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Laser frequency offset-locking using electromagnetically induced transparency spectroscopy of ^{85}Rb in magnetic field*

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We have experimentally offset-locked the frequencies of two lasers using electromagnetically induced transparency (EIT) spectroscopy of ^{85}Rb vapor with a buffer gas in a magnetic field at room temperature. The magnetic field is generated by a permanent magnet mounted on a translation stage and its field magnitude can be varied by adjusting the distance between the magnet and Rb cell, which maps the laser locking frequency to the space position of the magnet. This frequency–space mapping technique provides an unambiguous daily laser frequency detuning operation with high accuracy. A repeatability of less than 0.5 MHz is achieved with the locking frequency detuned up to 184 MHz when the magnetic field varies from 0 up to 80 G.

Keywords: electromagnetically induced transparency, offset-lock, rubidium atom, magnetic field

PACS: 42.50.Gy, 32.60.+i, 32.10.Fn, 32.80.Xx **DOI:** 10.1088/1674-1056/27/9/094205

1. Introduction

Laser beam sources with their relative frequency difference locked are important for the studies of laser–atom interactions, such as slow light,[1] lasing without inversion,[2–4] and atomic clocks.[5–8] These laser sources needed for experiments can be obtained from a single laser beam or two/multi different laser beams. The simplest approach is to employ an acousto-optical modulator (AOM),[9] or an electro-optical modulator (EOM),[10] or to directly modulate the driving current of a diode laser.[11] AOM can shift the laser frequency by GHz and easily separate the generated beam in space, but the diffraction efficiency of an AOM at modulation frequency up to several hundreds of MHz is usually low. The methods using EOM and by direct modulation of the laser current can provide rich band branches, but it is difficult to separate the generated beam from the mother one spatially.

Many experimental schemes have been proposed to lock the relative frequency of two laser beams. For example, laser frequency difference between two lasers up to 10 GHz can be attained by using their beating signal,[12,13] which needs complex electronic devices to achieve phase detection and rapid proportional-integral-derivative processes. The technique of cavity-assisted frequency locking[14,15] can synchronically lock the lasers with different wavelengths to one common cavity, where a stable cavity system with a precise cavity length should be guaranteed. The third method is using atomic spectroscopy, such as electromagnetically induced transparency (EIT),[16–19] where the frequency difference can be determined by the EIT resonance. With the aid of the Raman process, the two lasers are differentially locked to an atomic hyperfine splitting. As the EIT resonances can be much narrower than the natural transition linewidth, the frequency-locking is of high precision.

However, the frequency-locking based on EIT is not tunable. In this paper, we introduce a magnetic field to the ^{85}Rb atomic EIT system in the vapor cell and experimentally demonstrate a simple tunable laser frequency offset-locking technique at room temperature. When the magnetic field generated by a permanent magnet is perpendicular to the laser beam direction, the EIT resonance of the D_2 line of ^{85}Rb atoms will split into six components.[20,21] Since the coupling light is locked by the modulated saturated absorption spectroscopy (SAS), the probe laser will be subsequently stabilized in frequency by the error signal from one particular EIT splitting spectral line in the magnetic field. Thus the relative frequency offset between the two lasers can be altered as the magnitude of the externally applied magnetic field varies. Moreover, we can map the laser locking-frequency to the space position of the magnet, providing a mechanism to unambiguously detune the laser frequency in daily operation.

2. Experiment

Our experimental setup is shown in Fig. 1(a) and the related transition energy levels are shown in Fig. 1(b), which

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is similar to our previous work.[22,23] Both the master and slave lasers (Moglabs) have external cavity structures with line-width around 100 kHz. The master laser serves as the coupling beam, locked by a modulated SAS, and the slave laser is taken as the probe one, scanning across the D_2 line to record the EIT spectrum. The polarization and power of the two lasers can be controlled by an optical combination of the $\lambda/2$ plate and polarization beam splitters (PBS). The polarizations of the coupling and the probe lasers are linearly and mutually orthogonal with beam size around 1 mm^2 for each. The coupling and probe laser beams are carefully superimposed on one PBS and overlap almost completely throughout the two spherical shaped cells. Two permanent magnets are placed close to cells 1 and 2 to supply uniform magnetic fields for the ^{85}Rb atoms, respectively. The magnetic field direction is along the electric field of the probe laser (y-axis in Fig. 1). The magnetic field strength can be tuned by varying the distance between the magnet and the cell. PM 1 is mounted on a translation stage for accurate positioning while PM 2 is fixed. The strongest accessible magnitude can be up to 1000 G. It should be noted that the parts in the dotted frame of Fig. 1(a) are not necessary for the offset-locking. They are used to evaluate the stability of the offset-locking. We will refer to them in the concerned parts.

