Laser frequency locking based on Rydberg electromagnetically induced transparency*

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We present a laser frequency locking to Rydberg transition with electromagnetically induced transparency (EIT) spectra in a room-temperature cesium vapor cell. Cesium levels $6S_{1/2}$, $6P_{3/2}$, and the $nD_{5/2}$ state, compose a cascade three-level system, where a coupling laser drives Rydberg transition, and probe laser detects the EIT signal. The error signal, obtained by demodulating the EIT signal, is used to lock the coupling laser frequency to Rydberg transition. The laser frequency fluctuation, ∼0.7 MHz, is obtained after locking on, with the minimum Allan variance to be 8.9×10^{-11}. This kind of locking method can be used to stabilize the laser frequency to the excited transition.

Keywords: Rydberg, electromagnetically induced transparency (EIT), laser locking

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1. Introduction

The laser frequency stabilization has been playing an important role in the atomic physics experiments, especially in the fields of optical frequency standards, atomic clocks, quantum memory,[1–3] and so on. Many stabilization techniques lock laser frequency to the atomic ground state transitions, including dichroic atomic vapor laser locking (DAVLL),[4,5] combined saturated absorption spectra (SAS) and DAVLL,[6] polarization spectroscopy,[7] Sagnac interferometry,[8] modulation transfer spectroscopy,[9,10] and injection locking technique.[11] The other technique is locking the laser frequency to the reference cavity,[12,13] where the laser frequency couples the transition between two excited states or the molecular reference lines. The cavity-locking method strongly depends on the environmental factors such as temperature and pressure. Recently, the electromagnetically induced transparency (EIT) of the Rydberg (principal quantum number $n \gg 1$) cascade system[14] has been widely investigated and used as a dispersive reference to lock the laser frequency to excited state transitions. Abel *et al.*[15] stabilized the laser frequency to the Rydberg transition with a cascade Rydberg EIT in a rubidium vapor cell at room temperature using the frequency modulation spectroscopy.[16] The Rydberg EIT can be used to realize quantum logic gates,[17] single-photon sources,[18,19] and single-photon transistors[20] by means of the Rydberg blockade effect.[21,22]

In this work, we present a method of locking the laser frequency to the excited Rydberg transition. An EIT signal provides a direct relative frequency reference with the sub-natural spectral widths based on atomic coherence.[23,24] The locking method is mainly based on a cascade EIT involving highly excited Rydberg states in a cesium vapor cell at room temperature, which can be used to lock the laser frequency to the transition of two excited states. For getting the error signal, we apply a weak modulation to the probe laser resulting in the modulated EIT signal. We use a lock-in amplifier to demodulate the modulated EIT spectra to obtain the error signal and lock the laser frequency to Rydberg transition. The Allan variance is introduced to evaluate the frequency stability.

2. Experimental setup

We perform EIT experiments in cesium vapor cell at room temperature, in which a coupling laser, 510-nm laser with power of 3.5 mW and radius of 50 μm, strongly drives Rydberg transition, $6P_{3/2}$ $(F' = 5) \rightarrow nD_{5/2}$ $(n = 49)$, while a weak probe laser (852 nm, 4.5 μW, and radius of 80 μm), probes the ground transition $6S_{1/2}$ $(F = 4) \rightarrow 6P_{3/2}$ $(F' = 5)$. The coupling laser counter-propagates with the probe laser through a 50-mm long vapor cell.

The schematic of the experimental setup and the related Rydberg ladder three-level scheme are shown in Fig. 1. The ground state $|g\rangle$ and the Rydberg state $|r\rangle$ form a coherent state. The EIT signal can map the information of the excited state transition to the ground state transition. By probing the ground state transition $|g\rangle \rightarrow |e\rangle$, the excited transition $|e\rangle \rightarrow |r\rangle$ is detected using EIT. A diode laser (Toptica, DL100) is used as the probe laser, whose frequency is locked to the transition of $6S_{1/2}$ $(F = 4) \rightarrow 6P_{3/2}$ $(F' = 5)$ with a frequency modulation technique using an SAS, not shown here. The modulation frequency is 1 kHz and modulation amplitude is

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~10 MHz, which are produced with a function generator (FG) and by modulating the PZT of the probe laser. Meanwhile, the FG is used to trigger the lock-in amplifier for obtaining an error signal of the Rydberg transition. A commercial laser (Toptica, TA-SHG110) is used as the coupling laser, which is tuned to the Rydberg transition $6P_{3/2}$ $(F' = 5) \rightarrow nD_{5/2}$.

