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CONTROL OF LASER RADIATION PARAMETERS

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Frequency control of tunable lasers using a frequency-calibrated λ-meter in an experiment on preparation of Rydberg atoms in a magneto-optical trap

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Abstract. **A new technique is proposed and applied to study the frequency drift of an external-cavity semiconductor laser, locked to the transmission resonances of a thermally stabilised Fabry – Perot interferometer. The interferometer frequency drift is measured to be less than 2 MHz h^{-1}. The laser frequency is measured using an Angstrom wavemeter, calibrated using an additional stabilised laser. It is shown that this system of laser frequency control can be used to identify Rydberg transitions in ultracold ^{7}Li atoms.**

Keywords: *Fabry – Perot interferometer, tunable cw laser, frequency drift, magneto-optical trap.*

1. Introduction

This work is a continuation of the studies on the possibility of creating and applying Rydberg matter [1 – 3], the existence of which was predicted in [4 – 9]. One of the ways of preparing Rydberg atoms is multistep laser excitation with subsequent detection of the electrons extracted by a weak electric field [10 – 12]. Preferred diagnostic methods are nondestructive ones, such as detection of electromagnetically induced transparency [13].

We have developed a new method for measuring the Rydberg transition frequency using direct detection of fluorescence from a cloud of cold lithium atoms in a magneto-optical trap (MOT), which does not destruct the prepared Rydberg state of the atoms [3]. To monitor the excitation and optimisation of the atomic density in MOT, one must perform simultaneous and continuous monitoring of the frequency of two diode lasers with a wavelength of 671 nm and one UV radiation source (λ = 350 nm) based on a cw Ti:sapphire laser.

Frequency-stabilised external-cavity diode lasers (ECDLs) are widely used for laser cooling and trapping of atoms in MOTs [14]. In many cases it is necessary to perform precise continuous frequency detuning from a resonant transition. There are many ways to detune laser radiation from the optical transition frequency. One of the most popular (but not very convenient for our purposes) technique is the frequency detuning with acousto-optical modulators [14]. There is also a method for frequency detuning by a magnetic field [15].

In this study, we consider a technique of ECDL stabilisation with respect to the transmission resonances of a highly stable scanning Fabry – Perot interferometer (FPI), which makes it possible to tune the cooling laser frequency in a wide range [1, 2]. The frequency is continuously monitored by an Angstrom WS-U wavemeter, calibrated using the frequency of a diode laser stabilised at the resonant frequency of saturated absorption in ^{85}Rb. This approach makes it possible to tune the cooling laser in a wide frequency range and monitor continuously the ECDL frequency in the stabilisation regime.

2. Calibration and drift of wavemeter

Before starting work, the wavemeter is calibrated using a stable ECDL. Figure 1 shows schematically the frequency stabilisation for the laser whose radiation was used to calibrate the wavemeter.

A small fraction of ECDL radiation is split off (using a half-wave plate and a polarising beam splitter) to be sent to an optical fibre. The remaining part of radiation is split into two beams: a high-power pump beam and a weak probe beam. Saturated-absorption resonances are formed in the atomic cell, and the saturated-absorption spectrum is recorded by a photodetector.

To obtain the error signal, the laser frequency was modulated with a frequency of 10 kHz. The servo-system was locked to zero of the derivative of the absorption line profile. After lock-in detection, integration and amplification, the error signal was applied to a piezoelectric ceramic element to tune automatically the laser frequency to the nonlinear resonance frequency.