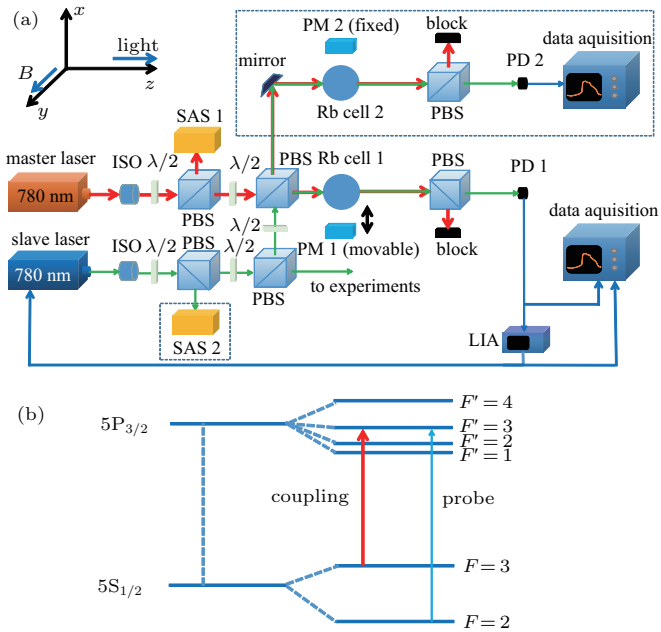


Fig. 1. (color online) (a) Experimental setup for frequency offset-locking using EIT and (b) the related transition energy levels. ISO: optical isolator; $\lambda/2$: half-wave plate; PBS: polarization beam splitter; SAS: saturated absorption spectroscopy; PM: permanent magnet; PD: photo detector; LIA: locking-in amplifier. Note that the parts in the dotted frame are not necessary for the offset-locking. They are used to evaluate the stability of the offset-locking. See text for details.

The frequency offset-locking is performed on the EIT spectral line of ^{85}Rb in cell 1. As shown in Fig. 1(a), the master laser, serving as the coupling beam, is stabilized by its SAS and the slave laser is locked to one of the EIT spectral lines of ^{85}Rb in cell 1. The locked probe laser frequency can be finely tuned by moving the stage holding the permanent magnet PM 1 since the atomic energy levels can be shifted by the applied magnetic field. Using this tunable laser source, we demonstrate its application in recording a sample spectrum of Rb in cell 2 and then evaluate its locking performance. Both cells are made of pyrex glass with spherical shape and filled with pure ^{85}Rb and N_2 buffer gas at a pressure of 5 Torr at room temperature, with a size of diameter 2 cm. No magnetic field shielding is applied outside the ^{85}Rb vapor cell.

3. Results and discussion

Figure 2 shows the observed EIT spectrum and its error signal of ^{85}Rb with N_2 buffer gas in a zero magnetic field. The line-width can be reduced by several orders of magnitude when the cell is filled with buffer gas since it can restrict the motion of the EIT atoms and thus increase the interaction time of alkali atoms with the laser beam.[24,25] The coupling laser is locked to the SAS transition $F = 3$ to $F' = 2\&4$ while the probe laser scans across the D_2 line of ^{85}Rb. The EIT resonance occurs when the frequency difference between the two lasers precisely matches the ground-state hyperfine splitting 3035.7 MHz. The probe laser is modulated at a frequency of 250 kHz and a lock-in amplifier is employed to decode the modulated EIT signal, giving a clear error signal. The error signal can be fed back to the probe laser driver to stabilize its frequency.

