 

***COOLING OF ATOMS***

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# Laser system for secondary cooling of $^{87}$Sr atoms

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***Abstract.*** **A laser system with a narrow generation line for secondary laser cooling of $^{87}$Sr atoms has been developed and investigated. It is planned to use ultracold $^{87}$Sr atoms loaded in an optical lattice in an optical frequency standard. To this end, a 689-nm semiconductor laser has been stabilised using an external reference ultrastable cavity with vibrational and temperature compensation near the critical point. The lasing spectral width was 80 Hz (averaging time 40 ms), and the frequency drift was at a level of 0.3 Hz s$^{-1}$. Comparison of two independent laser systems yielded a minimum Allan deviation: $2 \times 10^{-14}$ for 300-s averaging. It is shown that this system satisfies all requirements necessary for secondary cooling of $^{87}$Sr atoms using the spectrally narrow $^1S_0 - ^3P_1$ transition ($\lambda$ = 689 nm).**

***Keywords:*** *$^{87}$Sr atom, laser cooling, optical lattice, ultrastable cavity, clock transition.*

## 1. Introduction

The use of optical clocks based on cooled neutral atoms trapped in an optical lattice is a promising line in the development of frequency standards, because the stability of these clocks exceeded that of the best primary caesium frequency standards [1]. Atoms with an external electron shell of the ns$^2$ configuration (Sr, Yb, Ca) are widely used in optical clocks, because their energy-level diagram allows for application of laser-cooling methods and provides existence of spectrally narrow clock transitions, whose frequency is little sensitive to external fields.

One of the candidates for optical frequency standards is strontium ($^{87}$Sr, $^{88}$Sr). At the end of the 2006s, the absolute frequency of the clock transition in the Sr atom was measured by research teams from Tokyo-NMIJ (Japan) [2, 3], JILA (the United States) [4], and SYRTE (France) [5]. The consistency of the values obtained for the absolute clock-transition frequency was as high as $7.5 \times 10^{-15}$. Based on the results of these measurements, the Comité International des Poids et Mesures recommended optical clocks based on Sr atoms for secondary determination (and, in future, redetermination) of the second as a time unit. Currently, the errors in comparing a strontium optical clock with a primary standard and a Ca optical standard are, respectively, $10^{-15}$ [1] and $10^{-16}$ [6].

The energy-level structure of Sr allows one to carry out efficient laser cooling in two stages. In the first stage cooling is performed through the almost closed $^1S_0 - ^1P_1$ transition at a wavelength of 461 nm, with a natural linewidth $\gamma_1$ = 30 MHz. In this stage, temperatures of few millikelvins are obtained [the Doppler limit $T_D = h\gamma_1/(2k_B)$ = 770 μK], which correspond to thermal velocities of ~1 m s$^{-1}$ [7]. Since the $^1S_0 - ^1P_0$ clock transition in Sr ($\lambda$ = 698 nm) is strongly forbidden and has a spectral linewidth of 1 mHz, these temperatures are too high to implement an optical clock. In addition, the time during which the clock transition is probed must be about 1 s and the atoms must be strictly limited in space. Thus, it is necessary to cool atoms to lower temperatures (below 10 μK) and capture them in an optical dipole trap (optical lattice).

An optical lattice is formed of antinodes and nodes of a standing light wave. Atoms are trapped in the optical lattice due to the dynamic Stark shift in the standing-wave electric field. It was found that one can choose such an optical-lattice wavelength as to make the Stark shift of the clock transition zero (in the linear approximation) [2, 8]. The characteristic optical-lattice depth is only 10 – 20 μK [7]; therefore, the temperature of the trapped atoms must be much lower than that obtained in the first stage cooling.

Since the electron shell of a Sr atom in the ground state does not possess a magnetic momentum, this atom cannot be cooled by classical sub-Doppler cooling methods [9]. Therefore, a weaker $^1S_0 - ^3P_1$ transition, whose natural linewidth $\gamma_2$ is 7.4 kHz, is generally used to reduce the temperature even more. The use of the $^1S_0 - ^1P_1$ transition allows one to cool Sr atoms to few microkelvins and trap them in an optical lattice.

