

Two Schemes of Modulation-Free Frequency Stabilization of Grating-External-Cavity Diode Laser via Cesium Sub-Doppler Spectra

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ABSTRACT

We report two methods of modulation-free frequency stabilization of a laser to sub-Doppler atomic absorption line. The first one employs the magnetically induced sub-Doppler dichroism in cesium vapor cell based on Zeeman effect. The second one utilizes two acousto-optical modulators (AOM) as well as sub-Doppler spectra to generate dispersion-like signal. We compared the residual frequency fluctuation in preliminary stabilization with the case of free running. These two schemes can avoid the additional frequency noise as well as intensity noise due to the direct frequency dither on laser source.

Keywords: modulation-free frequency stabilization, magnetically induced dichroism, sub-Doppler spectra, cesium vapor cell, acousto-optical modulator

1. INTRODUCTION

In spite of its abroad application, single-mode diode lasers typically have a free-running linewidth of more than 10MHz, which is too larger for many fields of research and application, such as high-resolution spectroscopy, laser cooling and trapping, optical fiber communication, and etc ^[1]. To create a magneto- optical trap (MOT) of neutral atoms, the cooling/trapping lasers must have linewidth of at least as narrow as the natural linewidth of the atomic cycling transition, typically linewidth of 1 MHz. At the same time, long-term frequency stability of the corresponding diode laser must be required against drifts by locking it to a naturally broadened atomic transition.

Actually, laser frequency stabilization is to lock the laser frequency to some physical references, for example, optical cavity and atomic or molecular transition lines. Depending on whether the reference spectroscopy profiles are Doppler-broadened or Doppler-free, the methods can be divided two classes. The former has the advantages of wide capture range and large signal, whereas in all the labs dealing with laser cooling and trapping of atoms, the technique of Doppler-free saturated absorption spectroscopy is frequently used as a tool for locking the laser frequency to the center of the particular atomic hyperfine transitions or crossover resonances. Consequently, the sub-Doppler stabilization schemes are more perfect despite of its relatively small capture range, on which the saturated absorption spectroscopy (SAS) techniques are mostly relied. Velocity-selective optical pumping of a Doppler-broadened atomic or molecular transition is achieved by counter-propagating pump-probe configuration ^[2]. To get the dispersion-like frequency

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discriminating signal for frequency locking normally a direct frequency dither is applied on the laser in SAS lock technique. Though a high signal-to-noise ratio (S/N) is achieved, more or less, it will introduce additional noise in laser frequency and intensity, which might be unacceptable in some applications.

Alternatively, modulation-free frequency stabilization with sub-Doppler spectroscopy technique is applied. Instead of dithering the laser frequency directly, people desire to plus the modulation signal to the optical or the electrical elements, which produces various simple but effective methods. Based on different experimental situation, in this paper we introduce two methods of modulation-free laser frequency stabilization: 1) the first one is based on a behavior of the atomic vapor cell in an external magnetic field, which will induce sub-Doppler dichroism for σ^+ and σ^- Zeeman components. Combining the Doppler-free spectra and the magnetically induced dichroism detection method^[3], we can lock the laser frequency to cesium hyperfine transition without frequency dither; 2) the second one is based on two acousto-optical modulators (AOM) with slightly different driving frequency that is offered by corresponding voltage-controlled oscillators (VCO). We may realize the laser frequency stabilization with a certain detuning to atomic hyperfine line conveniently.