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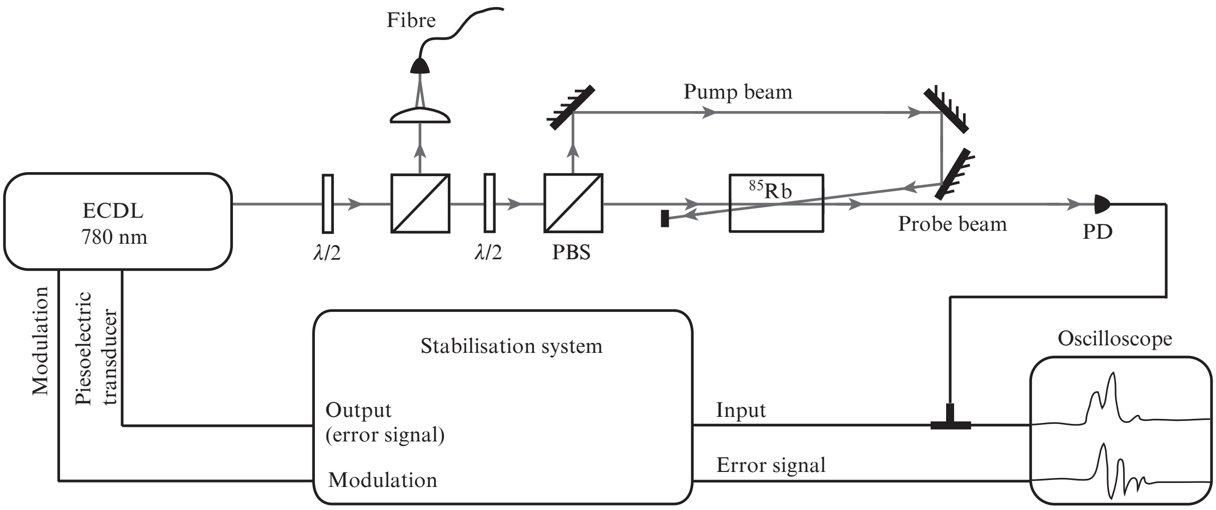

Figure 1. Schematic diagram of the calibration laser stabilisation: (ECDL) external-cavity diode laser; (PBS) polarising beam splitter; (PD) photodiode.

Figure 2 shows an oscillogram of saturated absorption in ^{85}Rb vapour; here, the frequency was stabilised at the frequency of the $5S_{1/2}$ (F = 3) → $5P_{3/2}$ (F′ = 4) transition, equal to 384.229242 THz [16] (the transition is indicated by an arrow).

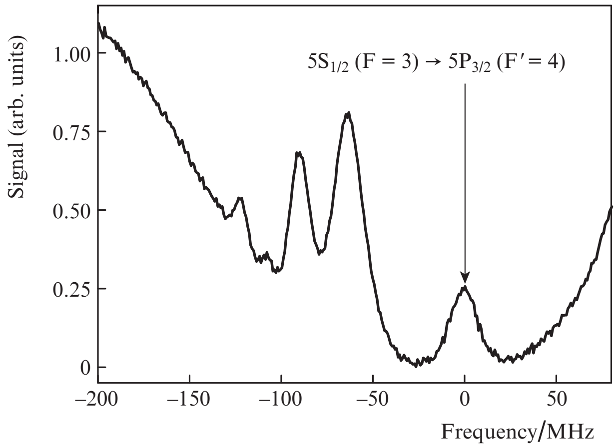

Figure 2. Doppler-free saturated-absorption resonances of ^{85}Rb vapour.

The radiation introduced into the optical fibre arrives at the input of multichannel fibre switch, which allows one to supply radiation to the Angstrom WS-U wavemeter and rapidly switch between signals from up to four independent lasers. To measure the wavelength, radiation is collimated into a parallel beam and sent to a solid Fizeau interferometer, after which the interference pattern is projected (using a cylindrical lens) onto a CCD line array (Fig. 3) and recorded. This pattern is compared with the previously recorded calibration interference pattern. The absence of movable mechanical parts in the wavemeter provides an absolute error of frequency measurements as low as 2 MHz, with a resolution of 500 kHz.

Nevertheless, small variations in air temperature and pressure lead to a drift of the measured frequency. To measure this drift, stable laser radiation, which is used initially for calibration, is supplied to the wavemeter. The time dependence of the wavemeter drift is shown in Fig. 4. Since the ECDL, stabilised with respect to saturated-absorption resonances, has a very high relative stability [17], the wavemeter drift for 3.5 h was found to be only about 2 MHz.

