ISSN 0021-3640, JETP Letters, 2023, Vol. 117, No. 7, pp. 504–508. © The Author(s), 2023. This article is an open access publication.
Russian Text © The Author(s), 2023, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2023, Vol. 117, No. 7, pp. 504–508.

OPTICS
AND LASER PHYSICS

Active Suppression of the Light Shift in an Atomic Clock Based on Coherent Population Trapping in ^{87}Rb Vapor Using the Phase Jump Technique

D. A. Radnatarov[a], *, S. M. Kobtsev[a], V. A. Andryushkov[a], M. Yu. Basalaev[a, b, c], A. V. Taichenachev[a, b], M. D. Radchenko[a, c], and V. I. Yudin[a, b, c], **

[a] *Novosibirsk State University, Novosibirsk, 630090 Russia*
[b] *Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
[c] *Novosibirsk State Technical University, Novosibirsk, 630073 Russia*
**e-mail: d.radnatarov@gmail.com*
***e-mail: viyudin@mail.ru*

Received February 28, 2023; revised March 3, 2023; accepted March 3, 2023

The active suppression of light shift of the reference coherent population trapping (CPT) resonance in ^{87}Rb vapor to improve the long-term stability of compact atomic clocks has been demonstrated experimentally. The approach is based on the phase jump technique used to synthesize an error signal, which is proportional to the light shift of the CPT resonance, from an optical transmission signal. The use of this error signal in an additional feedback loop allows one to stabilize the amplitude of a microwave signal for the phase modulation of laser radiation near a value at which the light shift of the CPT resonance is absent. This technique has made it possible to reduce the long-term instability of CPT atomic clocks in our experiments by a factor of 15 at an integration time of 10000–20000 s.

DOI: 10.1134/S0021364023600532

Coherent population trapping (CPT) resonances provide the foundation of a modern approach to the fabrication of compact atomic clocks [1, 2]. These devices have a low energy consumption, light weight, and small dimensions and have numerous applications in built-in and mobile navigation and communication devices. One of the factors that currently limit the field of application of such devices is a rather high instability at averaging times longer than 1000 s caused by light shifts of the reference CPT resonance [3].

As known, the reference resonance in CPT atomic clocks is excited by a field formed at microwave phase modulation of monochromatic radiation when an equidistant set of spectral components with the frequency difference equal to the modulation frequency arises [4]. In this case, only two resonant components spaced by the hyperfine splitting frequency of the ground state of alkali metal atoms (e.g., 6.835 GHz for ^{87}Rb) are involved in the excitation of the CPT resonance. Although the other components inevitably appearing under phase modulation are not involved in the excitation of the resonance, they noticeably affect its frequency because of the dynamic Stark effect (quadratic Stark shift). This effect transfers the negative influence of fluctuations of the laser radiation power, aging of cells (change in the transmittance of optical cell windows [3]), fluctuations of the microwave signal amplitude, and fluctuations of the temperature of cells [5] (because change in the optical density of the medium can also affect the light shift) to the long-term stability of atomic clocks. Furthermore, the motion of atoms and collisions with the walls of a gas cell also can affect the shape and shift of the resonance [6–9].

The light shift depends on the distribution of the amplitudes of spectral components and is determined by the phase modulation depth. At a certain microwave modulation depth, the total light shift (from all frequency components) of the CPT resonance is zero [10]. Several methods were previously proposed to reduce the effect of the light shift in CPT atomic clocks: careful selection of the power of microwave modulation [11], compensation of frequency detuning [12], compensation of cell aging [13], use of a cell with gold microdisks to prevent the sedimentation of an alkali metal on windows [14], comparison of CPT resonance frequencies at two optical powers [15, 16], and use of various modifications of Ramsey spectroscopy [17–22]. However, these methods require an external modulator of the laser radiation power (acousto-optic modulator), which limits their implementation in compact atomic clocks because it increases the dimensions and energy consumption of devices.

To suppress the light shift without the variation of the radiation power, we propose to use the phase jump technique [23] to form the error signal in a laser beam with a spatially inhomogeneous intensity profile (e.g., Gaussian profile). As shown in [24], because of the light shift, the position of the zero of the error signal in this case depends on the integration time of the dynamic part in the transmission signal after a phase jump. For this reason, we proposed in [24, 25] to use two different (long and short) integration times to generate two different error signals. When the frequency of the clock transition has the light shift, zeros of these error signals are at different points in two-photon detuning, whereas the positions of these zeros in the absence of the light shift coincide. This property can be used to form an additional feedback loop, which will stabilize the power of microwave modulation at a level such that the light shift of the CPT resonance disappears.

