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A Frequency Tuning and Locking System of a Deep UV Laser for Laser Cooling of Mercury Atoms

Liu Hongli[1,2]　Qian Jun[1]　Xu Zhen[1]　Wang Yuzhu[1,3]

[1] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201203, China

Abstract We develop a power saving frequency tuning and locking system of a deep ultraviolet (UV) laser at 253.7 nm, which will play an important role in a magneto-optical trap for neutral mercury atoms. Combined with two cascade acousto-optical modulators (AOMs) and frequency modulation (FM) spectroscopy in a mercury vapour cell, the deep UV laser can be locked and tuned on $^1S_0$-$^3P_1$ transition of Hg atoms, and the power for laser cooling can be saved. FM spectroscopy is also observed by demodulating the saturated absorption spectroscopy (SAS) of the FM laser. The UV laser is well locked on $^1S_0$-$^3P_1$ transition of ^{200}Hg atoms with the instability less than 0.1 MHz.

Key words lasers; frequency stabilization; frequency modulation; laser cooling; deep ultraviolet laser
OCIS codes 140.3425; 140.3320; 300.6380

用于汞原子激光冷却的深紫外激光调谐和锁频系统

刘洪力[1,2]　钱　军[1]　徐　震[1]　王育竹[1,3]

[1] 中国科学院上海光学精密机械研究所，上海 201800
[2] 中国科学院大学，北京 100049；[3] 中国科学院上海高等研究院，上海 201203

摘要 开发了一种用于 253.7 nm 深紫外激光器的低功耗频率调谐和锁频系统，这种锁频系统将在中性汞原子磁光阱中起到重要作用。该系统用两个级联的声光调制器分别做频率调谐和频率调制。利用该系统可将深紫外激光器的频率锁定在汞原子的$^1S_0$-$^3P_1$ 的能级跃迁上，并为汞原子的激光冷却节约了功率。同时通过解调频率调制激光的饱和吸收光谱观测了汞原子的调频光谱。采用该技术将紫外激光锁定在^{200}Hg 的$^1S_0$-$^3P_1$ 共振跃迁上，并且频率不稳定度低于 0.1 MHz。

关键词 激光器；频率稳定；频率调制；激光冷却；深紫外激光
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1 Introduction

As the heaviest non-radio-active atom that has been laser-cooled and trapped[1-3], Hg atoms play an important role in precision measurement of some physical constants such as permanent electric dipole moments[4] and the fine-structure constant[5]. Due to its low sensitivity to blackbody radiation[1], Hg atom is a good candidate of the most accurate optical lattice clock. For laser cooling of Hg atoms, the ultraviolet (UV) laser should be locked and tuned on the cooling transition ($^1S_0$-$^3P_1$) at 253.7 nm[6]. Compared with the conventional method, which tunes the laser frequency and switches the laser with acousto-optical modulator (AOM) in the main cooling beam, it is very important to save the power in UV region. Because it is very hard to generate a high power and narrow linewidth UV laser, the power of UV laser can reach 10～800 mW (but normally operated at 100 mW) which depends on

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作者简介：刘洪力(1984—)，男，博士研究生，主要从事汞原子冷却和光晶格钟方面的研究。E-mail：hongli.cmin@gmail.com

导师简介：王育竹(1932—)，男，院士，主要从事量子光学和原子频标方面的研究。E-mail：yzwang@mail.shcnc.ac.cn (通信联系人)

the method adopted. To lock the laser frequency on $^1S_0$-$^3P_1$ transition of mercury atoms, one should generate a dispersion-like signal with a zero-crossing at the resonance[7]. Due to its high vapour pressure at room temperature, two kinds of laser spectroscopy can be adopted in a very short mercury vapour cell: one is frequency modulation (FM) spectroscopy with high signal-to-noise ratio (SNR), such as frequency modulation spectroscopy[8] and modulation transfer spectroscopy[9-10], and the other is modulation-free spectroscopy, including dichroic atomic vapour laser locking (DAVLL) spectroscopy[11-12], Doppler-free dichroic lock (DFDL)[13-14] and polarization spectroscopy[15]. In this work, we introduce a power saving method to lock and tune the UV laser on $^1S_0$-$^3P_1$ transition of mercury atom, which combines the tunability of two AOMs and frequency modulation spectroscopy.

