Control system high-precision laser to obtain the ensemble of ultracold ions Th3+

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Abstract. One of key problems of nuclear standard frequency development is preparation assembly of ultracold thorium ions in Pauli trap. In this case semiconductive frequency-stabilized lasers with external resonator on frequencies 690 nm, 984 nm, and 1088 nm are used for excitation of corresponding electronic dipole and quadrupole cooling transitions for Th3+ ions. In the paper the results of development and creation of unified laser module, which is able to be used as base for full-featured system designed for laser cooling of Th3+ ions, are presented. The module is able to fine-tune necessary wavelength with accuracy ±5 nm.

1. Introduction

Laser cooling of atoms and ions confined in various traps are by far one of the most common methods to obtain and study the quantum properties of individual ultracold (1 uK) atoms and ions [1]. Significant progress is achieved with the use of such physical systems not only in the traditional ultra high resolution laser spectroscopy but also in new areas such as spectroscopy and quantum logic [2], the optical frequency and time standards [3].

From the standpoint of laser cooling of ions in a trap a number of advantages can be noted. This caused by the fact that the possibility of confining ions in the trap for a long time, up to several days, allows to explore an extremely narrow spectral lines without limitations due to the finite time of particle-field interaction. Spatial localization of ions in a trap in a small volume makes effective the use of ultra deep laser cooling techniques including the method of the sympathetic cooling [4, 5]. It is possible to suppress the Doppler shifts and other effects of decoherence up to the second order which is necessary to perform well protected quantum logic operations. Under the conditions of cooling up to the vibrational ground state of the ion the wave packet is localized in a volume less than a wavelength of light. Therefore, by using laser radiation one can selectively act on certain ions while monitoring their internal state, and translational motion. Since the ions are in an ultrahigh vacuum, it is possible to eliminate the interaction with other particles and significantly reduce the interaction with the environment.

By now it is possible to cool all of the alkali (e.g., Rb, Cs) and alkaline-earth metals (for example, Sr), all the inert gases in the metastable state (except Rn), some other elements (In, Al). This area is booming, and since 2007 were cooled Er [6], Cd [7], Hg [8]. Laser cooling of any new element is a major research challenge because it requires precise knowledge of the system levels, the presence of strong transition for this element, and availability of suitable laser sources.
Currently, the best results in the development of optical clocks on cold atoms and ions achieved at laboratory facilities in the United States (National Institute of Standards, NIST), Germany (PTB), the UK (NPL), France and Japan. Relative accuracy obtained for optical clocks on electronic transitions in single ions Al in an electromagnetic trap is $7 \times 10^{-18}$ [9] and several units of $10^{-17}$ for clocks on electronic transitions in neutral atoms of Sr in an optical lattice [10]. This accuracy corresponds to a lag in the fraction of a second for the lifetime of the Universe (13.7 billion years).

Two advanced research groups have started to address the problem by experimental optical spectroscopy of thorium ions: Georgia Institute of Technology (USA) and PTB (Germany). In the United States a system for laser spectroscopy of electronic transitions was set, and thorium ion trap for ion Coulomb crystals of Th3+ ions was constructed; first Coulomb crystals containing up to $10^4$ thorium ions Th3+ were received and detected [11]. In Germany, laser system for spectroscopy of electronic transitions was created, and thorium ion trap for Coulomb crystals of Th+ was designed; first Coulomb crystals containing up to 103 ions of Th+ were produced and detected [12]. The estimation of an error budget based on standard nuclear transition in thorium was given. Given into account the quadratic and linear Zeeman effect, Stark effect, linear Doppler effect, blackbody radiation, the influence of the gravitational field and micromotion of the ion in an electromagnetic trap, the total uncertainty of the clock is $10^{-19}$, and can achieve a level of $\sim 10^{-20}$ [13].

It should be noted that despite the significant progress in the field of direct cooling of thorium ions trapped in a linear Paul trap, the keeping time of the ions at temperatures of the order of 1 mK is limited and does not exceed 30 minutes. This is because thorium ion has ion «uncomfortable» electronic level structure from the viewpoint of the required laser sources, and the cooling transition has a small width. So the task of setting the laser on the corresponding transition is complicated greatly. However, the laser cooling of the ensemble of thorium ions in the trap is the necessary initial phase of the nuclear spectroscopy of the isomeric transition.