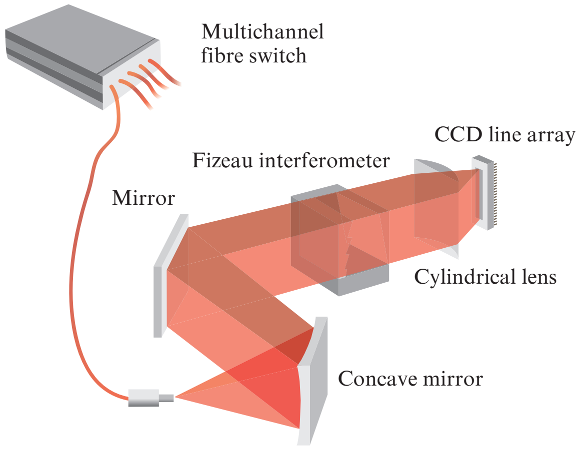

Figure 3. Block diagram of wavemeter.

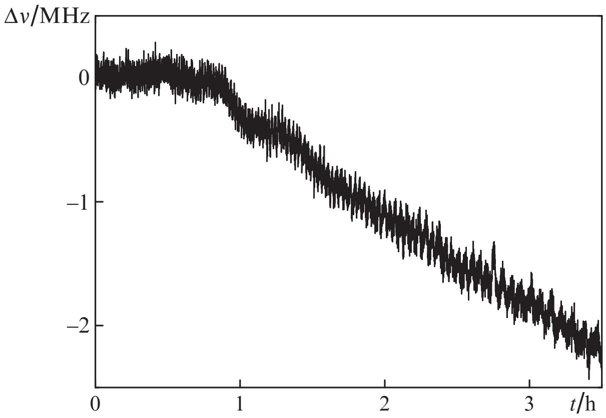

Figure 4. Time dependence of the Angstrom WS-U wavemeter drift.

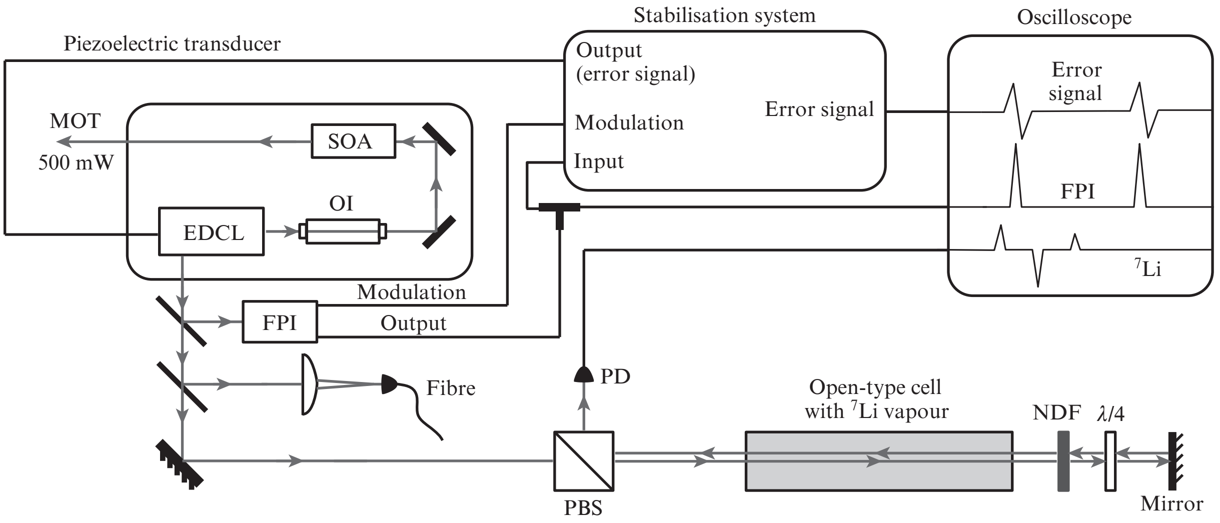

Figure 5. Schematic diagram of the ECDL stabilisation with respect to the transmission resonances of a thermally stabilised FPI: (OI) optical insulator; (SOA) semiconductor optical amplifier; (NDF) neutral density filter; ($\lambda/4$) quarter-wave plate.