2 Experiment

In our experimental setup for magneto-optical trap (MOT) of mercury atoms, the 253.7 nm laser (Toptica, TA-FHG pro) was generated with the fourth harmonic generation (FHG) of a fundamental 1014.9 nm laser with the linewidth less than 100 kHz[6]. The 1014.9 nm infrared (IR) laser was generated by a laser diode (LD). After amplified by tapered amplifier the power can reach 1 W. Then the 253.7 nm UV laser was generated by two cascaded second harmonic generation (SHG) stages from the amplified IR laser, and this configuration limited the UV power below 30 mW. The laser was split into two beams, one for frequency stabilization and the other for laser cooling of Hg atoms. As our previous work[16], it requires more than 10 mW for Hg MOT, and for the optimized DFDL spectroscopy, it needs 3.5 mW for pump laser and 0.4 mW for probe laser to get high SNR[17]. To lock and tune the laser frequency of UV laser, we inserted two series AOMs into the beam for frequency stabilization to avoid the power reduction of MOT beam and changed the locking scheme to frequency modulation spectroscopy, as shown in Fig.1. The first order diffraction efficiency of each AOM was limited to 75%, and the center frequency of AOM was about 180 MHz, so the total output efficiency was about 56%. The first AOM was used to tune the laser frequency in +1 order diffraction, and the second to deep modulate the frequency of UV laser in −1 order diffraction, so the detuning from locking frequency was the difference between the center frequencies of two AOMs. The frequency modulation spectroscopy was based on saturated absorption spectroscopy (SAS) in a 5-mm-long mercury vapour cell, which was detected by a photodiode (Hamamatsu, S1336) and amplified with 10^6 V/A. The power consumption in the SAS was much lower than that of DFDL spectroscopy. The pump power was 0.4 mW and the probe power was 0.2 mW. Therefore, we just need about 1 mW for frequency stabilization. After demodulated by a lock-in amplifier (LIA) (SRS, SR850), the FM signal was fed into the high-speed servo controller (New Focus, LB1005) to lock the FHG laser.

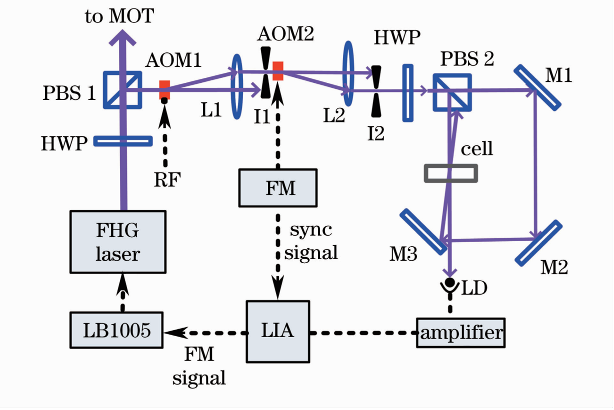

Fig.1 Experimental setup. HWP: half wave plate; PBS: polarization beam splitter; RF: radio frequency; FM: frequency modulated; L: lens; I: iris; M: mirror. The mercury absorption cell is made of UV fused glass with optical length of 5 mm

3 Results and discussion

To optimize the FM spectroscopy, it is necessary to study the principle of frequency modulation in AOM driver, i.e., voltage controlled oscillator (VCO). When driven by a sinusoidal signal, the VCO will generate a frequency modulated radio frequency (RF) signal, then AOM will produce a FM ultrasonic wave, and the first Bragg diffraction beam is also modulated. Given a driven signal with center frequency of ω_A, modulation frequency ω_m and modulation index of M, the first diffraction optical beam has the central frequency of $\omega_A+\omega_0$, where the ω_0 is optical frequency, and the electric field can be written as

$$E = E_0 \exp\{i[\omega_0 t + \omega_A t + M\sin(\omega_m t)]\} = E_0 \exp[i(\omega_0 + \omega_A)t]\sum_{n=-\infty}^{\infty} J_n(M)\exp(in\omega_m t). \quad (1)$$