In the first cooling stage, the requirements to the spectral characteristics of the cooling-laser radiation are not very stringent because of the large natural linewidth of the $^1S_0 - ^1P_1$transition. In turn, stringent requirements are imposed on the laser system used for secondary cooling: the lasing spectral width must be smaller than the natural linewidth $\gamma_2$ and the frequency drift should not exceed 1 Hz s$^{-1}$. The latter requirement is related to the necessity of long-term stable operation of the system. Note that the classical method for stabilising laser frequency to the atomic resonance in a metal-vapour cell is technically challenging because of the low scattering rate of photons.

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The linewidth of commercially produced external-cavity diode lasers (for example, DL pro and Toptica) is generally 1 – 10 MHz and, thus, they cannot be used for secondary cooling of $^{87}$Sr atoms. To narrow the lasing line and reduce frequency drift, we used ultrastable external cavities to perform electronic stabilisation of laser frequency [10 – 12].

In this paper, we describe a system for stabilising lasing frequency in order to perform secondary cooling of $^{8}$7Sr atoms; this system makes it possible to narrow the spectral linewidth to 100 Hz at a frequency drift less than 1 Hz s$^{-1}$. The spectral characteristics of radiation were studied in detail by comparing the frequencies of two independent stabilised lasers and the frequencies of a laser and a femtosecond optical synthesiser (FOS).

## 2. Deep laser cooling of Sr atoms

Deep cooling of atoms is one of the most important problems in the development of atomic clocks. This procedure makes it possible to suppress the Doppler effect, spatially localise atoms, and increase the interrogation time to several tenths of a second [7], which is important for precise spectroscopy. Laser cooling turned out to be an efficient and flexible tool, which is widely applied in different stages of preparation of atomic ensembles in frequency standards. Different variations of this method were studied and implemented in a number of studies [13].

First stage cooling of Sr atoms is performed through the cyclic, almost closed $^1S_0$ – $^1P_1$ transition (Fig. 1). Despite the significant decrease in the velocities of cooled atoms in comparison with the thermal velocities at room temperature, they are too large to load atoms in the optical lattice and perform spectroscopy of the $^1S_0$ – $^3P_0$ clock transition. The magneto-optical trap on the $^1S_0$ – $^1P_1$ transition is used to collect atoms and perform preliminary cooling of an ensemble of Sr atoms (up to $10^7$ particles).

In the second stage, the narrow cyclic $^1S_0$ – $^3P_1$transition is used to cool Sr atoms. Its natural linewidth corresponds to the Doppler limit $T_D = h\gamma_2/(2k_B)$ = 200 nK. However, the laser cooling of $^{87}$Sr on the $^1S_0$ – $^3P_1$ transition with a wavelength of 689 nm has specific features related to the large difference in the Lande g-factors of the excited and ground states. The g-factor of the excited $^3P_1$ level is determined by the electron-shell contribution, whereas the g factor of the $^1S_0$ ground state is controlled by only the nuclear spin (this circumstance impedes, in particular, application of Sisyphus cooling). As was shown in [14], the conventional laser cooling in three pairs of mutually orthogonal beams is also inefficient in this case because of peculiar redistribution of populations over magnetic sublevels. To recover the desired population distribution, one has to apply, along with a cooling laser on the $^1S_0$ (F = 9/2) – $^3P_1$ (F′ = 11/2) transition, a stirring laser on the $^1S_0$ (F = 9/2) – $^3P_1$ ( F′ = 9/2) transition (F is the quantum number of the total angular momentum).