2. METHODS OF MODULATION-FREE FREQUENCY STABILIZATION

2.1 Stabilization using Doppler-free magnetically-induced dichroism

2.1.1 Introduction to the principle^[3-6]

The basic idea of Doppler-free dichromatic spectroscopy is illustrated in Fig. 1. The experimental set up could be used to generate a dispersion-like signal due to Zeeman effect based on the saturation absorption spectroscopy techniques. In the case of simple model of $F=0 \leftrightarrow F'=1$ transition, under zero magnetic field, all Zeeman sublevels in the excite state $F'=1$ are degenerate with the same resonance frequency ω_0 . The Zeeman sublevels will be split due to the cesium vapor absorption cell placed in a longitudinal magnetic field. The linearly polarized probe laser can be considered as the coherent sum of equal intensities orthogonal circularly-polarized components, σ^+ and σ^- . As Fig.3 (a)

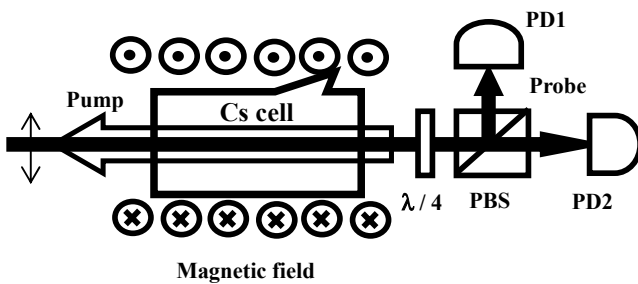


Figure 1 Setup to generate dispersion-like signal by Zeeman effect. PD1 and PD2 are photodetectors, PBS is a polarization beam splitter, $\lambda/4$ is a quarter wave-plate.

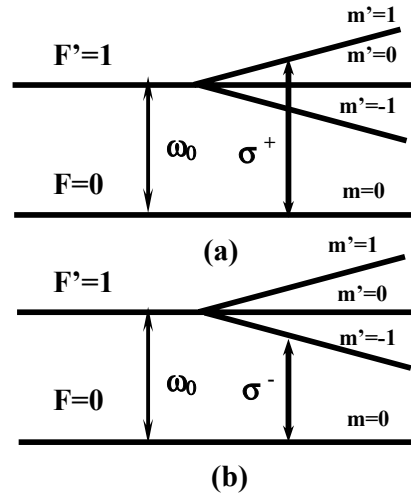


Figure 2 The simplest two-level atomic model $F=0 \leftrightarrow F'=1$ transition, with ω_0 the unperturbed transition frequency. (a). Atom interacting with a σ^+ photon. (b). Atom interacting with a σ^- photon because of the magnetic splitting of Zeeman sublevel.

shown, the weak magnetic field B_0 generated by a solenoid, which results in the splitting of the σ^+ and σ^- components in different frequency tendency separated by $\Delta E/h$ due to Zeeman effect. ΔE is the energy gap between $m'=1$ and $m'=-1$, and is approximately given in the weak field regime as $\Delta E = \Delta E(m' = 1) - \Delta E(m' = -1) = 2g_{F'} \cdot \mu_B \cdot B_0$, here $g_{F'}$ is the Lande factor of the $F'=1$ hyperfine excited state and μ_B is the Bohr magneton. In another picture, we use a simple hole-burning model of a velocity selective saturation, in which two Lorentzian dips are frequency shifted relatively to each other in the Doppler profile. The subtraction signal will be a dispersion-like signal that can be used to stabilize the laser frequency.