In this work, we report the results of the experimental test of a method [24] for the active suppression of light shift of the CPT resonance. The reduction of the long-term instability of the CPT atomic clock by more than an order of magnitude at an integration time of 10000–20000 s is demonstrated.

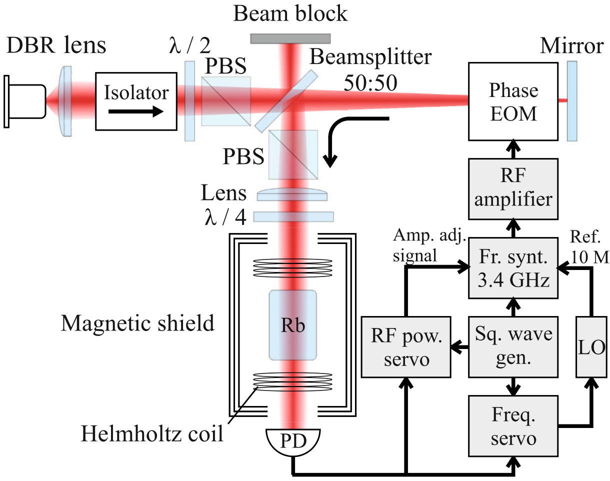

Fig. 1. (Color online) Layout of the experimental setup: (DBR) diode laser with a distributed Bragg reflector, (Phase EOM) electro-optic phase modulator, (λ/2) half-wave phase plate, (PBS) polarizer, (λ/4) quarter-wave phase plate, (LO) 10-MHz quartz oscillator, (Fr. synt.) microwave synthesizer, (Sq. wave gen.) square-wave generator, (RF pow. servo) self-tuning system for the microwave signal amplitude, and (Freq. servo) frequency stabilization system for the quartz oscillator.

The layout of the experimental setup is presented in Fig. 1. The radiation of a diode laser at a wavelength of 794.7 nm, which corresponds to the D1 ^{87}Rb absorption line, was focused by a lens on a mirror, which ensured the double passage of radiation through an electro-optic phase modulator (NewFocus$^{\mathrm{TM}}$ 4431); a 1 : 1 beam splitter plate was used to separate modulated radiation. The electro-optic modulator was applied to modulate the phase of radiation at a frequency of 3.417 GHz, which is half the hyperfine splitting frequency of rubidium (6.835 GHz). Modulation results in the set of equidistant spectral lines spaced by the modulation frequency. Side first-order frequencies were used to excite the resonance. A Faraday optical isolator was utilized to protect the diode laser from reflected radiation. To control the radiation power, we used a polarization beam splitter (PBS) and half-wave phase plate (λ/2). The polarization beam splitter PBS was placed at the position corresponding to the horizontal polarization of output radiation, which is necessary for the correct operation of the electro-optic modulator. The two-pass scheme of phase modulation is necessary because the maximum allowed power of the microwave signal supplied at the input of the electro-optic modulator EOM is 4 W, which allows one to obtain the maximum phase modulation index of 1.9 in one passage. The two-pass scheme makes it possible to increase the modulation index by a factor of $\sqrt{2}$ and to reach a modulation index of 2.4, which is necessary to suppress the light shift of the CPT resonance [10]. The prepared radiation passed through a quarter-wave phase plate and acquired the circular polarization, which is necessary to excite the CPT resonance. The laser beam passed through a rubidium cell and reached a photodetector (PD). The cylindrical rubidium cell has the internal volume with a length of 5 mm and a diameter of 4 mm [26]. Helmholtz coils induce a parallel magnetic field along the laser beam in order to split Zeeman sublevels. The cell was isolated from the external magnetic field by a shield consisting of three μ-metal layers.

The phase jump technique implies the rectangular phase modulation of the microwave signal to observe the CPT resonance. Figure 2 shows the transmission signal detected by the photodetector at zero detuning of the frequency from the resonance. To generate the error signal for the stabilization loop of the quartz oscillator for the CPT resonance, we used a lock-in amplifier; the signal from the photodetector was supplied to one input of this amplifier and the signal modulating the phase of the microwave signal was guided to its second input; in other words, the error signal is equal to the integral of the transmission signal multiplied by the modulating signal [23]. We used the distributed Bragg reflector diode laser with an external phase modulator rather than a vertical-cavity surface-emitting laser with the direct microwave modulation of the injection current because this approach makes it possible to form radiation with amplitude-symmetric side spectral components, which guarantees the suppression of the light shift of the resonance.

