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Technique of pulsed optical pumping and pulsed excitation of microwave resonances using the Ramsey scheme in a ^{87}Rb cell with a buffer gas

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Abstract. **A laboratory prototype of a compact quantum frequency standard based on a rubidium vapour cell with pulsed laser pumping is developed. With significantly smaller overall dimensions (a volume of ~10 L and a mass of ~10 kg), the frequency standard is expected to have the short-term instability comparable with that of the commercial passive hydrogen masers and even the laboratory fountain-type atomic clocks based on cold atoms. The advantages of the technique of pulsed optical pumping and pulsed excitation of microwave resonances over the traditional techniques of double radio-optical resonance detection are substantiated. The results of the experimental study of pulsed optical pumping of a rubidium cell with a mixture of buffer Ar–Ne gases implemented at the VNIIFTRI are presented, the Ramsey resonances are obtained, and the process of optimising the contrast of the central resonance peak is described.**

Keywords: *quantum frequency standard with a rubidium vapour cell, pulsed optical pumping, Ramsey scheme of microwave excitation, diode laser, saturated absorption spectroscopy, modulation transfer spectroscopy, acousto-optic modulator, Raman–Nath diffraction.*

1. Introduction

Currently, a vital need exists for compact (a mass of ~10 kg and a volume of ~10 L) quantum frequency standards (QFS's) possessing a short-term instability better than 5 × 10^{-13} (the averaging time 1 s) and a long-term instability at a level of 10^{-15} (the averaging time 10^5 s). Such QFS's can be applied in radio navigation systems, as well as for synchronisation of telecommunication networks and local time scales, including on-board ones. However, the existing microwave QFS's (including atomic beam tubes with magnetic selection of quantum states, atomic beam tubes with laser pumping, fountain-type clocks based on cold atoms, hydrogen frequency standards of active type, passive hydrogen frequency standards, and rubidium vapour cell frequency standards with lamp optical pumping) do not satisfy up-to-date requirements to on-board QFS's for rapidly progressing global navigation satellite systems, including GLONASS, by at least some of the parameters (instability, mass and overall dimensions, energy consumption, reliability of operation).

The passive hydrogen frequency standards and the rubidium vapour cell frequency standards are most close to the above requirements in instability and in mass-dimensional parameters and reliability, respectively. Although the existing commercial rubidium frequency standards (RFS's) based on the technology of double radio-optical resonance in a lamp-pumped cell demonstrate satisfactory characteristics and high reliability in both on-board and ground-based systems, their instability in principle cannot be better than 10^{-12} during 1 s, which is far above the limit level, determined by shot noises of the clock signal photodetection process.

The instability $\sigma(\tau) \approx (4 \times 10^{-12}–3 \times 10^{-11})\tau^{-1/2}$ (for the averaging time $\tau = 1–10^3$ s) of the clock transition frequency in industrially produced RFS's, divided according to the metrological characteristics into the consumer groups of commercial, military, and space application, is mainly determined by its strong dependence on the intensity and frequency instability of the optical radiation due to the light shift effect (dynamic Stark effect). This is a general drawback of microwave frequency standards with continuous lamp and even laser optical pumping [1].

However, in the 1960s an idea was proposed [2], the implementation of which could considerably decrease the light shift value and, therefore, the instability of frequency standards using optically pumped gas cells. The idea was to separate in time the three phases of QFS operation, i.e., optical pumping, pulsed microwave interrogation according to the Ramsey scheme, and optical detection. The mutual influence of different signals is minimised, and the clock transition occurs only when the laser radiation is absent in the cell, which provides essential suppression of the light shift. The up-to-date technological capabilities of diode lasers and digital electronics allowed an extremely efficient implementation of this original idea [3–5]. According to Ref. [3], in the laboratory version of a compact frequency standard using a rubidium cell with a mixture of buffer gases, pulsed optical pumping (POP) and pulsed Ramsey microwave excitation, the frequency instability was about 2 × 10^{-13} and 2 × 10^{-15} during 1 s and 10^4 s, respectively, the daily drift of the frequency being smaller than 1 × 10^{-14}.