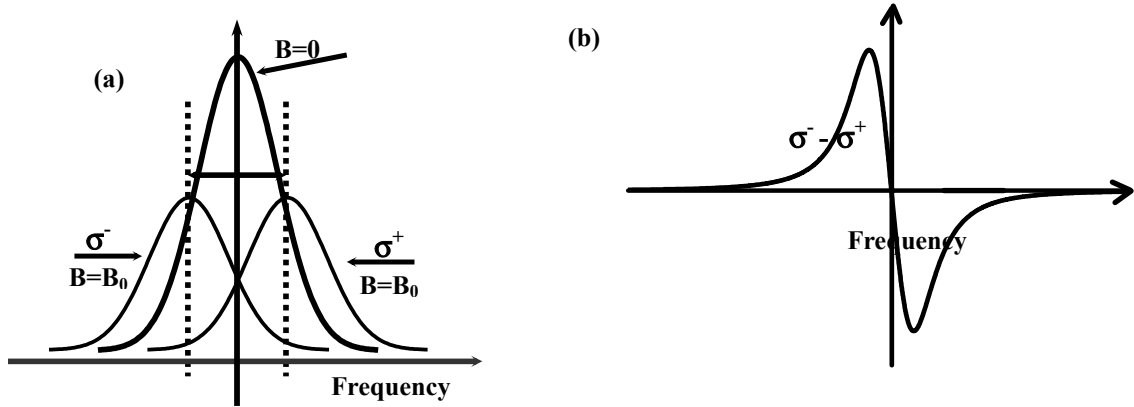


Figure 3 (a). The σ^+ and σ^- components are Zeeman shifted towards different frequency direction. (b). A dispersion-like signal can be obtained by subtraction and it will be used

As mentioned, to generate such a relative shift in frequency between two saturated absorption signals, we use magnetically-induced dichroism [3]. A vapor cell is placed in magnetic field along the propagation axis of two counter-propagating pump and probe beams as Fig.1 shown. The σ^+ and σ^- components of the linearly-polarized probe beam create corresponding saturated absorption profiles, which are Zeeman shifted by the same amount but in different directions. By detecting the two components and subtracting their signals from each other, a Doppler-free Dichroic Atomic Vapor Laser Lock (DAVLL) signal is created [4-6].

With the light beam passing through cesium vapor cell in a longitudinal weak magnetic field B_0 , the atomic transition splits into σ^+ and σ^- Zeeman components as in Fig.3 (a), which is the origin of a magnetically-induced dichroism of the medium. When using a linearly-polarized probe beam, we can get dichroic Doppler-free signal by using $\lambda/4$ plate and polarization beam splitter (PBS) cube.

2.1.2 Experimental setup

As shown in Fig.4, we explain our experimental setup from laser source to the photo-detectors and the proportion and integration amplifier (P-I) with which the signal will feedback to the laser. A grating external-cavity diode laser (ECDL) system operates at cesium D_2 line. The output beam is collimated within the laser head, and it passes through a

40-dB isolator to avoid optical feedback. A tunable beam-splitter unit consisting of $\lambda/2$ plate and PBS is used to pick up a small fraction of optical power from the main output for frequency locking.

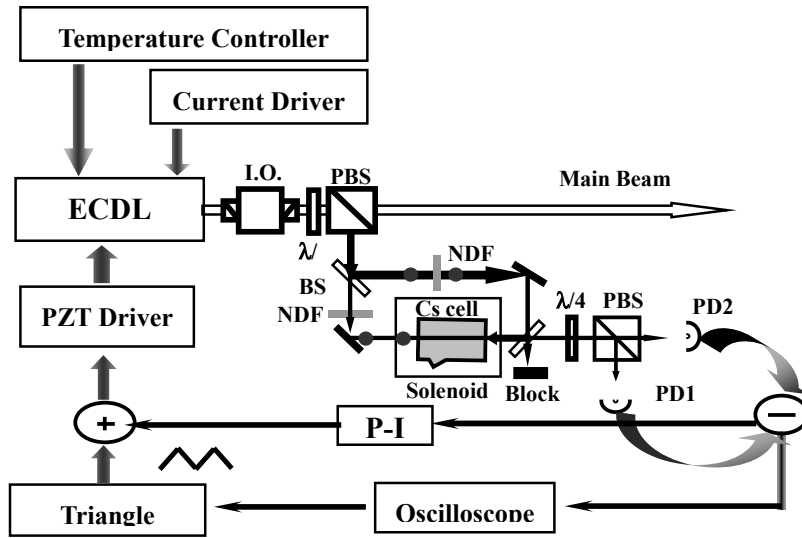


Figure 4 Experimental setup, the dashed-line frame displays the saturation absorption system. **ECDL**: grating external-cavity diode laser; **O.I.**: optical isolator; **PBS**: polarization beam splitter cubes; **BS**: beam splitter plate; **P-I**: proportion & integration amplifier; **NDF**: neutral density filter; **PDs**: photodiodes.