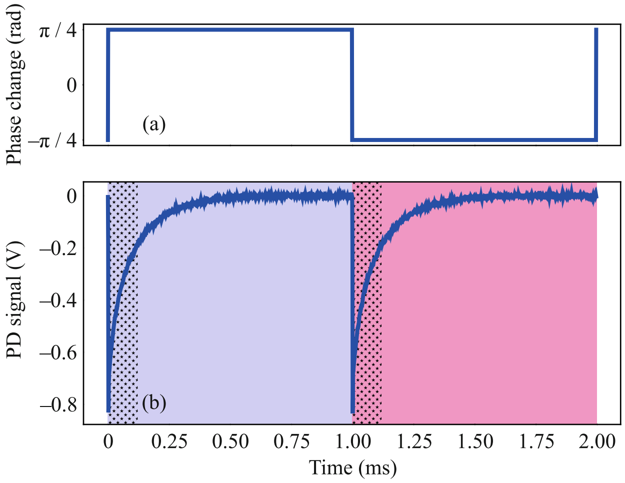

Fig. 2. (Color online) Schematic of the detection of the CPT resonance with the phase jump technique. (a) Phase of the microwave signal. (b) Transmission signal from the photodetector; the blue and red regions correspond to the parts of the signal after the up and down phase jumps, respectively; the shaded regions correspond to the parts of the signal used to synthesize the error signal, which is proportional to the light shift.

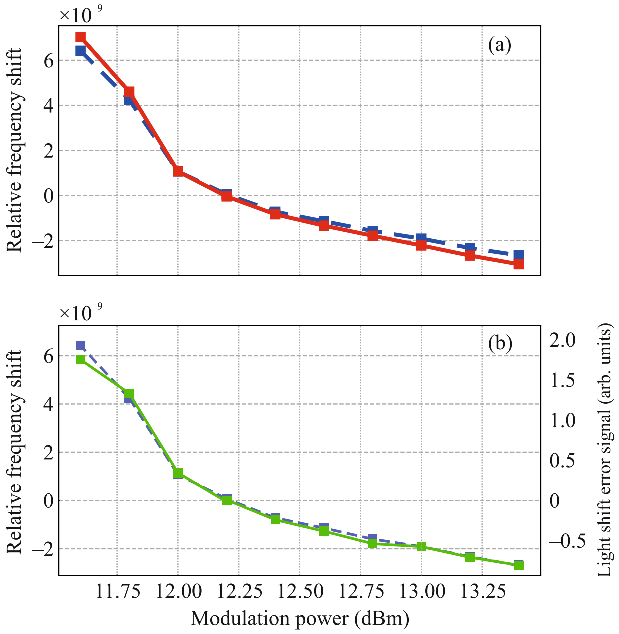

Fig. 3. (Color online) Measured (a) light shift of the CPT resonance at an optical radiation power of (blue dashed line) 10 and (red solid line) 20 μW and (b) (blue dashed line) light shift of the CPT resonance and (green solid line) the error signal at an optical radiation power of 10 μW versus the power of the modulating microwave signal.

Figure 3a presents the dependences of the relative shift of the CPT resonance on the microwave signal power at different optical radiation powers. It is seen that plots intersect at a microwave signal power of about 12 dBm. The point of intersection corresponds to the phase modulation amplitude at which the light shift is suppressed. Furthermore, information on the magnitude and sign of the light shift of the resonance can be extracted from the transmission signal. To this end, following [24], it is necessary to integrate only a relatively narrow time interval of the signal from the photodetector after the phase jump when the fastest dynamics of the transmission signal is observed (see Fig. 2b). The error signal thus synthesized is proportional to the light shift and, as seen in Fig. 3b, it has the form of the dependence of a similar frequency shift on the microwave modulation power and vanishes at the microwave modulation power corresponding to the suppression of the light shift. As a result, it is possible to create a feedback loop to actively suppress the light shift by the self-tuning of the microwave modulation power for the error signal to be zero.