It should be noted that at present an alternative version of a vapour-cell QFS is under development, namely, a QFS with pulsed excitation of coherent population trapping (CPT) resonances [6, 7]. Although the technique of continuous excitation of CPT resonances in vapour cells with buffer gases allows obtaining narrow (25–50 Hz wide) lines of the clock transition, the record-breaking stabilities of the CPT-based QFS amount to only a few parts in 10^{-12} for the averaging time 1 s.

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In the technique of pulsed CPT resonance excitation [6] in a cell with a buffer gas according to the Ramsey scheme, the coherence evolution of atomic states that form the clock transition occurs when the cell is free of laser radiation, as in the POP technique. The contrast of the clock transition line, comparable with that in the POP technique [7], depends only on the duration of the first pulse of the CPT excitation and the interval between it and the detection pulse. Since no cavity is used in the technique of pulsed excitation of CPT resonances in the cell with a buffer gas according to the Ramsey scheme, the QFS design is simplified and the mass and size parameters of the QFS physical part can be reduced. However, the necessity of bichromatic laser radiation for exciting the CPT resonances increases the volume of the QFS laser unit if this radiation is generated by two phase-correlated laser sources. Moreover, if the bichromatic radiation is generated by phase modulation of the radiation from a single laser by means of an electro-optic modulator, then to avoid the additional light shift of the clock transition frequency special efforts are needed to suppress the undesired nonresonance components in the radiation spectrum [7].

This paper presents the results of designing a laboratory prototype of a rubidium QFS with POP. We briefly describe the physical part of the laser system that forms the radiation at the wavelength, corresponding to the D_2 line of the Rb atom, the spectroscopy unit with the integrated acousto-optic modulators (AOMs) implementing the functions of an optical phase modulator and a generator of optical pulses, the system producing the interrogation microwave signal (6.834 GHz), and the digital control system forming all optical and electrical signals of the QFS prototype, including the signal of automatic frequency tuning of the quartz oscillator. The Ramsey fringe is measured and the process of its central peak contrast optimisation is described.

2. Experimental setup and results

The results of the first experimental studies of the method of pulsed optical pumping in a ^{87}Rb cell performed at the laboratory bench were presented in Ref. [8]. At present, the development of the QFS prototype with POP is aimed at minimising overall dimensions of individual systems and units at the expense of using compact laser sources and special acousto-optic devices, as well as the search for spectroscopic methods that provide long-term stability of the parameters of automatic frequency control of the laser radiation.

Our prototype of the QFS with POP consists of three main parts: the physical part, comprising the ^{87}Rb cell with a mixture of buffer Ar–Ne gases under a total pressure of 14.7 Torr and a ratio of partial pressures of 0.5, placed in a cylindrical resonator; the laser system with spectroscopic units and the generator of optical pulses; the synthesiser of interrogation signal (6.834 GHz); and the control system.

The cell with ^{87}Rb atomic vapour placed in the cylindrical resonator with the TE_{011} mode and moderate Q-factor of about 1000 contains the two-component mixture of buffer gases to compensate for the collision-induced frequency shift of the clock transition and to increase the time of atom localisation within the laser beam 10 mm in diameter. The resonator and the cell are located inside the solenoid, generating a longitudinal magnetic field (along the resonator axis) intended to remove the degeneracy of magnetic quantum states. The physical part is shielded from the external magnetic fields and temperature stabilised. This part of the prototype was not changed.