The pump and probe beams with parallel linear polarizations counter-propagate through a 30-mm-long cesium vapor cell which is placed inside a solenoid with approximately 10 Gauss of magnetic field. Two neutral density filters (NDF) are used to adjust power of pump beam and probe beam to $\sim 250\mu\text{W}$ and $\sim 14\mu\text{W}$, respectively. The σ^+ and σ^- components are separated by $\lambda/4$ plate and PBS, and detected by two photodiodes (PD1 and PD2). After subtracting the two signals, a sub-Doppler dispersion-like frequency-discriminating signal is obtained to lock ECDL.

For locking the laser, the amplified spectroscopic signal is sent to a P-I amplifier and the output signal with typically bandwidth of 10kHz, which is feedback to the piezoelectric transducer (PZT) port of the ECDL to correct the frequency error by adjusting the external cavity length.

2.1.3 Results and discussion

We reasonably choose the crossover of cesium $6S_{1/2} F = 4 \leftrightarrow 6P_{3/2} F' = 4$ and 5 as the reference frequency standard. A typical frequency fluctuation at free-running condition in 50 s is approximately 12 MHz, mainly due to mechanical noise. After dichroic locking an estimated residual frequency fluctuation is less than ± 240 kHz in the preliminary stabilization as shown in Fig.5. In our experiment, only the slow feedback signal is used to PZT port of ECDL system,

which can against the frequency shift in the long term. If the fast signal is added to the laser current modulation port, we can restrain the high frequency jitter effectively.

This scheme is insensitive on power fluctuation and drifts in comparison of the DAVLL method ^[3], despite the DAVLL method has a large capture range based on the Doppler-broadened linewidth. Another point is, it will offer a bigger slope of the dispersion-like signal for locking the laser frequency powerfully.

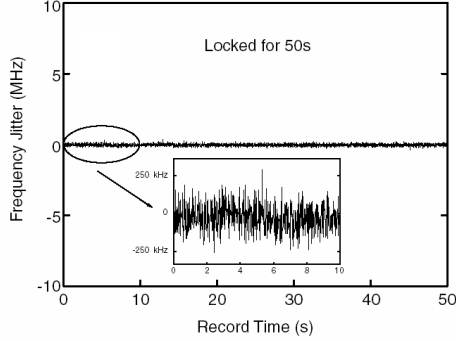


Figure 5 After dichroic locking the residual jitter is estimated less than ± 240 kHz in 50 s, compared with 12MHz in free running.

Such simple and low-cost method to stabilize the laser frequency has many advantages. Firstly, the spectroscopic signals are relatively insensitive to power fluctuations and varying stray magnetic fields. Secondly, it provides a dispersion-like signal with a zero-crossing at the unperturbed transition frequency with low offset, on which a laser can easily be locked. Finally, it is so economical that the expensive lock-in amplifier not needed anymore.

2.2 Stabilization using AOM shifting

2.2.1 Principle ^[7-10]

Based on the idea of the saturated absorption spectroscopy, we suppose that a simple atoms model with only two internal states, the ground state for $|g\rangle$ and the excited $|e\rangle$. When two counter-propagating laser beams derived from a laser are sent through atomic vapor cell, typically the pump beam has about ten times higher intensity than the probe beam, which causes a velocity selection saturation of a Doppler-broadened spectroscopy profile that a Gaussian absorption profile $G(\omega)$ with a Lamb dip in the center of $\omega = \omega_0$, ω_0 is the atomic resonance frequency. Thus we can get the total signal

$$S_{\text{sat}}(\omega) = G(\omega) - L(\omega), \quad (1)$$

$G(\omega)$ is the Gaussian absorption profile

$$G(\omega) = A \exp \frac{-(\omega - \omega_0)^2}{\sigma^2}, \quad (2)$$

here σ is the width of this distribution arising from the Maxwell-Boltzmann velocity distribution of the atoms, A is the amplitude of this distribution, and $L(\omega)$ is the Lamb-dip corresponding to a Lorentzian line profile

$$L(\omega) = \frac{(\Gamma/2)^2}{(\omega - \omega_0)^2 + (\Gamma/2)^2}, \quad (3)$$

here Γ is atomic natural linewidth.