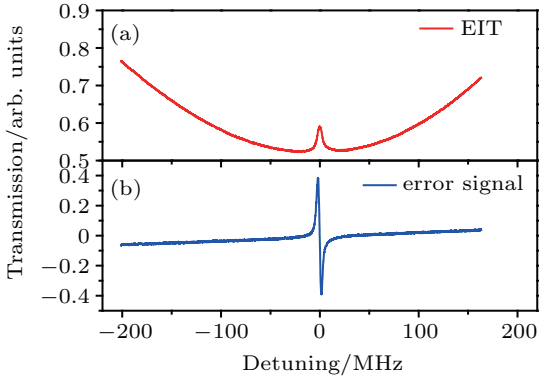


Fig. 2. (color online) (a) The field-free EIT spectrum and (b) the corresponding error signal for ^{85}Rb with N_2 buffer gas.

The EIT resonance of the D_1 or D_2 line of Rb atoms in a magnetic field has been studied a lot both theoretically and experimentally.[20–23,26–28] For example, corresponding to the polarization combination of the coupling and probe beams shown in Fig. 1(a), where the magnetic field is perpendicular to the laser directions, there are ten Λ-EIT subsystems satisfying the resonant condition $\omega_p - \omega_c = [E(F = 2, m_F) - E(F = 3, m_F)]/\hbar$ as shown in Fig. 3(a). They give only six spectral components since some transitions overlap each other for

the same resonance frequency, as shown in Fig. 3(b). The six groups of spectral peaks correspond to the transitions 10, (5,9), (4,8), (3,7), (2,6), and 1, where the numbers are the labels shown in Fig. 3(a). The experimental observations of ^{85}Rb spectrum in magnetic fields agree well with our theoretical prediction shown in Fig. 3(b). To achieve a wider tunable offset-locking frequency range for the probe laser in the same magnetic field, it is better to lock the laser to the EIT signal peak of transition 1 since it has a maximum frequency shift due to Zeeman splitting.

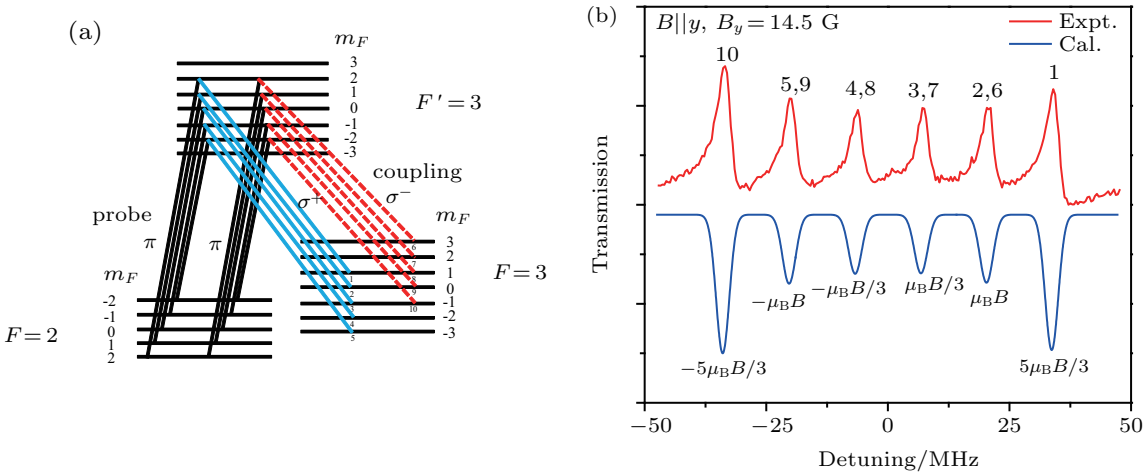


Fig. 3. (color online) Magnetic sublevel diagram of ^{85}Rb atoms in the presence of magnetic field. All possible polarization combinations for the Λ-EIT scheme are shown in panel (a). The observed and calculated splittings of EIT resonances in magnetic field $B = 14.5$ G along the probe laser polarization direction are shown in panel (b) as an example.