The problem of the isomeric transition excitation is even more complicated in terms of experimental realization, as direct excitation of the transition is virtually impossible because of the large uncertainty energy range of the desired transition, and also due to the long lifetime of the excited state. To measure the energy of the isomeric level different mechanisms of excitation of the nuclear transition were suggested. The first one relates to the doping of broadband crystals with 229Th ions followed by scanning the nuclear transition at the synchrotron source in the vacuum ultraviolet region. However, besides the fact that there is currently no synchrotron radiation source of the desired power in Russia, the problem of synthesizing these crystals with the necessary degree of purity is also resource consuming. Another approach appears to be more realistic in the Russian conditions and is based on the implementation of the mechanism of inverse electron bridge (excitation of nuclear states by the resonant excitation of the electron system) proposed by the head of this project [14].

At the current moment in Russian Federation experiments on laser cooling of thorium ions in traps are not being carried out. But they are a fundamental step for nuclear frequency standard. In the paper the results of development and creation of unified laser module are given.

2. Approach and methodology

Fine tuning of wavelength and high quality factor of lasers are ensured by configurable external resonator and original electronic control block [15, 16]. Comparative analysis of technical specifications of developed laser system show that suggested laser system for cooling thorium ions is not inferior to currently used foreign analogs.

Development and creation of universal platform for high-precision laser system with high quality factor is performed in several steps:

- choosing optical system of laser (with resonator by Littrov or Littman scheme);
- calculating and modelling of optical-mechanical system;
- creating of constructing documentation;
- calculating and modelling of proportional-integral control controller for controlling the system for maintaining temperature of specified laser diode pn-transition;
- production of external system resonator movement control system.
- currently the schemes of external resonators of semiconductor lasers, represented on Figure 1.

Figure 1. Semiconductor laser with an external cavity of the scheme: a) Littrov’s; b) Littman’s.

Littrov’s resonator feedback is performed by diffraction at non-zero order of lattice, and output of radiation from resonator at zero order of diffraction. However, this arrangement does not allow to work at very high angles of diffraction that are necessary for increasing the dispersion of the resonator. Littman resonator already allows to work at high angles of diffraction grating, and the share of output from the resonator radiation can be easily controlled by selection of exit mirror transparency. However, in Littman's scheme the emitted ions interact with the lattice during full detour in resonator two times, thus the quality factor of resonator decreases significantly. In single-mode lasers with Fabry-Pérot interferometer the spectrum contains a large number of single modes. Temperature and electric current influent on frequency on laser emission.

3. Experiment setup
For maintaining constant temperature of laser working mode is necessary to use PI-controller with fixed specifications of maintaining temperature with accuracy of 0.01 K in the range 295–330 K [17, 18], with constant of time of controlling not exceeding five seconds and with a control object made on Peltier element. The flowchart for automatic controller is represented on Figure 2.

Figure 2. Block diagram of ACS thermos-controller diode laser.

For the laser diode have been obtained curves of the wavelength on temperature, for currents 70–110 mA. The results of an experiment with a laser diode MLD-694-050. The spectral characteristics of the research goniometer-spectrometer GS-5 that has, at the reflection diffraction-grating. Measurement and setting of temperature was made on done to research the thermal-controller. The temperature sensor is a current sensor AD590 [19, 20] produced by Analog Devices Corporation. Heating and cooling the laser diode to upkeep the set temperature, is carried out by a Peltier element.

4. Results and discussion
The curve for the wavelength of the laser radiation on the temperature of the diode crystal is drawn on Figure 3.
The curve is defined by the ratio $\lambda (I, T)$ [21, 22] displays the dependence of the wavelength from temperature and current:

$$\lambda (I, T) = \gamma TI + \alpha \gamma$$  \hspace{1cm} (1)

The resulting coefficient included in the function of the system temperature control. The equation of dependence of the temperature set values of the wavelength at a constant value of current:

$$T(\lambda) = (\lambda \text{set} - \alpha I) / (\gamma \lambda)$$  \hspace{1cm} (2)