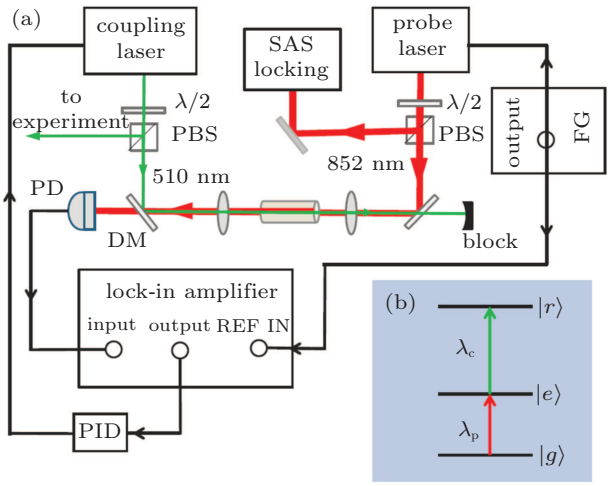


Fig. 1. (color online) (a) Schematic of the experimental setup. The 510-nm coupling laser, counter-propagates with the probe laser, 852 nm, through a cesium vapor cell. The probe beam, modulated using a function generator (FG) with the modulation frequency of 1 kHz, is detected using a photodiode (PD) resulting in a modulated EIT signal. The error signal, demodulated EIT signal produced using a lock-in amplifier, is fed back to the controller of the coupling laser through PID and used to lock the coupling laser frequency to Rydberg transition. (b) The energy levels, the ground state $6S_{1/2}$ $(F = 4)$ $(|g\rangle)$, the excited state $6P_{3/2}$ $(F' = 5)$ $(|e\rangle)$, and the Rydberg state $nD_{5/2,3/2}$ $(|r\rangle)$ consist of a cascade three-level system. By probing the ground state transition $|g\rangle \rightarrow |e\rangle$, the excited transition $|e\rangle \rightarrow |r\rangle$ is detected using EIT.

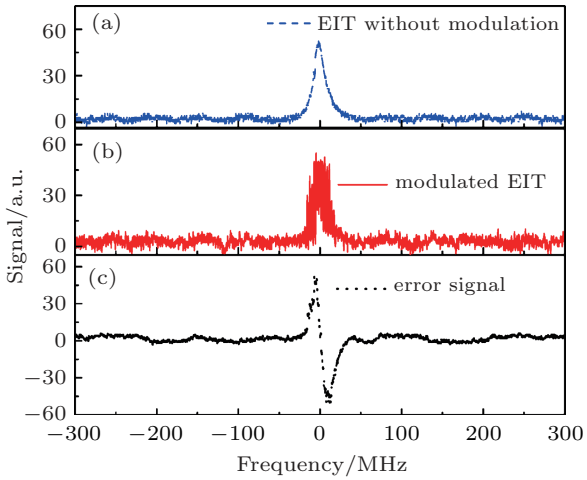


Fig. 2. (color online) (a) An EIT signal without frequency modulation. A typical modulated EIT spectrum (b) and corresponding error signal (c) for the probe beam locking to transition $6S_{1/2}$ $(F = 4) \rightarrow 6P_{3/2}$ $(F' = 5)$ with SAS spectrum and the coupling laser scanning through resonance $6P_{3/2}$ $(F' = 5) \rightarrow 49D_{5/2}$.

The transmission of the probe laser, which is resonant with the lower transition $|g\rangle \rightarrow |e\rangle$, is detected with a photodiode (PD) after a dichroic mirror (DM). Due to the current/frequency modulation of the probe laser, we obtain a modulated EIT signal, as shown by the red line in the middle curve in Fig. 2. The EIT signal can be demodulated using a lock-in amplifier (Stanford, SR830) triggered by the same FG in the port REF IN, leading to the error signal, shown by the black dotted line in the bottom curve in Fig. 2, obtained by the lock-in output. The error signal is fed back to the current import of the laser controller for compensation of the laser cavity using the feedback PID.

3. Results and analysis

In experiments, the probe laser is locked to the $6S_{1/2}$ $(F = 4) \rightarrow 6P_{3/2}$ $(F' = 5)$ transition using the SAS technique, while the coupling laser is scanned through the Rydberg transition $6P_{3/2}$ $(F' = 5) \rightarrow nD_{5/2}$ $(n = 49$ in this work). When the coupling laser frequency is resonant with the Rydberg transition, we can get the EIT signal. As the coupling laser is slowly and linearly scanned, the probe laser is rapidly modulated (at 1 kHz) to about its fixed central frequency. The rapid oscillations in EIT signal reflect the 1 kHz probe modulation (see Fig. 2(b)). Comparing with the EIT spectra without modulation (see the blue dashed line in Fig. 2(a)), it is clearly demonstrated that the EIT profile is broadened and strongly modified due to the weak modulation of the probe laser. Note that, the modulated EIT signal is likely observed for the Rydberg EIT spectroscopy due to the large polarizabilities $(\sim n^7)$[25] of the Rydberg level. From the modulated EIT signal, we can obtain an error signal using the lock-in amplifier (see the black dotted line in Fig. 2(c)), which provides a method to stabilize the coupling laser frequency to the Rydberg transition using the Rydberg EIT.