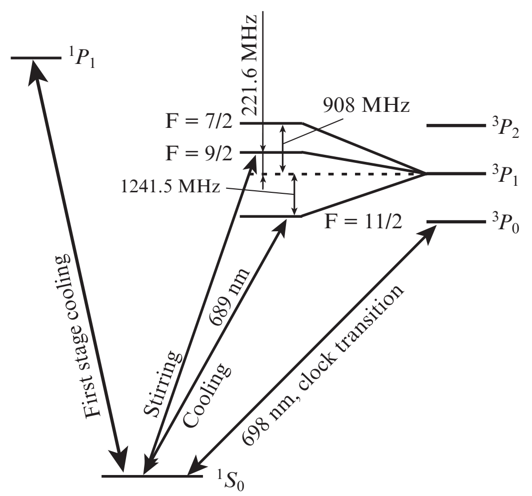


**Figure 1.** Diagram of the $^{87}$Sr energy levels involved in cooling.

The cooling laser frequency is red-shifted from the $^1S_0$ (F = 9/2) – $^3P_1$ (F′ = 11/2) resonant transition by 1.6 MHz. The stirring laser frequency (Fig. 1) is also red-shifted from the $^1S_0$ (F = 9/2) – $^3P_1$ ( F′ = 9/2) transition by 1.6 MHz. Rapid population mixing guarantees filling of states with a magnetic momentum projection that is necessary for effective trapping. Since the sensitivity of the F = 9/2 – F′ = 9/2 transition to magnetic field is lower than that of the F = 9/2 – F′ = 11/2 transition, the atoms remain in resonance for a longer time, and the stirring laser performs also optical molasses cooling, in addition to the main cooling laser. The combination of stirring and cooling laser radiations makes it possible to obtain temperatures of few microkelvins in a magneto-optical trap and trap more the $10^5$ atoms from the initial ensemble containing $10^7$ atoms in a 10-μK-deep lattice.

One needs lasers with a linewidth narrower than the transition linewidth and low frequency drift to cool efficiently atoms using the narrow $^1S_0$ – $^3P_1$ transition. Narrowing of lasing linewidth is the top priority problem in implementing secondary cooling. To solve it, the frequency of 689-nm Toptica DL pro semiconductor laser was stabilised by the Pound – Drever – Hall (PDH) method [15] using a high-*Q* ultra-low expansion (ULE) glass cavity. Two similar systems (ULE1 and ULE2) were fabricated to stabilise lasers; they are considered in detail below. The principles of vibrational and temperature stabilisation used by us are similar to those described in [10 – 12].

## 3. Cavity design

The cavity spacer was made of glass characterised by ultra-low thermal expansion (ULE, Corning) [16]. The thermal expansion coefficient $\eta$ is approximately described by the expression

$$\eta \approx 10^{-9}(T - T_c)^2, \qquad (1)$$

where $T$ is the temperature of the cavity material and $T_c$ is its critical temperature. The cavity sensitivity to external-temperature fluctuations is minimal at the critical point. Typically, the critical point for ULE lies in the range of 0 – 30 °C and is found experimentally from optical measurements.

The ULE1 cavity spacer was produced at the ATF Films (the United States), and the ULE-2 body was fabricated at the Laboratory of Optical Systems of the P.N. Lebedev Physics Institute (FIAN) from a previously selected ULE glass (Premium Grade) with the best characteristics. Both cavities were 7.5 cm long, and their shape was chosen close to biconical to reducetr sensitivity to vibrations (Fig. 2a).