The equation for regulation of thermal control is:

$$P_{\text{Adj}} = \frac{1}{K_p} ((\frac{\lambda \text{set} - \alpha I}{\lambda} + T_{\text{meas}}) + \frac{1}{K_i} \int_0^t (\frac{\lambda \text{set} - \alpha I}{\lambda} + T_{\text{meas}}) dt)$$  \hspace{1cm} (3)

- $P_{\text{Adj}}$ – adjustment function;
- $K_p$ – the coefficient of proportional component;
- $K_i$ – the coefficient of the integral component;
- $\lambda \text{set}$ – set wavelength;
- $\gamma$ – the coefficient of thermal;
- $\alpha$ – the coefficient of current for wavelength and constant temperature;
- $T_{\text{meas}}$ – the measured value of the temperature diode now.

Installation shown on Figure 4 was utilized to measure the laser wavelength depending on the current through the pn-junction. The installation is a heavy goniometer spectrometer with a laser system attached to one ocular and an infrared camera attached to the other ocular.
Figure 4. Appearance goniometer spectrometer GS-5 to research the spectral characteristics of the semiconductor laser.

At low current densities through the pn-junction of the radiation intensity is low, it is incoherent and the wavelength is shifted to minimum semiconductor laser operating range. By increasing the current, when the number of photons produced by the recombination exceeds the number of photons absorbed in the substance (current threshold), the emission intensity sharply increases – it becomes coherent and spectral maximum is shifted to the right as seen in Figure 5.

Figure 5. Graph of spectral peaks of the laser radiation on the current density flowing through the laser diode.

Furthermore, when a small spectral width of the pump current is sufficiently large, such behavior is consistent with the spontaneous emission of a conventional semiconductor light emitting diode with increasing current up to the rated values - generation is observed and the emission spectrum is narrowed. With further increase of current spectral characteristic appreciably narrows the quality
factor of the laser is increased, in addition significantly increases the stability of the resonator and the laser output power. By increasing the current density flowing through the pn-junction and the corresponding angle tuning external cavity laser diode passes from multimode to single mode lasing mode, with an average width of a single longitudinal mode is equal to 0.5–1.5 nm. Further reduction in the spectral linewidth selected mutual adjustment of the current strength, temperature and the reflection angle of the external cavity.

After successful testing and adjustment works of the laser module on the working wavelength of 690 nm we started to develop a semiconductor laser module for laser diode with an operating range of wavelengths 1080–1090 nm. Given the previous experience in the development of optical-mechanical circuits of the laser module laser system with an external cavity of Littrow model has been completely redesigned concept and approach in the design of the external cavity. The improved design (Figure 6) grating external cavity located on a slotted V-shaped holder, with the possibility of adjusting the vertical and horizontal reflection angle, with mutual compensation of the oscillations of the mechanical system holder.

**Figure 6.** 3D-model of advanced opto-mechanical system for diode laser LD 1088 nm with a removed housing cover.

In addition, two additional alignment system micrometric screws are provided for balancing the vertical node, with additional piezoceramic nozzles for fine adjustment. Conjugation of the two V-shaped holders split due not only to input additional degrees of freedom, but also removal of excess strain on the holder assembly design that subsequently a positive effect on the mechanical stabilization of the assembly of the external cavity. Since the implementation of this scheme will increase the interval between successive adjustment of the semiconductor laser module of optical-mechanical system.

Additionally, it is worth considering the laser diode collimator block and holder shown in Figure 7. Figure 7 represent 3D-model improved opto-mechanical system for the laser diode LD 1088 nm with a removed side housing cover and the side cover removed collimator-holder.
The collimator of the laser diode holder is formed in a monolithic body of duralumin, and introduced into heat-insulated from the rest of the opto-mechanical system capsule, to maintain a predetermined temperature. This is necessary in order to reduce the environmental impact directly on the thermal stabilization of the laser diode.

Figure 7. Appearance of modernized design of the laser module.

To reduce the heat-affected thermostabilizing camera-collimator holder to neighboring nodes opto-mechanical systems, heat exchange of the collimator is made not to the base of the optical system, and the radiator grille, derived on the cover of the laser module housing. Figure 7 shows the appearance of modernized design of the laser module, depicting the cooling radiator assembly thermoregulation collimator carrier, as well as basic input-output interfaces the control signals from the aforementioned control ACS modules.

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