3. Stabilisation of the ECDL on the transmission resonances of a thermally stabilised FPI

Below we consider a stabilisation system that makes it possible to tune in real time the frequency of the cooling ECDL with respect to the transmission resonances of an absorbing cell with lithium atoms in a very wide range (more than 100 MHz, which obviously exceeds the detunings necessary for experiments with MOTs). Note that the stabilisation system must provide the frequency stability on the order of few tenths of natural width $\gamma = 6$ MHz. In this case, the lasing linewidth must be much narrower than γ to provide efficient operation with MOTs; therefore, modulation-induced broadening of the lasing spectrum must be excluded, and it is the reference resonance of FPI transmission that is modulated.

In the MOT described in [1, 2], cooling laser radiation is stabilised with respect to the transmission peak of a thermally stabilised confocal scanning FPI with a free spectral range (FSR) of 1.5 GHz and a spectral sharpness of 300. The interferometer was developed and assembled at the Lebedev Physics Institute, Russian Academy of Sciences (FIAN), under the guidance of V.V. Vasiliev. The master laser beam with a power of ~1.5 mW arrives at splitting glass plates; a small part of radiation is directed to the FPI, and the other radiation is focused into an optical fibre. Part of radiation plays the role of a saturating beam in an open-type cell (cell with cold windows) filled with lithium vapour. Radiation transmitted through the cell and reflected back from a mirror is used as a probe beam. Rotating the polarisation plane by a quarter-wave plate, one can separate the probe and saturating beams (Fig. 5).

Saturated-absorption resonances are formed in the cell heated to a temperature of about 400 °C; the FPI transmission resonance is set with respect to these resonances using an oscilloscope (Fig. 6). One of the advantages of this stabilisation method is that it does not require modulating the master laser beam. To obtain the error signal, the FPI length was modulated with a frequency of 10 kHz.

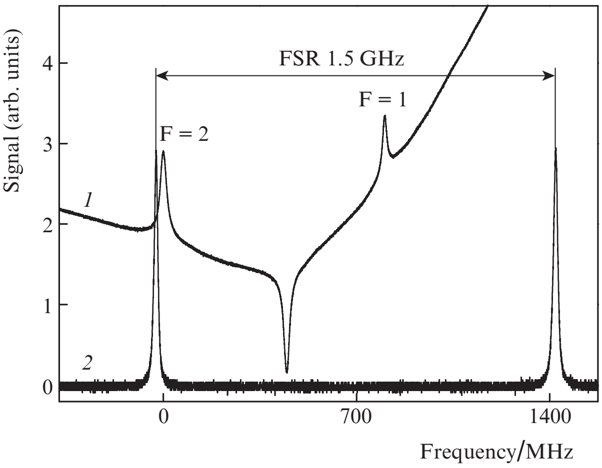

Figure 6. (*1*) Doppler-free saturated-absorption resonances of ^{7}Li vapour and (*2*) FPI transmission resonances.

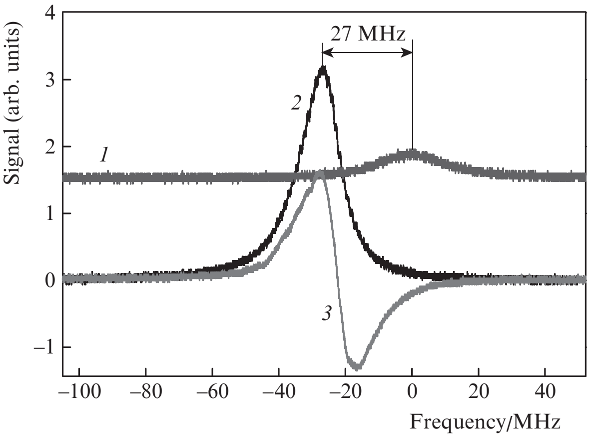

Figure 7. (*1*) D_2 line of ^{7}Li, transition with F = 2; (*2*) FPI transmission resonance; and (*3*) and signal error.

To monitor the detuning frequency of the FPI transmission resonance from the atomic resonance in the cell, one must switch off the stabilisation regime and determine the detuning frequency using transmission resonances in the cell (Fig. 7). However, the frequency monitoring using the Angstrome WS-U wavemeter, calibrated with respect to the saturated-absorption resonance in the cell with ^{85}Rb atoms, is more convenient and reliable. It allows one to determine the cooling laser frequency detuning in real time, without switching off the stabilisation regime.