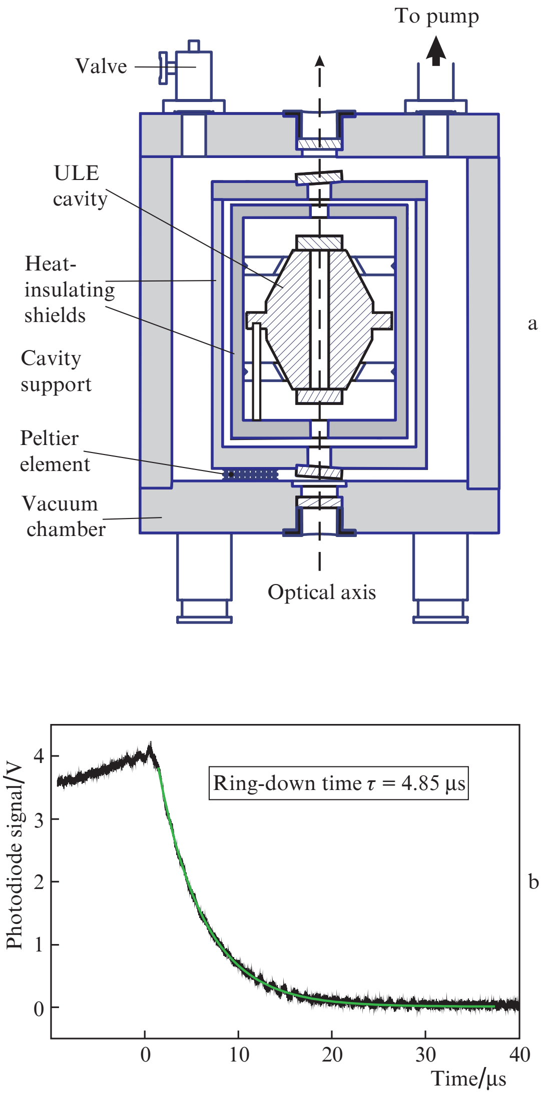


**Figure 2.** (a) Schematic of the vacuum chamber with a ULE cavity and (b) a response of the ULE1 cavity (tuned to the $TEM_{00}$ mode) to sharp switching off the light at the instant $t = 0$; the time constant of the system without a cavity is 0.5 μs.

The cavity is formed by two ULE mirrors with radii of curvature $R_1 = \infty$ and $R_2 = -0.5$ m and a reflectivity of 99.996% (ATF Films, the United States). The mirrors are attached to the cavity spacer via an optical contact. The cavity is installed vertically on a three-point support in a vacuum chamber; in this configuration, the reference plane passes through the cavity centre of mass and serves as a symmetry plane, due to which the external vibrations can be reduced by 40 dB [17]. To suppress vibrations even more, the vacuum chamber with a cavity is mounted on a passive vibrational platform (NANO k 100bm-4c). The vacuum chamber is pumped by a getter-ion pump (speed 10 L $s^{-1}$) to a pressure of $2 \times 10^{-8}$ mbar. The cavity is enclosed in two heat-insulating duralumin shoelds; the temperature of the external screen is stabilised using a two-step Peltier element and a DTC110 temperature controller (Toptica), whose sensor (AD590) is in close proximity of the Peltier element. Measurements with the aid of the independent sensor, mounted on the internal shield, showed that the time constant of the system is 12 h; this indicates good thermal isolation. The temperature stabilisation system makes it possible to change the shield temperature in the range of 0–40 °C and maintain the temperature stability at a level of several tenths of millikelvin.

The cavity finesse was measured by analysing the damping of radiation power circulating in the cavity. To this end, 689-nm semiconductor laser radiation was fed into the cavity through an acousto-optical modulator (AOM), which played the role of a fast optical gate. The photodiode with a time response of 100 ns recorded the radiation transmitted through the cavity. The $TEM_{00}$ mode was optimised using a video camera, which also recorded transmitted radiation. The decay of the signal at the cavity output after switching off the acousto-optical modulator is shown in Fig. 2b. The decay curve can be described by an exponential dependence with a time constant $\tau$. The cavity finesse $F$ is calculated from the formula

$$F = \frac{\pi\sqrt{R}}{1-R} = \frac{c}{2L}2\pi\tau,$$

where $c$ is the speed of light, $L$ is the distance between the mirrors, and $R$ is the reflectivity of the mirrors.

The measurements revealed the finesse of the $TEM_{00}$ mode in the ULE1 and ULE2 cavities to be, respectively, 60000 and 45000. The cavities have a nondegenerate structure of transverse modes, and the free-dispersion range is 1.92 GHz.