In our experiment, we utilize two radio-frequency (RF) voltage-controlled oscillators (VCO) connected with power amplifier modules (MiniCircuits ZHL-1-2W) to drive the corresponding acousto-optical modulators (AOM) (Crystal Technology 2080-122) with slightly different frequency of $\Omega - \Delta$ and $\Omega + \Delta$, which makes the frequency shifted with $\pm \Delta$ to the resonance frequency $\omega_0 + \Omega$, as shown in Fig. 6. We have two pump-probe setups, and consequently results in two saturated absorption signals, $S_1(\omega) = S_{\text{sat}}(\omega_0 + \Omega - \Delta)$ and $S_2(\omega) = S_{\text{sat}}(\omega_0 + \Omega + \Delta)$. By subtracting the two signals detected by a pair of same characteristic detectors, $S(\omega) = S_1(\omega) - S_2(\omega) = [G_1(\omega) - G_2(\omega)] + [L_1(\omega) - L_2(\omega)]$, one can get the dispersion-like signal to lock laser to $\omega_0 + \Omega$ point. For $\Delta, \Gamma \ll \sigma$, it is easily shown that $[G_1(\omega) - G_2(\omega)] \ll [L_1(\omega) - L_2(\omega)]$ at $\omega \approx \omega_0 + \Omega$.

The signal is dominated by the subtraction of the two frequency shifted Lamb-dip. On the one hand, the larger the relative detuning Δ , the larger the capture range. On the other hand, the steeper the slope of dispersion-like signal, the more powerful the recapturing capability. So we trade off between these two factors and choose Δ typically half the width of the Lamb-dip.

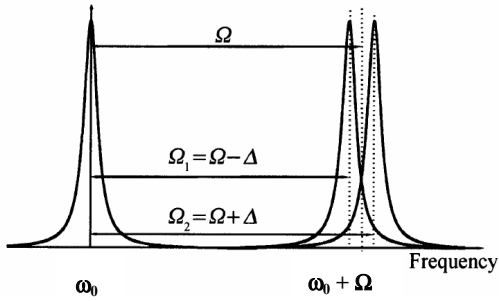


Figure 6 Two Doppler-free absorption peaks around $\omega_0 + \Omega$ frequency-shifted by the AOMs.

2.2.2 Experimental setup

Our experimental setup is shown in the Fig. 7 with the same ECDL system as the part of 2.1.2. A tunable beam-splitter unit consisting of $\lambda/2$ plate and PBS is used to pick up a small fraction of optical power about 4mW. After 50/50 beam splitter two beams with the same power are generated. They pass through corresponding AOM system each other consisted of lenses of $f=200\text{mm}$, $f=100\text{mm}$ and AOM, and their frequencies are shifted 80MHz-5MHz and 80MHz+5MHz relative to cesium $6S_{1/2} F = 4 \leftrightarrow 6P_{3/2} F' = 5$ hyperfine transition, respectively.

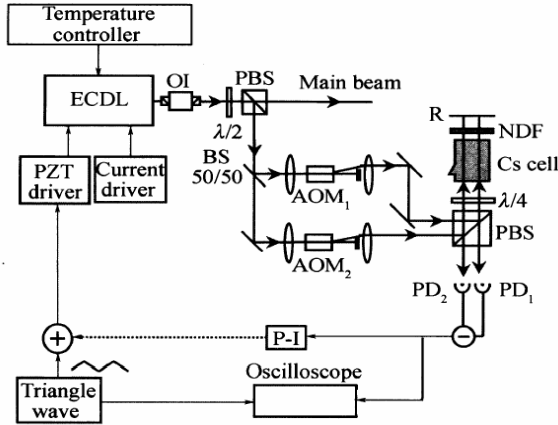


Figure 7 Experimental setup, **ECDL**: grating external-cavity diode laser; **O.I.**: optical isolator; **PBS**: polarization beam splitter cubes; **BS**: beam splitter plate; **P-I**: proportion & integration amplifier; **NFD**: neutral density filter; **PDs**: photodiodes; **AOM**: acousto-optical modulator.