4. Drift of thermally stabilised FPI

A tunable confocal interferometer is a widely used optical device for analysing the laser radiation spectrum. The frequency degeneracy of spatial interferometer modes simplifies significantly its matching with the laser beam, and the presence of a movable mirror, which is generally installed on a piezoelectric transducer, makes it possible to tune the resonant frequency of the interferometer, recording successively all generated laser modes. However, despite the obviousness of this solution, tunable interferometers are almost not used to stabilise laser frequency because of the significant drift of their intrinsic frequencies [18]. The drift, related to the change in the interferometer base, is due to (i) the temperature expansion of the piezoelectric transducer and housing (on which mirrors are mounted), (ii) the dependence of the optical density of the medium between the mirrors on the external atmospheric pressure, and (iii) the constancy of the voltage applied to the piezoelectric transducer.

An attempt to minimise the negative influence of variations in external temperature and pressure on the optical resonance frequency of the tunable confocal interferometer, a special designed was made at the Laboratory of Frequency Standards of FIAN.

The interferometer is a pyroceram monolithic block, with mirrors mounted on the end faces by optical contact. One of the mirrors was designed on a substrate, which allowed for deformation from the external side by 1 – 2 μm. Deformation was performed by a piezoelectric cell fixed in an Invar ring so as to compensate for the relative elongation caused by variations in temperature. To fulfil the confocality condition, the pyroceram housing length was maintained at a specified level with high precision (the error was less than 10 μm). The monolithic block was placed in a hermetic duralumin chamber with optical windows; the chamber temperature was maintained constant using a Peltier element, onto which it was installed. Thus, the FPI was designed as a 'matreshka' (Russian doll) (Fig. 8).

Figure 8. Design and external appearance of the FPI.

The laser radiation, stabilised with respect to FPI transmission resonances, was transferred through an optical fibre to the wavemeter, which made it possible to measure the drift of FPI resonant frequencies (Fig. 9). Note that the wavmeter and FPI drifts were observed simultaneously. It can be seen in Figs 2 and 9 that, with allowance for the wavemeter drift, the FPI drift is less than 2 MHz h^{-1}.

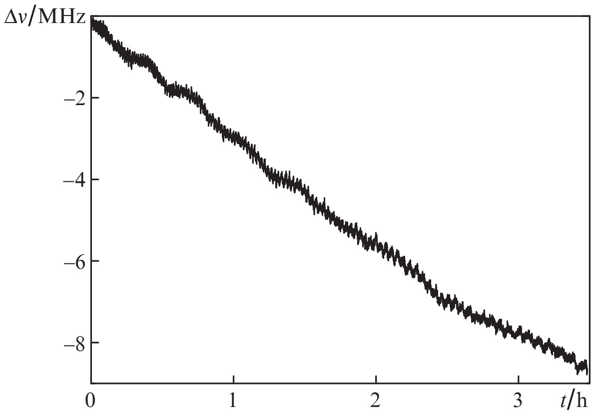

Figure 9. Time dependence of the FPI frequency drift.

Our measurements of the drift of the interferometer showed that it can be reduced even more by increasing the thickness of chamber walls and using electronic components with high thermal stability in the control unit.

5. Measurements of the Rydberg-transition frequency

An MOT was used to obtain highly excited Rydberg atoms [1 – 3]. Excitation was performed by a tunable cw UV laser (λ = 350 nm), the frequency of which was monitored by a wavemeter. The change in the fluorescence of a cloud of cold atoms, caused by the scanning the UV laser frequency in the Rydberg-transition range, was recorded directly. The fluorescence of the cloud at a wavelength of 671 nm was recorded by a photodetector, onto which part of radiation was focused, and a CCD camera. Figure 10 shows fluorescence signals detected by the CCD camera when scanning frequency in the vicinity of the $2P_{3/2}-95S$ and 95D transitions.