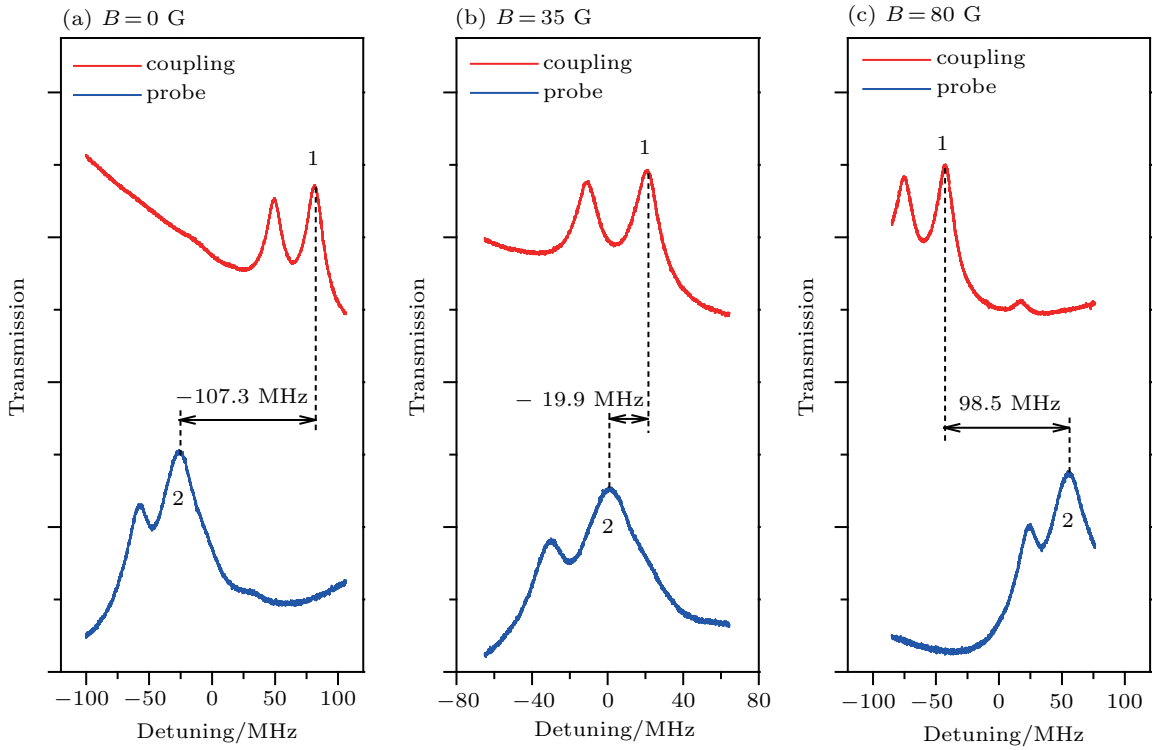


Fig. 4. (color online) The SAS of the coupling laser and the corresponding SAS of the probe laser with different magnetic fields applied on cell 1: (a) $B = 0$ G, (b) $B = 35$ G, (c) $B = 80$ G. The frequency difference corresponds to the additional energy shift based on the hyperfine-splitting of the ground state.

To evaluate the frequency offset-locking performance, we simultaneously record the SAS spectra of the coupling and probe lasers after the two lasers have been offset-locked using EIT. In this case, SAS 2 in Fig. 3(a) is complemented into the optical scheme while the error signal to the master laser driver is disconnected from SAS 1. Once the probe laser is offset-locked to the coupling laser by the EIT signal peak of transition 1 shown in Fig. 3(b), the frequency difference between the two lasers should be constant. Thus the probe laser frequency will subsequently follow the coupling laser and even the cou-

pling laser frequency is varied. Therefore, we can record the SAS spectra of ^{85}Rb in both SAS cells at the same time, just by scanning the coupling laser frequency. The recorded spectra are shown in Figs. 4(a)–4(c), respectively, corresponding to different magnetic fields $B = 0$ G, 35 G, and 80 G applied to cell 1. The spectral peak 1 in SAS 1 corresponds to transition $F = 3$ to $F' = 3\&4$ while peak 2 in SAS 2 corresponds to transition $F = 2$ to $F' = 2\&3$, where the transition frequency difference is determined by the hyperfine splitting of the ground state $^5S_{1/2}$. We can see that the offset-locking frequency difference can be slightly tuned by applying a different magnetic field to the EIT atoms in the vapor cell, which is very useful for extending the offset-locking frequency. In our case, the additional offset-locking frequency varies from a negative value -107.3 MHz at zero field to a positive value 98.5 MHz at magnetic field $B = 80$ G, which is caused by the Zeeman energy shifts for the EIT atoms in cell 1.