## 4. Stabilisation of lasing frequency using an ultrastable cavity

The semiconductor laser frequency is stabilised to the ULE cavity transmission peak by the PDH modulation method (Fig. 3). To this end, laser radiation is fed to the vibration-insolation platform (with a ULE cavity mounted on it) through a single-mode fibre. An optical insulator with an isolation coefficient of 30 dB is used to suppress the feedback. The DL1 diode laser frequency, stabilised to the ULE1 cavity, can be tuned with respect to the cavity transmission peak using an acousto-optical modulator AOM1, operating at the central frequency of 110 MHz. This element is absent in the optical scheme of the DL2 laser. Rough tuning to the transmission peak and choice of a certain mode were performed using a WS-7 wavemeter (Angstrom).

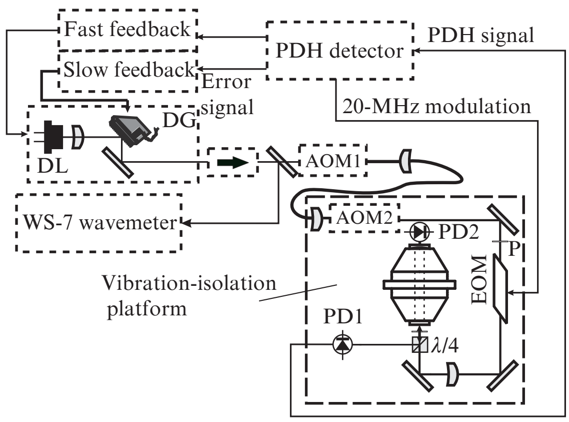


**Figure 3.** Laser frequency stabilisation scheme: (FL) feedback loop, (AOM1, AOM2) acousto-optical modulators, (EOM) electro-optical modulator, (PD1, PD2) photodetectors, (P) polariser, (DL) diode laser, and (DG) diffraction grating.

The vacuum chamber with a cavity is installed in the centre of the vibration-isolation platform, where the highest vibration protection is provided. Radiation supplied through an optical fibre passes through AOM2, operating at a frequency of 40 MHz; this modulator is used for optical isolation of the output fibre collimator from the ULE cavity. Then the radiation is modulated by an electro-optical modulator. We used an LM0202 phase modulator (Linos) for the ULE1 system and a potassium titanyl phosphate (KTP) crystal, oriented at the Brewster angle, for the ULE2 system. The electro-optical modulator, connected to the resonant circuit, performs phase modulation of laser radiation at a frequency of ~20 MHz with a modulation index of ~10%. Modulated radiation is supplied through a mode-matching lens to the cavity. The radiation reflected from the cavity mirror plane arrives at the photodiode with a frequency band of 500 MHz (the PDH signal). The PDH electric signal is applied to a PDH (Toptica) error module, and the modulation signal from this module arrives at the electro-optical modulator. The demodulated error signal is separated into two channels: for fast and slow feedback loops. Fast feedback, implemented using a proportional integro-differential FALC110 module (Toptica), controls the laser diode current. The slow feedback loop is formed using a proportional integral controller; it controls the voltage across the piezoelectric element of diffraction grating. Closing feedback loops leads to narrowing of the laser spectrum and frequency stabilisation to the centre of cavity transmission peak. The phase modulation depth, time constants, and feedback loop gains are optimised to provide the maximum cavity transmission and minimum noise in this signal. To ensure stable operation of the feedback loop, the radiation power at the cavity input should be 30 μW. In this case, the transmissivities of the ULE1 and ULE2 cavities are 40 and 20%, respectively. The laser was continuously stabilised for nearly 12 h.

The assembly and tuning of the laser systems stabilised to the ULE1 and ULE2 cavities was performed at the FIAN. Then the systems were transported in a minibus at a distance of 60 km: to the All-Russian Scientific Research Institute of Physical-Technical and Radiotechnical Measurements (VNIIFTRI). The vacuum in the chambers was maintained by a getter-ion pump fed from an accumulator. After mounting the cavities at the VNIIFTRI, the only thing to be done was to slightly align them to the $TEM_{00}$ mode; this fact indicates high cavity stability to overloads.