The direct measurement of the stability of the atomic frequency standard with and without the feedback loop for the suppression of the light shift confirms that the developed method allows one to suppress the light shift of the CPT resonance and thereby to significantly improve the long-term stability of the laboratory CPT atomic frequency standard. The results of this measurement are presented in Fig. 4, where it is seen that the method made it possible to reduce the long-term instability of the atomic clock by a factor of 15 (from 7.6×10^{-12} to 5.1×10^{-13}) at an average time of 20000 s and almost to reach a theoretical value of long-term instability (4.0×10^{-13}), which is caused by short-term instability (5.6×10^{-11} per second).

It is noteworthy that the duration of the measurements in our experiments was limited to ~8 h because new buildings of a university were built near our laboratory. For this reason, the measurements were carried out only at nighttime when heavy equipment was not in use. It is also worth noting that the total optical path length was about 1.5 m. The entire optical path was surrounded by plastic screens to protect the elements of the setup from air flows. However, this measure incompletely suppressed fluctuations of the temperature of the elements of the setup that rather strongly affected the stability of the frequency standard in the time interval up to 5000 s, which is manifested in the characteristic “hump” in the stability plot.

To summarize, a method for the active suppression of light shifts of the reference resonance in the CPT atomic clock without the modulation of the laser radiation power has been demonstrated experimentally. The phase jump technique has been used to form the error signal, which is proportional to the light shift. The use of this error signal in an additional feedback loop allows one to stabilize the amplitude of a microwave phase modulation of laser radiation near a value at which the light shift of the CPT resonance is absent. This technique has made it possible to reduce the long-term instability of CPT atomic clocks in our

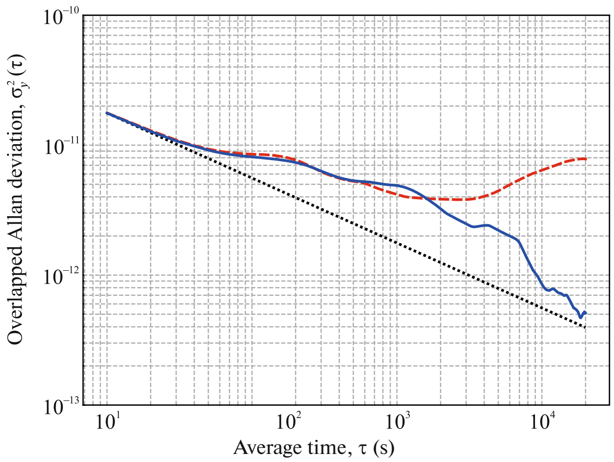

Fig. 4. (Color online) Time dependences of (red dashed and blue solid lines) the measured instability of CPT atomic clocks (red dashed line) without and (blue solid line) with the active suppression of the light shift and (dash-dotted straight line) the theoretical instability $5.6\times10^{-11}/\sqrt{\tau}$ of the passive frequency standard.

experiments in a cell with ^{87}Rb vapor by a factor of 15 to 5.1×10^{-13} at an integration time of 10 000–20 000 s and almost to reach a theoretical value of long-term instability (4.0×10^{-13}), which is caused by short-term instability (5.6×10^{-11} per second).

FUNDING

This study was supported by the Russian Science Foundation (project no. 21-12-00057) and by the Ministry of Science and Higher Education of the Russian Federation (state assignment no. FSUS-2020-0036, development of a system for active control of the parameters of optical pump radiation).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

