Long-term frequency stabilized and linewidth-narrowed cw-laser system for excitation of lithium Rydberg states

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Abstract. We transfer the frequency stability from a diode laser, which was locked to Doppler-free saturation absorption resonance in lithium vapor cell, to a tunable Ti-sapphire laser. We get the laser linewidth $<100 \text{kHz}/100 \text{ms}$ and absolute frequency stability $\pm0.5 \text{MHz}$. The uv laser system which included the stabilized Ti-sapphire laser and frequency doubler has output optical beam with power near 100 mW and wavelength 350 nm. This uv laser system will be used for excitation and study of Rydberg states in lithium atoms.

1. Introduction
Investigations of ensembles of strong coupling Rydberg atoms and non-ideal plasma are very important for fundamental physics and different applications like quantum information [1–3]. For optical excitation atoms to Rydberg states frequency stable lasers are necessarily. The standard technique is frequency locking of lasers to reference atomic or molecular narrow resonances. This approach is not suitable for research projects where frequency tuning with a high absolute accuracy in a broad range is required.

For optical excitation of $^7\text{Li}$ atoms to Rydberg states in magneto-optical trap (MOT) the uv laser systems are needed with central wavelength near 350 nm and tuning $>2 \text{nm}$ for two-photon excitation Rydberg states from principal quantum number $n=38$ to ionization threshold. The required wavelength can be obtained by frequency doubling of Ti-sapphire laser frequency. We used laser system Matisse TX-light with reference cell unit and cw frequency doubler WaveTrain from Newport Spectra Physics. In this model there is the frequency stabilization on resonances of an evacuated thermo-stabilized Fabry–Perot interferometer (FPI), installed inside reference cell unit, is performed by using Pound–Drever–Hall technique (PDH) [4]. This technique allows obtain a narrow laser linewidth ($\leq 60 \text{kHz}$). The internal FPI shows a large thermal drift near 100 MHz/hour. There is a serious technical problem with long-term frequency stability.

A stabilization system for this kind of lasers is described in [5]. In this work a stability transfer from stabilized He-Ne laser to two Ti-sapphire lasers by additional FPI (transfer cavity). The laser systems in [5] differ from our system. They have not the internal stabilization system with PDH feedback. The error signal was calculated by computer. A computerized electronic system calculated a frequency interval between FPI resonances then the error signal was fed to piezo-actuator in FPI inside the reference cell. The stability $\pm2.8 \text{MHz}$ was obtained for 5
In this work [5] there is a statement that main contribution to the drift is related with instability of He-Ne laser.

In the work [6] a tunable dye laser Matisse was locked to saturation resonances in sodium vapor. A signal of saturated absorption was fed to Matisse commander. The feedback signal was applied to piezo-actuator in FPI inside reference cell of the laser. This technique was described in Matisse User’s Guide [7]. The frequency stability $\pm 4$ MHz per hour was obtained.

In the work [8] the similar laser system from Coherent was used. The transfer FPI was stabilized by injection-locked diode laser. The Ti-sapphire laser was locked to this FPI. The laser was used for excitation of rubidium Rydberg atoms in MOT. The long term stability of the laser frequency was 1 MHz per hour. The stability was seasonally varied from 0.17 MHz to 1.4 MHz per hour.

In present paper a simple reliable analog technique of frequency stabilization is described. This technique is working without additional transfer cavity. The obtained stability is $\pm 0.5$ MHz per hour.

2. Experimental setup

Our MOT is described in [9, 10]. For registration of energy spectra of Rydberg transitions a spectroscopic technique based on observation of the resonance fluorescence of atoms in MOT is used [11–16]. For optical excitation of Rydberg states in $^7$Li atoms we use laser system Matisse TX-light with frequency doubler WaveTrain. The output emission with power of 100 mW has wavelength of 350 nm [17].

For cooling and trapping lithium atoms the external cavity diode laser (master laser) with tampered amplifier (Toptica) with output power 500 mW and wavelength 671 nm [18]. The frequency of the cooling laser is locked to the saturation absorption resonance in a hot lithium cell.
Figure 2. (a) Frequency deviation of Ti-sapphire laser stabilized by using transfer cavity method. (b) Histogram statistics and Gaussian curve; FWHM—full width at half maximum.

without modulation of the laser frequency (figure 1). To produce the error signal the frequency of the probe optical beam is modulated by double-pass acousto-optic modulator (AOM) [19] (in figure 1 it is DP AOM-1). The frequency stabilization system consist a lock-in unit and a PID control unit. The error signal is fed to piezo-transducer in the maser laser. A part of output beam from the cooling laser is used for stabilization of a length of the thermo-stabilized FPI which is installed in the reference cell unit of the laser system.

This optical beam after double-pass AOM (in figure 1 it is DP AOM-2) is sent to the thermo-stabilized FPI in the reference cell unit. For this purpose the reference cell unit was slightly modified. Two mirrors were added and photo-detectors for the FPI was installed outside the unit. The optical beams with wavelength 671 nm and 700 nm are separated by polarization optics and sent to photo-detectors.

Signal from photo-detector is fed to frequency stabilization system. In this scheme for creation of the error signal the frequency of emission with wavelength 671 nm was modulated by using double-pass AOM (in figure 1 it is DP AOM-2). The error signal from the stabilization system is fed to control input of Reference Piezo in Matisse Control Box which control the length of the reference FPI. After that Ti-sapphire laser frequency is stabilized by using integrated PDH technique [4]. Locked Ti-sapphire ring laser may be precisely scanned by double-pass AOM by changing control voltage.

3. Results

For measurements of laser frequency drift the frequency calibrated wavemeter Anstrom WSU is used [20]. The results of the measurements during 1 hour are presented in figure 2(a). The Histogram statistics and Gaussian curve are shown in figure 2(b). A small variation of measured frequency is associated with thermal drift of wavemeter.

The laser linewidth measured by optical spectrum analyzer EagleEye described in paper [17]. The measured linewidth is less than 100 kHz/100 ms. By using our frequency stabilization approach the two-photon excitation of Rydberg states in optically cooled $^7$Li atoms was made. Experimental setup is described in [21]. For excitation two counter propagating optical beams are used. The red optical beam ($\lambda = 671$ nm) is detuned from transition $2S_{1/2}(F = 2) - 2P_{3/2}(F = 3)$ by interval 0.59 GHz. This beam is split from output beam of the cooling laser. The frequency of
Figure 3. Coherent two-photon resonance corresponding Rydberg state 58S: solid curve is the observed resonance; dashed curve is result of fitting experimental data by Gaussian function with FWHM of 9 MHz.

uv laser system is fine tuned by double-pass AOM (figure 1 DP AOM-2). In figure 3 dependence of resonance fluorescence on frequency of uv laser system is presented.

4. Conclusions
We demonstrate frequency-doubling cw-laser system for optical excitation of lithium Rydberg states. Obtained stability of the uv laser system is $\pm 0.5 \text{ MHz/h}$. The assembled experimental arrangement allows study energy spectra of Rydberg states. In order to increase number density and investigate inter-atomic interactions the short optical pulses will used. For these applications the long-term stability of the lasers are very important.

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