The choice of the laser source type for the compact rubidium vapour-cell QFS, as well as its spectral characteristics, is substantiated in detailed theoretical and experimental studies presented in Ref. [3]. In the same paper, the choice of the D_2 line ($\lambda = 780.24$ nm) of the ^{87}Rb isotope for pump and detection is substantiated, too. In the frequency standard using a vapour cell with POP, microwave excitation according to the Ramsey scheme and optical detection of the clock transition, the spectral width of laser radiation directly affects the frequency instability. The amplitude fluctuations of the probe detection radiation, by means of which the clock signal is formed, restrict the short-term stability of the atomic clock with POP and optical detection. Since this additional noise manifests itself only during the registration of the probe laser pulse, its contribution to the QFS instability, expressed as Allan variance, can be presented in the same form as the contribution of the noise due to the Dick effect [3]:

$$\sigma_y^{\mathrm{an}}(\tau) = \frac{1}{CQ_{\mathrm{line}}}\left[\sum_{n=1}^{\infty} \mathrm{sinc}^2\left(n\pi\frac{T}{T_{\mathrm{c}}}\right)S_{\mathrm{an}}(nf_{\mathrm{c}})\right]^{1/2}\tau^{-1/2}, \qquad (1)$$

where T_{c} is the duration of a single measurement cycle, including a pump pulse, two Ramsey pulses, and a probe optical pulse (Fig. 1); f_{c} is the cycle repetition rate; T is the time interval between the end of the first Ramsey pulse and the beginning of the second one; C is the central peak contrast of the Ramsey fringe; Q_{line} is the line Q-factor; and $S_{\mathrm{an}}(nf_{\mathrm{c}})$ is the spectral power density of amplitude noises, recorded at the photodetector. In the quantity $S_{\mathrm{an}}(nf_{\mathrm{c}})$ both the residual intensity noise of the laser radiation that is transferred to the probe signal and the frequency noises of the radiation converted into the amplitude fluctuations are taken into account.

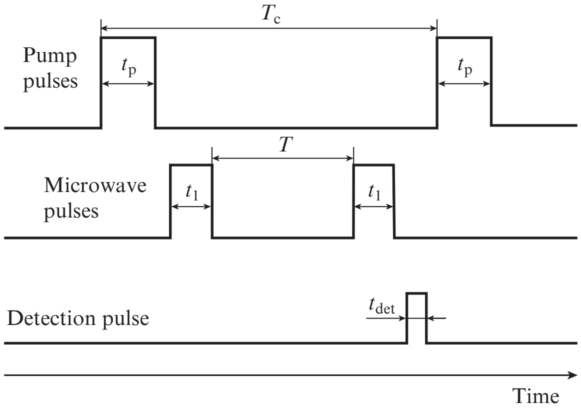

Figure 1. Time sequences of pump, microwave, and detection pulses.

For the alkali caesium and rubidium atoms, at a small width of the laser radiation spectrum (about 1 MHz or less) the contribution to instability due to the conversion of frequency noises to the amplitude fluctuations can be reduced by nearly an order of magnitude [3] as compared to the contribution to instability introduced by the laser source with the radiation spectrum width 10–20 MHz.

The laser diode with distributed Bragg reflection and the radiation spectrum width below 1 MHz provides an output radiation power of no less than 80 mW at the wavelength

780.24 nm, which is sufficient for the rubidium atomic vapour spectroscopy, the formation of optical pulses for pump and detection, as well as for spatial filtering of radiation, implemented by introducing part of radiation into the single-mode polarisation-maintaining optical fibre cable (Fig. 2).

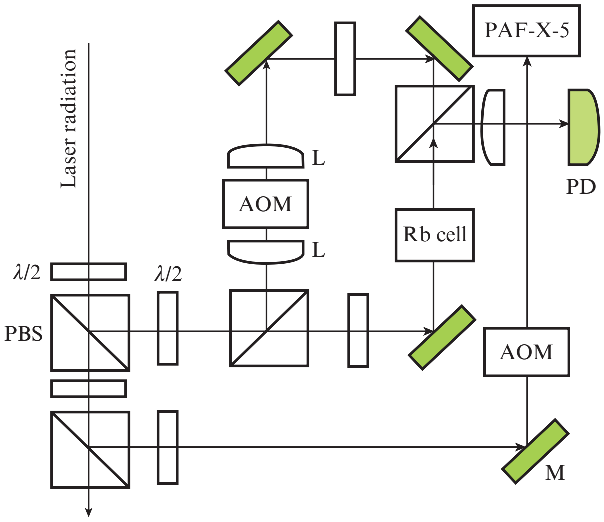

Figure 2. Schematic of the experimental setup for performing saturated absorption and modulation transfer spectroscopy:
(PD) photodetector; (PBS) polarising beam splitter; (M) mirror; (L) lens; ($\lambda/2$) half-wave plate; (PAF-X-5) optical fibre port.

