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# Frequency stabilization of 480 nm laser using two-photon DAVLL

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**Abstract:** Frequency stabilization of a diode laser at 480 nm is crucial for coherently exciting rubidium atoms to Rydberg states. A laser frequency stabilization technique is reported based on electromagnetically induced transparency in a ladder configuration with a polarization spectrum stabilized 780 nm diode laser as the probe laser and a 480 nm laser as the coupling laser. With a uniform magnetic field, a two-photon dichroic atomic vapor laser lock (DAVLL) spectroscopy was generated. Then this spectroscopy was fed back through two proportion-integral-differential circuits to lock the 480 nm diode laser. A combined linewidth of about 1 MHz is achieved during the locking period.

**Key words:** laser techniques; laser frequency stabilization; two-photon dichroic atomic vapor laser lock; Rydberg transition

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# 480 nm 激光器的双光子 DAVLL 谱稳频

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**摘　要：** 480 nm 激光的稳频对于实现铷原子从基态双光子相干激发到里德堡态必不可少。基于梯形构型下的电磁诱导透明现象，一种新的 480 nm 激光器稳频技术采用偏振谱稳频的 780 nm 激光作为探测光而 480 nm 激光则作为耦合光，在外加偏置磁场作用下产生的双光子双色原子气体激光锁频 (DAVLL) 谱，将该谱信号通过比例 - 积分 - 微分电路后反馈回 480 nm 激光器即可实现稳频。在频率锁定后，480 nm 激光器和 780 nm 激光器长时间稳频的总线宽为 1 MHz 左右。

**关键词：** 激光技术；激光稳频；双光子双色原子气体激光锁频；里德堡态跃迁

## 1　Introduction

Highly excited Rydberg atoms with principal quantum number $n > 30$ have attracted worldwide interest in the last decades. Due to their large transition dipole moments, many researches focus on strong interactions

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between Rydberg atoms[1] and interactions between Rydberg atoms and surface[2]. Also Rydberg atoms can be taken to implement controlled NOT gate[3] or demonstrate entanglement of two neutral atoms[4]. These Rydberg atoms are usually excited by two frequency stabilized lasers in a noncoherent step or in a coherent process, with one laser exciting atoms from ground state to intermediate states and the second laser from intermediate states to Rydberg state.

For rubidium atoms, the first laser corresponding to rubidium D1 or D2 transition can be easily stabilized with conventional methods[5] such as dichroic atomic vapor laser lock(DAVLL)[6], polarization spectroscopy(PS)[7], frequency modulation(FM) spectroscopy[8], Sagnac interferometry[9,10], and so on. Meanwhile the second laser which is about 480 nm can be locked to excited-Rydberg state transitions only in two ways: stabilizing with a stable reference cavity[11~14] or using electromagnetically induced transparency (EIT) based on FM[15]. In this paper, we demonstrate another method to stabilize the 480 nm laser to rubidium $5P_{3/2}$-$n$D transition which is based on two-photon DAVLL. It is suitable for different Rydberg states with principal quantum number $n$ between 39 and 85. Compared with the other two methods, this one is simple and robust. There is no extra alignment of a cavity or an electro-optic modulator (EOM) or additional care with cavity drift. With careful alignment in mechanics and precision feedback control in electronics, we are also able to stabilize the frequency to a narrow linewidth in long term and short term using this method.

## 2 Theory and experimental setup

The two-photon DAVLL is based on an EIT ladder system in a rubidium vapor cell at room temperature[16]. A weak probe laser which is frequency locked to ground state and intermediate state transition counter-propagates with an intense coupling laser in the cell. As the frequency of the coupling laser scans across the transition of the intermediate and a Rydberg state, intensity of the probe beam will show a Gaussian transmission peak induced by EIT as shown in Fig.1(a). So with a uniform magnetic field to increase (decrease) the central frequency of the right (left) circularly polarized probe laser, the result of subtracting this $\sigma^+$ and $\sigma^-$ probe laser will show a dispersion-like lineshape[17] which can be used as the error signal for locking.

In our experiment, we use $^{85}$Rb with the energy level shown in Fig.1(b). The linear polarized probe laser propagates along the axis of the 100 mm long vapor cell at the power of 0.2 mW and beam waist of 0.8 mm. The probe laser is generated by a homemade diode laser in the Littrow configuration, and it is locked to $5s^2S_{1/2}(F=3)$-$5p^2P_{3/2}(F=4)$ transition using polarization spectroscopy. Meanwhile 200 mW coupling laser with beam waist of 1.5 mm is adjusted to overlap with the probe laser in the cell but propagate in the opposite direction as showed in Fig.1(c). The coupling laser is produced by a commercial frequency doubled diode laser system (Toptica TA-SHG 110). We tune its wavelength to desired transitions[18] using a wave meter. The uniform magnetic field is generated by a galvanic solenoid bound outside the vapor cell. Proper current will generate desired error signals. And these error signals are fed back to TA-SHG 110 with slow signals to piezo and fast signals to laser current. It is executed by a Toptica DigiLock 110 module with two PID circuits inside and the locking bandwidth is about 10 MHz.