At the beginning, the cloud of atoms is transparent for UV radiation. The coincidence with the Rydberg-transition frequency leads to reduction (up to complete disappearance) of the fluorescence of the cloud of cold ^{7}Li atoms. The changes in the sizes and brightness of the cloud can be seen in the left part of the figure, while in the right part the cloud completely disappears, because the probability of the transition to the 95D level is higher than for the 95S level. The complete absence of fluorescence corresponds to the transition of atoms from the $2P_{3/2}$ state to the 95D state. In the first stage, excitation is performed by the cooling (MOT-forming) laser, which excites atoms from the ground $2S_{1/2}$ state to the $2P_{3/2}$

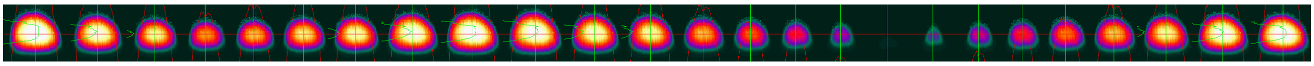

Figure 10. Detection of variations in the fluorescence intensity by a CCD camera when scanning the UV laser frequency in the vicinity of the $^2P_{3/2}-95S$ and 95D Rydberg transitions.

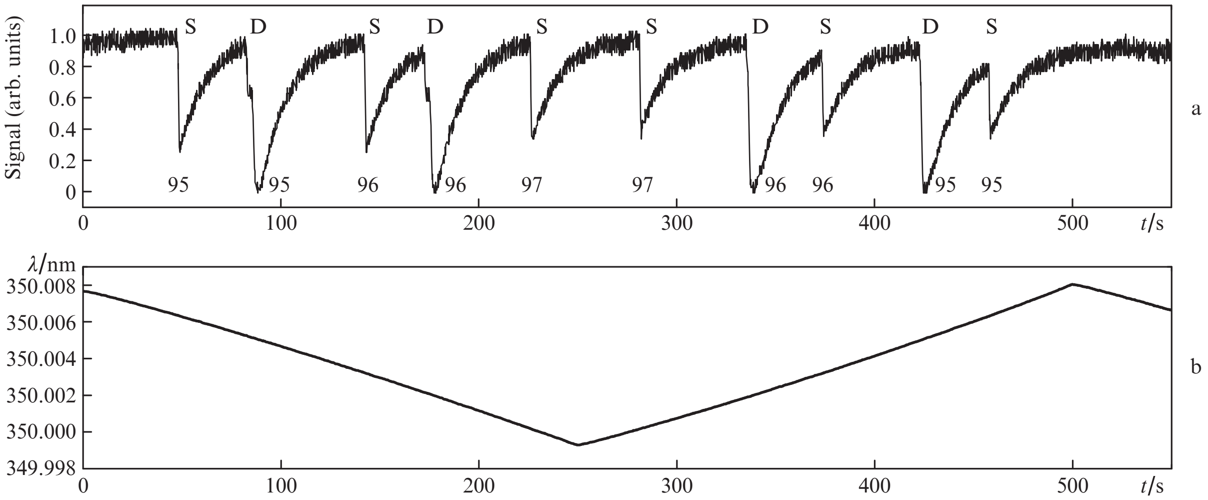

Figure 11. (a) Detection of changes in the fluorescence signal by a photodetector and (b) the time dependence of the UV laser wavelength.

state. The procedure of level identification is described in more detail in [3].

A change in the cloud fluorescence with time, recorded by the photodetector, is shown in Fig. 11a. Zero corresponds to complete absence of fluorescence and unity corresponds to a maximum fluorescence signal. The scanning range of the UV laser frequency contains the frequencies of the 95S, 95D, 96S, 96D, and 97S transitions. The time dependence of the UV laser frequency, which was directly recorded by the wavemeter, is shown in Fig. 11b.

6. Conclusions

A technique for measuring and controlling the diode laser frequency using an Angstrom WS-U wavemeter, calibrated with respect to the saturated-absorption resonances of ^{85}Rb atoms, was described. A technique for stabilising ECDL for subsequent calibration of the wavemeter was reported. The wavemeter drift was measured to be ~0.6 MHz h^{-1}; with allowance for this value, the drift of our thermally stabilised FPI turned out to be less than 2 MHz h^{-1}. A possibility of determining the frequency of highly excited Rydberg transitions by analysing the change in the fluorescence signal from a cloud of cold atoms in an MOT was demonstrated. This technique for frequency control appears to be very convenient for further study of the nature of two-step excitation of a cloud of ultracold ^{7}Li atoms in an MOT.

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