The universal spectroscopic unit allows both saturated absorption spectroscopy in the control rubidium vapour cell and modulation transfer spectroscopy (MTS). The latter is implemented by means of the AOM specially designed at the VNIIFTRI for this spectroscopic technique. The AOM operates in the Raman–Nath diffraction mode [9, 10] as a phase modulator with the modulation frequency band 4–10 MHz. The MTS technique allows achieving high long-term stability of the zero of the frequency-tuning signal that does not depend on the residual effects of linear absorption, such as a temporal change in the laser radiation intensity, temperature fluctuations, and fluctuations of the radiation polarisation or the magnetic field. This is the main advantage of MTS over other methods of frequency stabilisation of diode lasers in the design of QFS's with high long-term stability.

In Refs [3, 4, 8] the optimal pump parameters were provided by shifting the laser radiation frequency, locked to the frequency of the saturated absorption cross-resonance $5S_{1/2}(F = 1) \leftrightarrow 5P_{3/2}(F' = 1, 2)$ at –170 MHz in a separate cell with a natural mixture of rubidium atom isotopes. A 1205C-2-804B AOM (www.isomet.com) in a cat's eye double-pass configuration was used [6] as a generator of optical pump and detection pulses, as an optical switch, and also for the frequency shift of the radiation.

A single-pass acousto-optic device for shifting the frequency by –170 MHz was specially constructed at the VNIIFTRI to reduce the dimensions of the AOM unit in a cat's eye double-pass configuration, comprising a cubic beam splitter, an AOM, a quarter-wave plate, a lens, a gate, and a mirror. The device operates in the Bragg anisotropic diffraction mode (Fig. 3) and can significantly reduce (almost by an order of magnitude) the volume of the modulator unit in the QFS with POP.

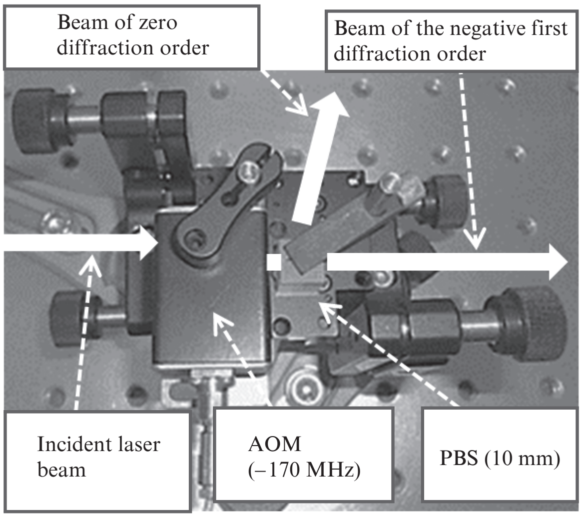

Figure 3. Single-pass AOM (–170 MHz) operating in the Bragg anisotropic diffraction mode and the geometry of diffracted beams (PBS is a polarising cubic beam splitter).

At a fixed modulation frequency, the beam incident on the AOM and the diffracted beam are parallel to each other with a displacement smaller than 0.3 mm. The angle between the beams of the first and the second diffraction order, outgoing from the AOM, amounts to 10°. Due to the anisotropic diffraction character, these beams possess mutually orthogonal polarisations, which makes it easy to separate them by placing a polariser at the AOM output. The AOM dimensions are 48 × 25 × 23 mm. The diffraction efficiency at the radiation wavelength 780 nm and the power 200 mW of the modulation signal applied to the AOM was equal to 85%, the AOM modulation bandwidth was 20 MHz, and the diameter of the active aperture amounted to 2 mm. The degree of radiation suppression at the output of the AOM (switched on and off) was equal to 49 dB.