## 3 Results and Analysis

To examine the feasibility of our method to different Rydberg state transitions, we generate error signals of transitions $5p^2P_{3/2}(F=4)$-$n$D with $n$ between 39 and 85. For transitions to 39D, we tuned the coupling laser to 480.843 nm. Then we get two EIT peaks of probe transmission as shown in Fig.2(a) by scanning the coupling laser in the range of dozens of megahertz. The two peaks represent transitions to $39D_{5/2}$ and $39D_{3/2}$

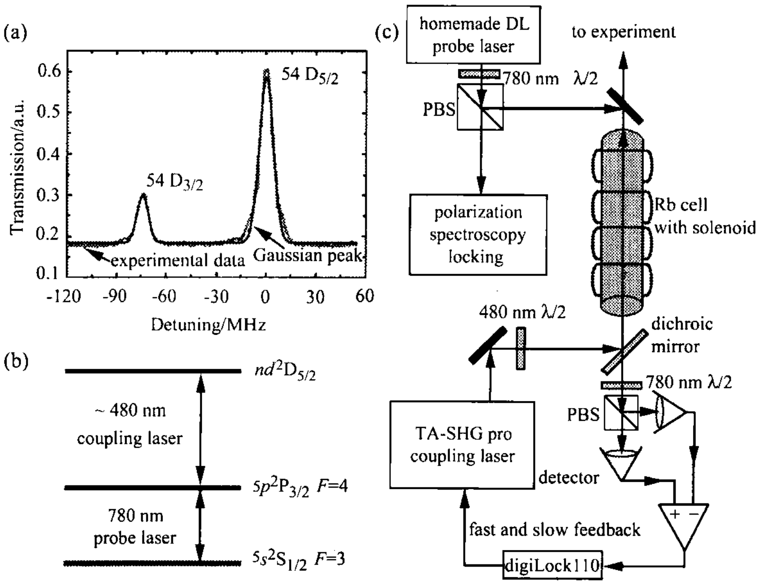
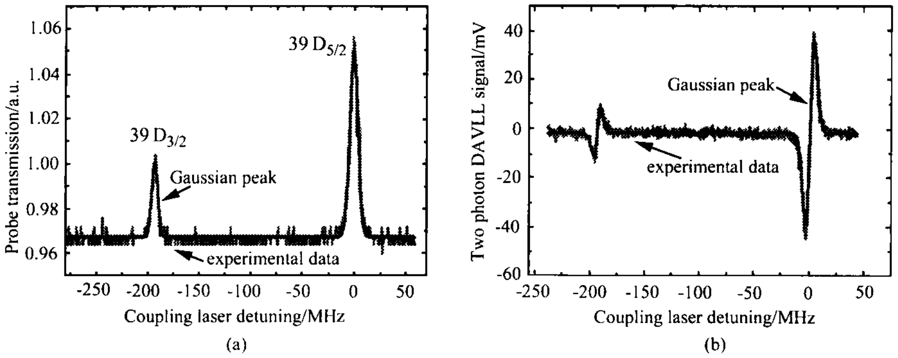


Fig.1 (a) Probe transmission as coupling laser is scanned over $5p^2P_{3/2}(F=4)$-54D transition while the probe laser is locked to D2 transition. Experimental data fitted by two Gaussian peaks with interval of 74 MHz. (b) Energy level for EIT ladder system. (c) Schematic of the experimental setup



(a) (b)

Fig.2 Probe transmission as coupling laser is scanned over $5p^2P_{3/2}(F=4)$-39D transition while the probe laser is locked. (a) Experimental data fitted by two Gaussian peaks with $39D_{3/2}$ peak located at −93.5 MHz and $39D_{5/2}$ peak at 1.05 MHz. (b) Generated two-photon DAVLL signal for 39D Rydberg state. Experimental data fitted by dispersion-like curve. The dispersion-like curve is the subtraction of two nearby Gaussian peaks

respectively and the frequency interval between them is calibrated to be 195 MHz. This value is in agreement with the measured 39D fine structure splitting of (204±10) MHz[19]. We calibrate the frequency by relating frequency to the scanning voltage where scanning 71 mV results in 40 MHz frequency change. A current of 0.02 A is applied to the solenoid to generate 1 Gauss uniform magnetic field. Then we get two-photon DAVLL signal as shown in Fig.2(b). We use the $39D_{5/2}$ two-photon DAVLL signal as the error signal whose slope is 14.55 mV/MHz. We also tried transitions to 85D with the coupling laser tuned to 479.419 nm. The merely separated two peaks have the frequency interval of 15.8 MHz which is close to a theoretical value of 18.4 MHz[19]. And the slope of two-photon DAVLL signal is measured to be 5.06 mV/MHz.