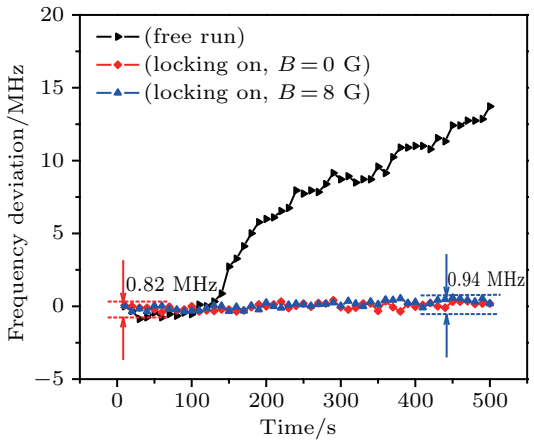


Fig. 5. (color online) Monitored frequency deviation of the probe laser with and without locking. The red line corresponds to frequency offset-locking using the EIT signal under zero magnetic field while the blue one corresponds to frequency offset-locking using the EIT signal with transition 1 in the magnetic field of 8 G. Compared to the free-running denoted by the black line, the laser frequency deviation is strongly suppressed after locking on. The frequency deviation is less than 1 MHz in a given period of 500 s, resulting in a linewidth estimation of less than 0.5 MHz for each single laser.

In this way, we can obtain the probe laser frequency offset-locking performance in the cases with and without magnetic field, as shown in Fig. 5, where a free-running frequency deviation is also presented for comparison. We can see that the laser frequency varies in a wide range when it is free-running, while the laser frequency offset-locking using EIT works well in both cases without and with the magnetic field ($B = 8$ G). The laser frequency deviation is strongly suppressed after locking on, which is less than 1 MHz in a given period of 500 s. The linewidth of a single laser can be estimated as $0.82/2 = 0.41$ MHz and $0.94/2 = 0.47$ MHz for the cases of $B = 0$ and $B = 8$ G based on a Gaussian profile model. The narrower linewidth in the case without a magnetic field is due to the better signal-to-noise ratio for the EIT spectrum used for offset-locking in a free field, which will be discussed later.

The tunable laser frequency offset-locking system using EIT still works well even when the externally applied magnetic field on cell 1 is up to 80 G, as shown in Fig. 6. When the magnetic field increases from $B = 0$ G to $B = 16$ G, the offset-locking uncertainty for a single laser gets larger linearly from 0.41 MHz to 0.56 MHz, but after that it drops down to 0.26 MHz when the magnetic field increases to 35 G. After crossing this critical point, it becomes larger and larger again until it gets nearly saturated after $B = 55$ G, stabilizing at 0.52 MHz or so. In the whole magnetic field range, the best working point is located at magnetic field $B = 35$ G, corresponding to a locking uncertainty 0.26 MHz. From the recorded SAS spectra for both lasers after frequency offset-locking in different magnetic field conditions as shown in Figs. 4(a)–4(c), we can see that the locking stability strongly relies on the signal-to-noise ratio of the spectrum in the applied magnetic field. Here, in Fig. 6, the best signal-to-noise ratio occurs around $B = 35$ G for both SAS spectra, while at other magnetic fields, one of them becomes very weak, leading to a worse locking performance. At most magnetic fields, the locking uncertainty is below 0.5 MHz. In the accessible locking range, we can obtain a tunable frequency offset-locking of about 184 MHz when the externally applied magnetic field on the cell 1 varies from 0 to 80 G. The offset-locking δ_v here is evaluated based on the hyperfine-splitting of the ground state Δ_g as discussed previously, that is, the actual total frequency offset is $\delta_v + \Delta_g$.