Each AOM is driven by RF VCO with amplifier (Mini-Circuits ZHL-1-2W) which allows the frequency of the shifted light exiting the AOM to be precisely controlled. Two SAS setups are established through cesium vapor cell with the frequency shifted light from each AOM with the intensity ratio about 10:1. The absorption signal of each probe beam is monitored on photodiodes (Hamamatsu: 3399). We obtain frequency-shifted sub-Doppler absorption spectra. In 2.2.1 we explained that the relative frequency shifting $\Delta = 5\text{MHz}$ and the natural linewidth of the cesium atomic D_2 transition $\Gamma = 5.2\text{MHz}$, which is much less than the Doppler background profile $\sim 500\text{MHz}$. After subtracting the two signals, the appropriate frequency-discriminating signal is attained, as shown in Fig. 8. We can lock the laser frequency to cesium $F = 4 \leftrightarrow F' = 5$ hyperfine transition by adjusting the suitable proportion and integral parameters of P-I amplifier.

2.2.3 Results and discussion

This scheme provides us a simple tool to lock ECDL system to desired and reproducible detuning from the cesium D_2 line for long time. We can change the value of the relative frequency shift 2Δ , which may be used to optimize the stabilization. As a result shown in Fig. 9, we reduce frequency fluctuation to $\sim \pm 270\text{ kHz}$ in 50 s when we set

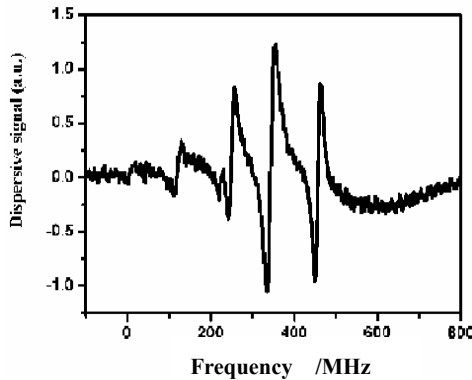


Figure 8 Dispersion-like line shape signal is produced by the configuration shown in Figure 7.

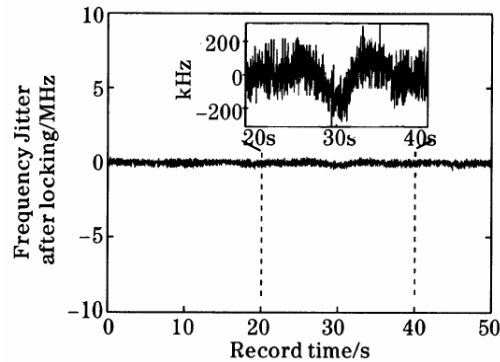


Figure 9 After AOM shifting locking, the estimated frequency jitter is about $\pm 270\text{ kHz}$ during 50 s, compared with 12MHz in free running.

$2\Delta = 10$ MHz. This frequency stabilized ECDL system can be used to realize cesium magneto-optical trap to get cold cesium atoms.

3. CONCLUSION

In conclusion, we have presented two methods of modulation-free laser frequency stabilization. On the one hand, it offers an advantage of high precision of frequency stability, similar to conventional technique of saturation absorption spectra. On the other hand, both the stabilization systems only use a differential amplifier and proportion and integration amplifier, without the requirement of a lock-in amplifier and laser frequency modulation. Despite their simplicity, the schemes will be a effective tool for precisely locking a laser to an atomic transition. Finally, the methods are insensitive for fluctuations in beams power and external factors such as stray magnetic fields, further more the two schemes of frequency stabilization can be extended to other wavelengths using different atomic vapor samples.

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