The frequency components are characterized by the Bessel function J_n, and they have typical FM configuration. The FM signals have remarkable dependence on the modulation index and the modulation frequency, which has been discussed by Supplee *et al*.[18]. When the modulation frequency is 0.01 times of linewidth, to get the optimal FM signal, the modulation index should be 100. The linewidth of the SAS signal was 12 MHz. Limited to the bandwidth of VCO at 0.1 MHz, we used the low modulation frequency of 93 kHz, which was about 0.008 times of linewidth, and the modulation index was 141. In our experiment, the UV laser was sweeping in 2.05 GHz/s. We can compare the FM signal with the SAS signal, as shown in Fig. 2. The peak-to-peak amplitude of the FM signal is 2.5 V and the slope is 418 mV/MHz, while the amplitude of the SAS signal is 3 mV. It is clear that, the SNR of the FM signal is much better than that of the SAS signal, and the laser can be locked on the peak of SAS signal by FM signal.

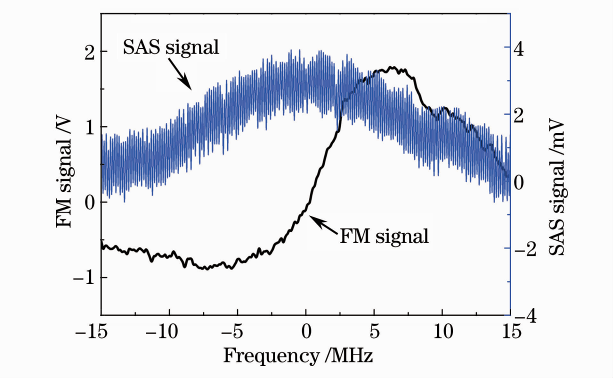

Fig. 2 FM signal and SAS signal of ^{200}Hg

By virtue of the FM method, the laser can be locked on the $^1S_0$-$^3P_1$ transition of Hg atoms. We used a high-speed servo controller (New Focus, LB1005), which is based on proportional integral (P-I) controller, as the servo loop to the FHG laser. Fig. 3 shows the error signal of the laser when the servo loop is on or off. We could find that the error signal ranges from −1.0 V to 2.0 V without the servo loop, which means that without the servo loop, the frequency shift of the UV laser from the resonance frequency could drift from −2.4 MHz to 4.8 MHz. While the natural linewidth of the $^1S_0$-$^3P_1$ transition of Hg is 1.3 MHz, so the UV laser could not be used for laser cooling without the frequency stabilization system. When the servo loop is on, the error signal (laser frequency) can be controlled below 0.04 V (0.1 MHz), so we consider that the laser frequency of UV laser has been effectively stabilized on the $^1S_0$-$^3P_1$ transition. The time constant of the LIA is 30 μs, which means that the bandwidth of the LIA is 4.8 kHz. This also limits the bandwidth of the servo loop. The FM signal is also observed in other isotopes and transitions, and the UV laser is very easy to be locked.

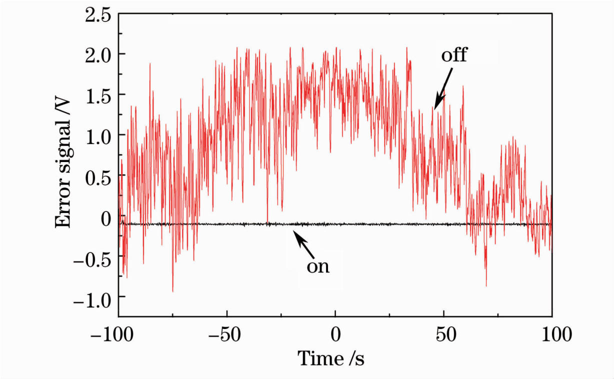

Fig. 3 Frequency stabilization of the UV laser when the servo loop is switch on or off

4 Conclusion

Insummary, we realized a frequency tuning and locking system for the deep UV laser, which could be used for laser cooling of Hg atoms. It includes two AOMs as frequency shifter and frequency modulator of the UV laser, respectively, and the frequency modulation spectroscopy based on SAS configuration is utilized in a mercury vapour cell. The power consumption is about 1 mW for the tuning and locking of the UV laser, and about 28 mW is left for laser cooling. The UV laser is tightly locked on $^1S_0$-$^3P_1$ transition of ^{200}Hg atoms. This is an important step towards the laser cooling of mercury atoms.

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