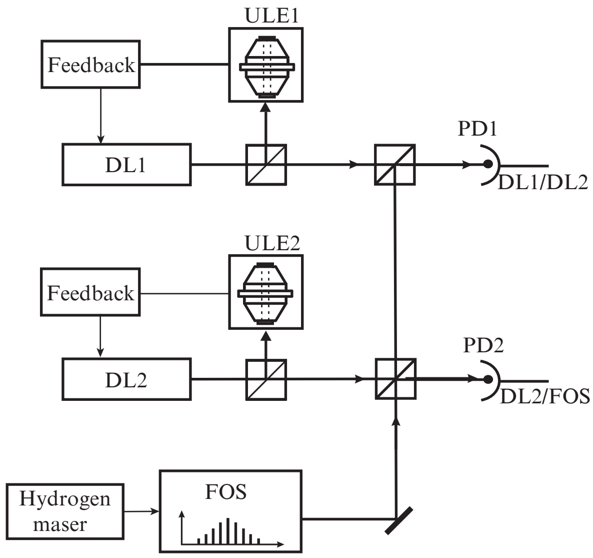


**Figure 4.** Comparison scheme for laser systems (thin and bold lines indicate electric signals and optical paths, respectively).

## 5. Study of the spectral characteristics

To study the spectral characteristics of cavities, two almost identical systems were compared at the VNIIFTRI: DL1–ULE1 and DL2–ULE2. In addition, the optical lasing frequency was measured using an FOS. A schematic of the comparison system is shown in Fig. 4.

The lasers were compared by analysing the beat signal formed at the output of the fast photodetector PD1 with a band of 1 GHz. The frequency of the amplified signal was measured by a Pendulum CNT90 frequency counter, the data of which were recorded in a computer. The beat signal was investigated using an Agilent G4445A spectrum analyser.

The critical temperature $T_c$ was determined for each ULE cavity. As can be seen from expression (1), the cavity length is minimal at the critical point, which is found by analysing the DL1/DL2 beat signal frequency. To this end, the temperature of one of the ULE cavities was varied (once per several days, to ensure stabilisation of the system), while the temperature of the second ULE cavity was maintained constant. The critical temperatures for ULE1 and ULE2 were found to be 12 and 27 °C, respectively. The measurements results are shown in Fig. 5.

The reason for the difference in the critical temperatures of the ULE1 and ULE2 cavities is that their bodies are made of different blocks of ULE glass. Thus, preliminary glass selection allows one to obtain a critical point above room temperature, which is convenient for some applications. Furthermore, the cavity temperatures were maintained constant and equal to their critical temperatures.

Spectral analysis of the DL1/DL2 beat signal showed that the beat signal FWHM is 110 Hz. Figure 6a presents the result of measuring 14 spectra at a detection time of 40 ms and a resolution of 47 Hz. It was found that the DL2 laser (which is more sensitive to vibrations) is likely to give the main contribution to the spectral linewidth. This circumstance may be related to insufficient optical isolation of the laser diode. On the assumption that both laser systems equally contribute to