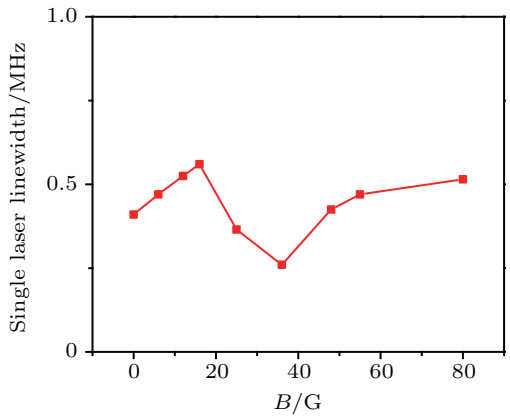


Fig. 6. (color online) The estimated line-width of the probe laser after locking on with different magnetic fields applied on cell 1.

This tunable frequency offset-locking technique based on the EIT spectrum of ^{85}Rb in a magnetic field can provide a method to map the laser frequency scanning to the space position of the permanent magnet on the stage, which is very vital in the daily operation for the high precision spectroscopic measurement. In this test bench, the coupling laser has been locked by SAS 1. As discussed previously, the offset-locking can be slightly tuned by varying the external magnetic field intensity applied on the EIT atoms in cell 1. To precisely control the magnetic field strength, we mount the permanent magnet PM 1 on a mechanical stage with stepsize in order of μm,

through which a stable and repeatable laser frequency for the probe laser can be managed.

To check the reliability of this frequency detuning scheme, another Rb cell 2 of the same size as cell 1 has to be employed to record its spectrum by moving the permanent magnet PM 1. Unfortunately, its resonant frequency is out of our tuning range. As shown in the dotted frame of Fig. 1(a), a second permanent magnet PM 2 is used to raise the energy levels of atoms in cell 2. The recorded Zeeman EIT spectra in this cell are shown in Fig. 7 twice but obtained on two different days. The applied magnetic field on cell 2 is 22.5 G. The first signal peak corresponds to the transition group $(2,6)$ while the second to the one 1 shown in Fig. 3(b). For the first signal peak, the recorded magnetic field magnitude difference between the two experimental measurements is about 0.2 G. The corresponding scaling coefficient of frequency shift to magnetic field magnitude is about 2.3 MHz/G, obtained from a calculation, giving an uncertainty estimation for the tunable frequency-offset locking about 0.46 MHz. It might be caused by a slightly different daily locking point of the coupling laser on its own SAS spectral line.

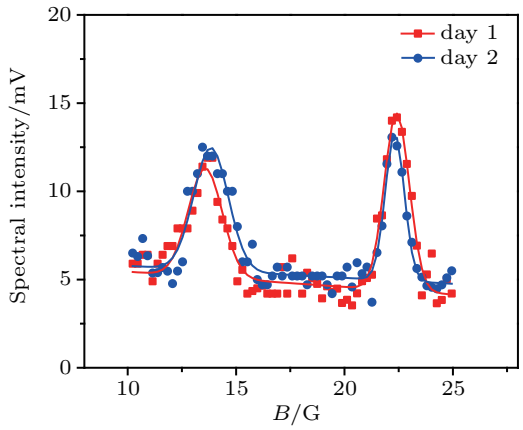


Fig. 7. (color online) The recorded EIT spectrum of Rb atom in cell 2 by tuning the magnetic field on cell 1. The tuning of the magnetic field on cell 1 can shift the locking point of atoms in cell 1, subsequently driving the probe laser frequency, which scans across the transition resonant lines of atoms in cell 2. The magnetic field on cell 1 varies from 10 G to 25 G while an additional magnetic field of 22.5 G is applied to raise the resonant energy to an appropriate position accessible by the probe laser. The blue and red lines stand for the experimental recordings on two different days, respectively.

4. Conclusion

In summary, we are able to lock the laser frequency by using electromagnetically induced transparency spectroscopy in a buffer gas cell with a magnetic field applied. The offset-locking frequency of the laser can be tuned by altering the applied magnetic field. This tunable frequency offset-locking technique excludes the limitation of low diffraction efficiency in AOM-frequency-shifting. Furthermore, it can provide a method to map the laser frequency scanning to the space position of the permanent magnet on a mechanical translation stage, making an unambiguous frequency scaling for daily laser detuning, which is useful and suitable for many experiments with tunable frequency locking. It is expected that a better repeatability can be achieved if a magnetic field shielding is applied.

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