To achieve the instability level of Refs [3, 4], the contribution of the phase noises of the 6.8-GHz frequency synthesiser should not exceed $1 \times 10^{-13}/\tau^{1/2}$. In our prototype, we use the signal at the frequency 6.8 GHz from the E8257D signal generator (Keysight Technologies). The power density of the phase noise measured for it amounts to –95 and –105 dB Hz^{-1} for the shift from the 6.8-GHz carrier frequency by 100 Hz and 1 kHz, respectively. This level of noises determines the contribution of the microwave Dick effect to the QFS instability slightly above $2 \times 10^{-13}/\tau^{1/2}$, also calculated using Eqn (1) presented in Ref. [3].

The optimal parameters for our prototype of the QFS with POP are as follows: the pump pulse duration $t_{\rm p}$ = 0.6 ms, the microwave pulse duration t_1 = 0.4 ms, the detection pulse duration $t_{\rm det}$ = 0.15 ms, and the time interval between the end of the first microwave pulse and the beginning of the second one T = 2.7 ms. The total duration of the cycle amounts to 4.37 ms, including some pauses between the optical pulses and the microwave ones. The total width of the central peak of the Ramsey fringe at the half-maximum level is determined by the known relation $\Delta\nu = 1/(2T)$. It is insensitive to the variation of such parameters as the power of the interrogation microwave signal and the intensity of laser radiation.

Figure 4 shows a typical Ramsey fringe with a central peak width of 185 Hz and its contrast of 40% obtained by

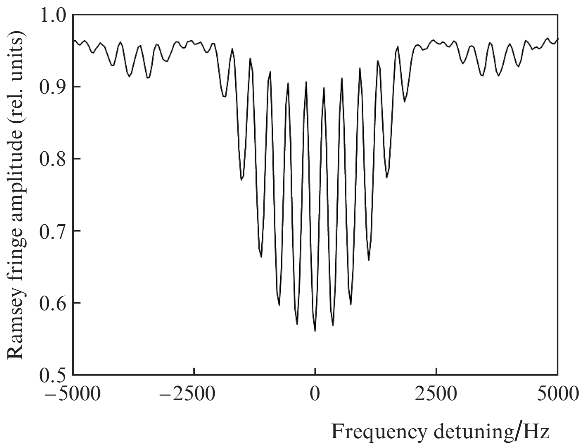

Figure 4. Amplitude of the Ramsey fringe with a central peak width of 185 Hz.

sweeping the synthesiser frequency with respect to the cock transition frequency of 6.834682610 GHz. The cell temperature $T_{\rm cell} = 65\,°{\rm C}$. In Ref. [8] the contrast of about 30 % was achieved at $T_{\rm cell} = 55\,°{\rm C}$. The power of pump radiation before the cell input was 3.6 mW. The absorption of the detecting radiation at $T_{\rm cell} = 65\,°{\rm C}$ in the pulsed mode amounted to 80%. We did not achieve saturation of the Ramsey fringe contrast by increasing the cell temperature. The choice of the temperature $T_{\rm cell} = 65\,°{\rm C}$ is determined only by the technical capabilities of the thermostating system.

The procedure of optimising the contrast of the Ramsey fringe central peak consisted in the study of the effect of the duration and intensity of the pump and detection pulses on it. The dependences of the contrast C of the central peak of Ramsey fringe on the powers $P_{\rm p}$ and $P_{\rm det}$ of the control signals applied to the AOM to form the pump and detection pulses are presented in Figs 5 and 6. The dependence of C on the duration $t_{\rm p}$ of the pump pulse is presented in Fig. 7. The growth of the control signal power leads to an increase in intensity of pump and detection pulses, formed by the diffracted radiation from the AOM.