We then achieved frequency stabilization as shown in Fig.4 by feeding back these error signals to the 480 nm laser. For short-term stability measurement of the 480 nm laser, we use the self-heterodyne methods by observing the beat signal of the laser with itself frequency shifted by 80 MHz meanwhile delayed by a 1.2 km

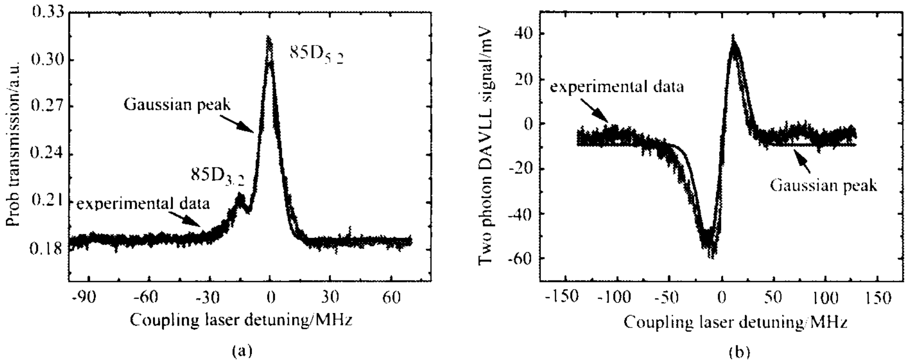


Fig.3 Probe transmission as coupling laser is scanned over $5p^2\mathrm{P}_{3/2}(F=4)$-85D transition while the probe laser is locked. (a) Experimental data fitted by two Gaussian peaks with $85\mathrm{D}_{3/2}$ peak located at −15.8 MHz and $85\mathrm{D}_{5/2}$ peak at 0.02 MHz. (b) Generated two-photon DAVLL signal for 85D Rydberg state. Experimental data fitted by dispersion-like curve

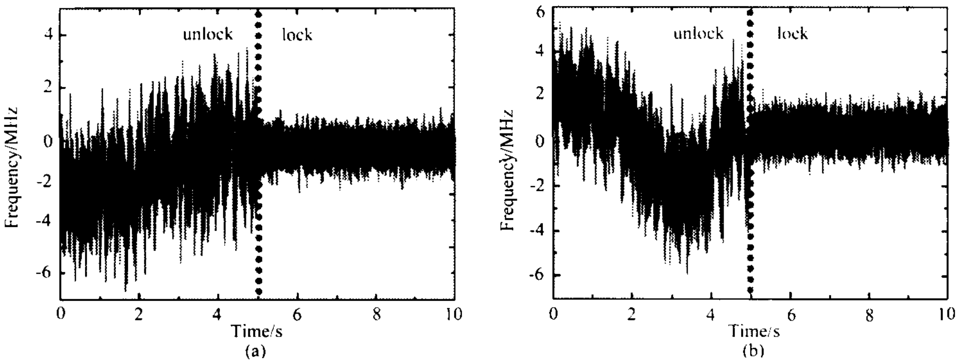


Fig.4 Fluctuation of error signals of unlocking and locking statuses for (a) 39D transition and (b) 85D transition

long fiber. We have then measured the linewidth of the 480 nm coupling laser to be about 400 kHz in 6 μs. For stability measurement in seconds, we analyze the fluctuations of the locking signals which show Gaussian fraction distribution. Multiplied by the slope of the error signal, we get the combined linewidth for 39D to be $\sigma$=488 kHz and for 85D $\sigma$=1.06 MHz in hours. This linewidth well fits the requirement[14] for coherently exciting Rydberg states.

Also we have tried locking 480 nm laser to 54D transition which is at the middle between 39D and 85D, and a combined locking linewidth of 747 kHz is achieved with hours of locking time. It is noted that for bigger $n$D, the locking linewidth is larger. This is because when $n$ increases, the peak height of the probe transmission caused by EIT decreases, then the slope of error signal causes the locking linewidth to increase. With enough high EIT transmission peak, the slope of error signal will be sufficient for locking and our method can be expanded to higher $n$D. Similar result can be obtained when we use $^{87}$Rb but with larger locking linewidth due to smaller EIT transmission peaks.

## 4 Conclusions

In conclusion, we have experimentally demonstrated another method for locking 480 nm laser to excited-Rydberg state transitions. With this method, the two step excition from $5s^2\mathrm{S}_{1/2}(F=3)$ to $n$D state with 780 nm and 480 nm lasers showed a total locking linewidth of about 1MHz during hours of locking time. This

linewidth is narrow enough for coherently exciting Rydberg atoms and is comparable with the existing locking methods. We expect this result will be soon applied in experiments of quantum computation with Rydberg atoms.

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