Figure 3 presents the frequency stability of the coupling laser with and without lock switch on, which is measured with a wavelength meter (HighFinesse-Angstrom WSU-30). Compared with the large fluctuation for laser free running, the frequency stability is improved significantly after PID switching on, the corresponding frequency stability of the coupling laser reaches ± 0.7 MHz, and the frequency fluctuation is less than 1 MHz in a given period of 220 s.

The method we presented in this work, the current/frequency modulation of the probe laser, provides us with two kinds of error signals: one coming from the SAS of the probe laser for locking the laser to the ground state transition, the other from the Rydberg EIT signal for locking the coupling laser to the Rydberg transition.

The error signal is recorded and analyzed using the square root of the Allan variance, $\sigma(\tau)$,[26] which is measured as a function of the averaging time, τ. The results of $\sigma(\tau)$, with a measure interval of 0.1 s, are shown in Fig. 4, where the black squares denote the laser free-running and the red circles

denote the laser stabilized to the Rydberg transition. The minimum $\sigma(\tau)$ is 6.3×10^{-10} at 1.6 s for the laser free-running and 8.9×10^{-11} at 6.4 s for the laser stabilization. The dashed line represents the theoretical calculation, $\sigma(\tau)$, due to the white noise and flicker phase noise for locking on, which is proportional to $\tau^{1/2}$. Comparing two results, we find that the frequency stability is improved considerably. The frequency stability is sufficient for the Rydberg experiments.

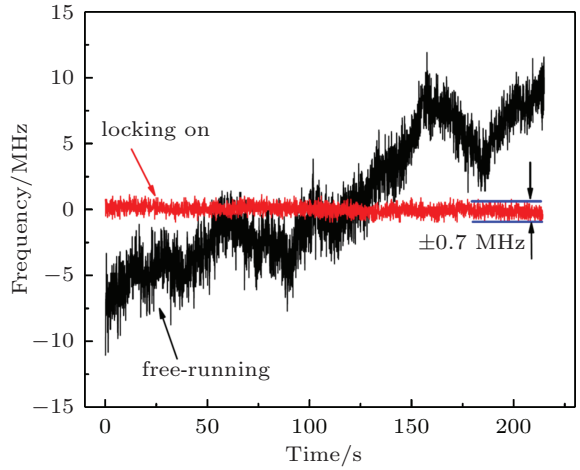


Fig. 3. (color online) Monitored laser frequency of the coupling laser with and without locking on. After locking on, the laser frequency fluctuation is strongly suppressed, the frequency stability is ±0.7 MHz, and the frequency fluctuation was less than 1 MHz in a given period of 220 s.

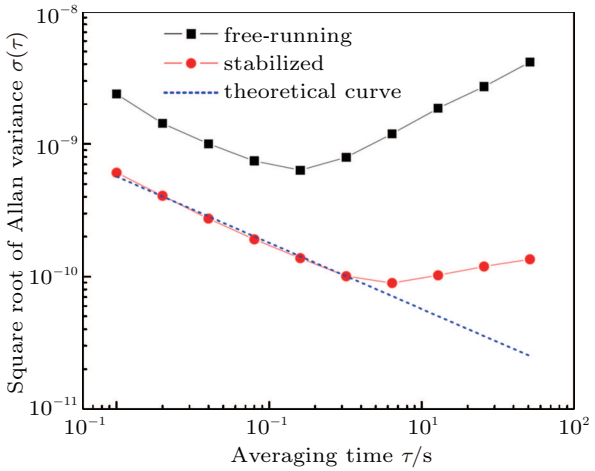


Fig. 4. (color online) Square root of Allan variance as a function of averaging time, τ, for the coupling laser locking on (red circles) and free running (black squares). The measured minimum, $\sigma(\tau)$ with a measure interval of 0.1 s, is 6.3×10^{-10} for free-running and 8.9×10^{-11} for laser stabilization. The dashed line represents the theoretical curve.

4. Conclusion

In summary, we have performed a laser frequency stabilization to excited Rydberg transition based on a Rydberg cascade three-level EIT. The modulation of the probe laser can be used to produce two kinds of error signals at the same time, both for locking the probe laser to the ground state transition and the coupling laser to Rydberg transition. The modulated EIT signal also enables the detection of a weak Rydberg EIT signal due to the small dipole matrix of Rydberg transition 6P→*n*S/*n*D by using the demodulation technique.[27]

This kind of locking method can be used to stabilize laser frequency to excited Rydberg transition and lock two lasers with a fixed frequency difference related to the atomic transition line. The case of Rydberg excitation displays power dependence due to the dipole matrix of 6P→*n*S/*n*D being strongly dependent on *n*.[28] This approach may be particularly useful for experiments of Rydberg atoms and other excitation schemes in atomic physics experiments.

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