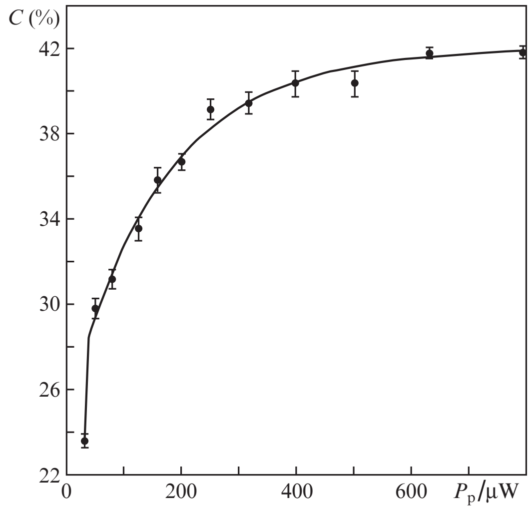

Figure 5. Dependence of the contrast C of the central peak of the Ramsey fringe on the power $P_{\rm p}$ of the control signal, applied to the AOM to form the pump pulse.

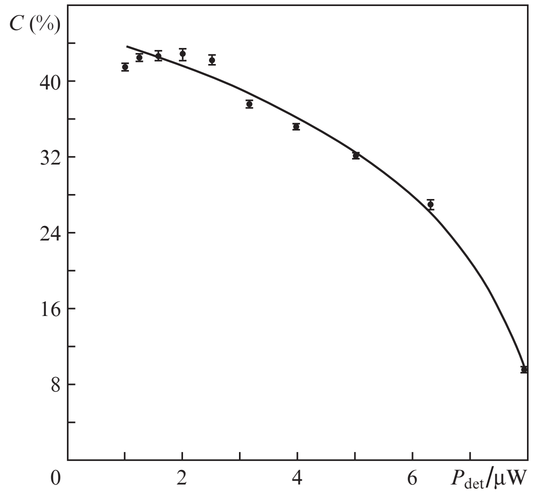

Figure 6. Dependence of the contrast C of the central peak of the Ramsey fringe on the power $P_{\rm det}$ of the control signal, applied to the AOM to form the detection pulse.

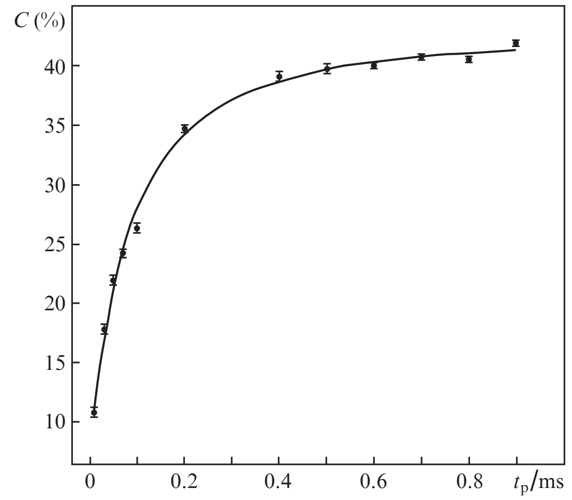

Figure 7. Dependence of the contrast C of the central peak of the Ramsey fringe on the duration $t_{\rm p}$ of the pump pulse.

3. Conclusions

The paper presents the experimental results of the study and performance try-out of a rubidium vapour cell QFS with POP. In the process of optimising the duration and intensity of pump and detection pulses, the Ramsey fringes were obtained with the central peak contrast exceeding 40 %.

For long-term frequency stabilisation of the laser and formation of optical pulses, special AOMs were designed, the use of which in the future will allow a considerable reduction of the dimensions of the QFS with POP laser optical systems.

Besides the advantages related to the operation principle of such clocks (essential suppression of the light shift), the choice of POP for the design of a compact frequency standard is governed by the high technological reproducibility of the results presented in Ref. [8] and in the present paper, as well as in Refs [3–5].

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