsev, S., “Atomic clock based on a coherent population trapping resonance in ^{87}Rb with improved high-frequency modulation parameters,” Proc. SPIE **9378**(March 2015), 93780A (2015).

[7] Kobtsev, S., Donchenko, S., Khripunov, S., Radnatarov, D., Blinov, I.., Palchikov, V., “CPT atomic clock with cold-technology-based vapour cell,” Opt. Laser Technol. **119**(May), 105634, Elsevier Ltd (2019).

[8] Miletic, D., Affolderbach, C., Hasegawa, M., Boudot, R., Gorecki, C.., Mileti, G., “AC Stark-shift in CPT-based Cs miniature atomic clocks,” Appl. Phys. B **109**(1), 89–97 (2012).

[9] Levi, F., Godone, A.., Vanier, J., “The light shift effect in the coherent population trapping cesium maser,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**(2), 466–470 (2000).

[10] Engelbrecht, R., Lins, B., Zinn, P., Buchtal, R.., Schmauss, B., “Line shapes of near-infrared DFB and VCSEL diode lasers under the influence of system back reflections,” Appl. Phys. B **109**(3), 441–452 (2012).