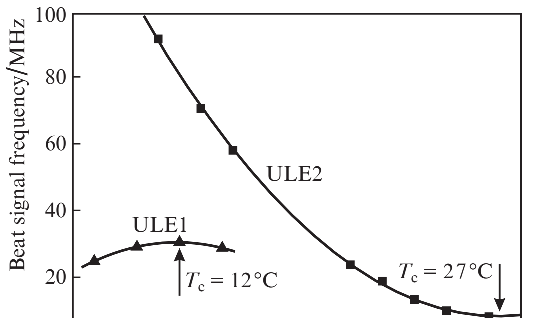


**Figure 5.** Dependence of the DL1/DL2 beat signal frequency on the temperature of the ULE1 and ULE2 cavities.

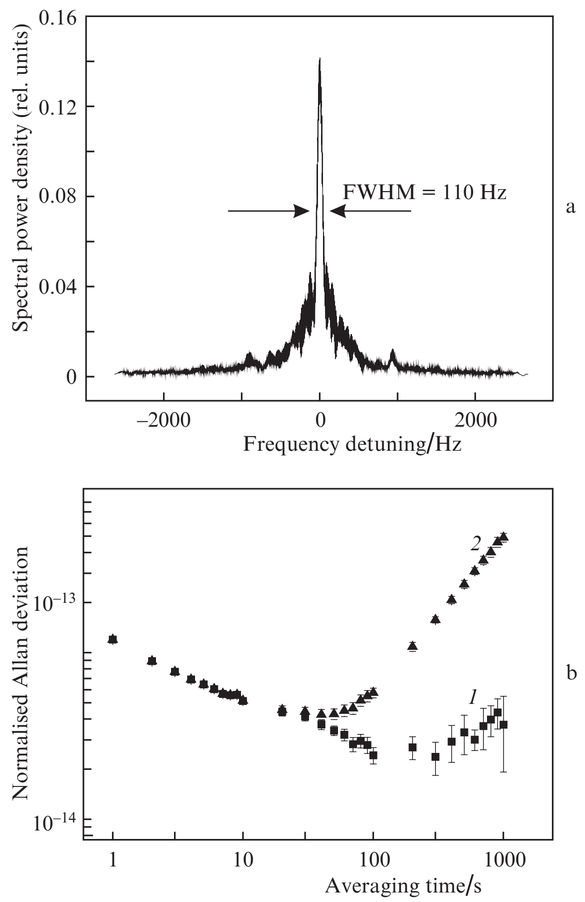


**Figure 6.** (a) Spectrum of the beat signal of two identical lasers stabilised to the ULE1 and ULE2 cavities (14 spectra, recorded with a resolution of 47 Hz during 40 s, are averaged) and (b) the normalised Allan deviation for the beat signal of two identical lasers, stabilised to the ULE1 and ULE2 cavities, with (*1*) subtracted and (*2*) nonsubtracted linear drift.

the beat signal linewidth, the spectral linewidth of each laser can be estimated as $\sim$80 Hz = 110 Hz/$\sqrt{2}$.

The DL1/DL2 beat signal frequency was recorded for several hours by a frequency counter. The time dependence of the relative frequency drift of the two laser systems was almost linear, with a slope of 300 mHz s$^{-1}$. This behaviour is typical of ULE cavities operating near $T_c$ [12] and is caused by recrystallisation of the ULE material, which leads to a gradual decrease in the cavity body length. The drift is also known to decrease with time (on the order of 1 year). The small deviation of the relative drift from the linear dependence (at a level of 30 Hz per 2000 s) indicates insignificant influence of external-temperature fluctuations on the temperature-compensated ULE cavity.

Figure 6b shows a plot of normalised Allan deviation for comparing the frequencies of the two systems with a linear drift subtracted (curve *1*) and nonsubtracted (curve *2*). The data were recorded with a time interval of 1 s; long averaging times were obtained by combining successive 1-s measurements. It can be seen that the Allan deviation with linear drift disregarded reaches $(2-3) \times 10^{-14}$ at time intervals from 100 to 1000 s.

Tuning to the narrow secondary-cooling transition was performed using an FOS stabilised to the hydrogen maser frequency. The error in measuring the DL1/FOS beat signal frequency is such that the laser transition can be tuned with an absolute frequency error not larger than 1 kHz.

## 6. Conclusions

A laser system for secondary cooling of $^{87}$Sr atoms on the $^1S_0-^3P_1$ transition ($\lambda$ = 689 nm) was developed and characterised. Stabilisation to the external temperature- and vibration-compensated ULE cavity made it possible to narrow the lasing line to 80 Hz at a frequency drift of 300 mHz s$^{-1}$. The minimum Allan deviation at comparison of two identical systems with linear drift disregarded was found to be $2 \times 10^{-14}$ for 300-s averaging time. The spectral characteristics obtained make it possible to perform a secondary-cooling cycle for long times (up to 10 h) without additional tuning the laser frequency. The spectral characteristics of the high-reflecting mirrors of the ULE1 and ULE2 cavities also allow one to stabilise laser for spectroscopy on the $^1S_0-^3P_0$ clock transition ($\lambda$ = 698 nm). The expected spectral characteristics are similar to those presented in this study; they are sufficient for recording narrow clock-transition spectra.

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