OPEN ACCESS

REFERENCES

1. J. Kitching, Appl. Phys. Rev. **5**, 031302 (2018).
2. P. Cash, W. Krzewick, P. MacHado, K. R. Overstreet, M. Silveira, M. Stanczyk, D. Taylor, and X. Zhang, in *Proceedings of the 2018 European Frequency and Time Forum (EFTF), Turin, Italy* (2018), p. 65.
3. J. Camparo, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **52**, 1075 (2005).
4. N. Cyr, M. Tetu, and M. Breton, IEEE Trans. Instrum. Meas. **42**, 640 (1993).
5. D. Radnatarov, S. Kobtsev, V. Andryushkov, and T. Steschenko, in *Applied Optical Metrology IV,* Proc. SPIE **11817**, 118170O (2021).
6. A. N. Litvinov and I. M. Sokolov, JETP Lett. **113**, 763 (2021).
7. K. A. Barantsev, A. S. Kuraptsev, and A. N. Litvinov, J. Exp. Theor. Phys. **133**, 525 (2021).
8. Ya. A. Fofanov and I. M. Sokolov, J. Exp. Theor. Phys. **135**, 255 (2022).
9. K. A. Barantsev, G. V. Voloshin, A. S. Kuraptsev, A. N. Litvinov, and I. M. Sokolov, J. Exp. Theor. Phys. **136** (2023, in press).
10. M. Zhu and L. S. Cutler, in *Proceedings of the 32nd Annual Precise Time and Time Interval Systems and Applications Meeting, Reston, Virginia, November, 2000,* p. 311.
11. R. Boudot, P. Dziuban, M. Hasegawa, R. K. Chutani, S. Galliou, V. Giordano, and C. Gorecki, J. Appl. Phys. **109**, 014912 (2011).
12. Y. Zhang, W. Yang, S. Zhang, and J. Zhao, J. Opt. Soc. Am. B **33**, 1756 (2016).
13. S. Yanagimachi, K. Harasaka, R. Suzuki, M. Suzuki, and S. Goka, Appl. Phys. Lett. **116**, 104102 (2020).
14. S. Karlen, T. Overstolz, J. Gobet, J. Haesler, F. Droz, and S. Lecomte, in *Proceedings of the 2018 European Frequency and Time Forum (EFTF), Turin, Italy* (2018), p. 91.
15. V. I. Yudin, M. Yu. Basalaev, A. V. Taichenachev, J. W. Pollock, Z. L. Newman, M. Shuker, A. Hansen, M. T. Hummon, R. Boudot, E. A. Donley, and J. Kitching, Phys. Rev. Appl. **14**, 024001 (2020).
16. M. Abdel Hafiz, R. Vicarini, N. Passilly, C. E. Calosso, V. Maurice, J. W. Pollock, A. V. Taichenachev, V. I. Yudin, J. Kitching, and R. Boudot, Phys. Rev. Appl. **14**, 034015 (2020).
17. V. I. Yudin, A. V. Taichenachev, M. Yu. Basalaev, T. Zanon-Willette, J. W. Pollock, M. Shuker, E. A. Donley, and J. Kitching, Phys. Rev. Appl. **9**, 054034 (2018).
18. M. Abdel Hafiz, G. Coget, M. Petersen, C. Rocher, S. Guérandel, T. Zanon-Willette, E. de Clercq, and R. Boudot, Phys. Rev. Appl. **9**, 064002 (2018).
19. M. Shuker, J. W. Pollock, R. Boudot, V. I. Yudin, A. V. Taichenachev, J. Kitching, and E. A. Donley, Phys. Rev. Lett. **122**, 113601 (2019).

20. V. I. Yudin, A. V. Taichenachev, M. Yu. Basalaev, T. E. Mehlstäubler, R. Boudot, T. Zanon-Willette, J. W. Pollock, M. Shuker, E. A. Donley, and J. Kitching, New J. Phys. **20**, 123016 (2018).
21. M. Shuker, J. W. Pollock, R. Boudot, V. I. Yudin, A. V. Taichenachev, J. Kitching, and E. A. Donley, Appl. Phys. Lett. **114**, 141106 (2019).
22. M. Yu. Basalaev, V. I. Yudin, D. V. Kovalenko, T. Zanon-Willette, and A. V. Taichenachev, Phys. Rev. A **102**, 013511 (2020).
23. M. Y. Basalaev, V. I. Yudin, A. V. Taichenachev, M. I. Vaskovskaya, D. S. Chuchelov, S. A. Zibrov, V. V. Vassiliev, and V. L. Velichansky, Phys. Rev. Appl. **13**, 034060 (2020).
24. V. I. Yudin, M. Yu. Basalaev, A. V. Taichenachev, D. A. Radnatarov, V. A. Andryushkov, and S. M. Kobtsev, J. Phys.: Conf. Ser. **2067**, 012003 (2021).
25. V. Andryushkov, D. Radnatarov, S. Kobtsev, M. Basalaev, and V. Yudin, in *Proceedings of the 15th Pacific Rim Conference on Lasers and Electro-Optics CLEO-PR 2022, July 31–Aug. 5, 2022, Sapporo, Japan* (2022), P-CTh6-01.
26. S. Kobtsev, S. Donchenko, S. Khripunov, D. Radnatarov, I. Blinov, and V. Palchikov, Opt. Laser Technol. **119**, 105634 (2019).

Translated by R. Tyapaev