Laser frequency stabilization using a dispersive line shape induced by Doppler Effect

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Abstract: We report a simple and robust Doppler-free spectroscopic technique to stabilize a laser frequency to the atomic transition. By employing Doppler Effect on the atomic beam, we obtained a very stable dispersive signal with a high signal-to-noise ratio and no Doppler-background, which served as an error signal to electronically stabilize a laser frequency without modulation. For validating the performance of this technique, we locked a DFB laser to the $^{133}$Cs D2 line and observed an efficient suppression of the frequency noise and a long-term reduction of the frequency drifts in a laboratory environment.

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1. Introduction

Stabilizing the laser frequency to atomic transition lines is always essential for many applications, for example, precision metrology, frequency standards, laser cooling experiments, and coherent optical communications. A variety of methods have been reported in literatures. In general, the main idea of all these methods is devoted to find a dispersive signal around an atomic resonance, which acts as feedback to lock the laser frequency. Such dispersive signal is conventionally named error signal.

The most popular way is generating such a dispersive signal from saturated absorption spectroscopy through modulation and demodulation technique [1–3]. This technique can provide a dispersive signal with a high signal-to-noise ratio to suppress the low-frequency 1/f noise, however, at the cost of a limitation of the feedback bandwidth by the modulation frequency. For increasing the feedback bandwidth to suppress the frequency noise in a typical experimental environment, several modulation-free schemes have been reported in literatures, such as Dichroic Atomic Vapor Laser Lock (DAVLL) [4] and its variants [5], Polarization Spectroscopy (PS) [6–8], Atomic Non-linearly GEnerated Laser Locking Signal (ANGELLS) [9] and so on. These works mostly rely on thermal vapor cells, so the Doppler Effect can hardly be avoided during the experiments. This effect will reduce the sensitivity of frequency discrimination by broadening the spectral line, and bring Doppler background to the spectral signal, which leads to a shift of the zero-crossing point used for frequency locking. Most importantly, these disadvantages caused by Doppler Effect are closely connected the temperature of vapor, the light power and the magnetic field [8], making the spectroscopic signal unstable. In addition, as to Polarization Spectroscopy scheme, the dispersive signal is sensitive to the two light beam polarizations, which rotates due to the variation of light power in the cell.

In order to overcome this problem, in this paper we used an atomic beam instead to interact with the laser perpendicularly. This method enables us to make use of the Doppler Effect [10, 11] to generate a dispersive signal with strong robustness but no Doppler background, and stabilize the laser frequency without modulation of light.

2. General idea

As is illustrated in Fig. 1(a), a weak probing laser interacts with the atomic beam perpendicularly. When the laser is tuned around the atomic resonance, atoms will absorb photos and emit fluorescence at the same time. Scanning the laser frequency and monitoring the transmission light by a photoelectric detector, we will obtain the absorption spectrum. Supposing that the divergence angles of the atomic beam and the laser beam are both small enough to be ignored, we consider the absorption spectrum as a Lorentzian shape without Doppler broadening. The absorption spectrum can be written as:

\[
G(\omega) = A \left( \frac{1}{\left( \frac{\Delta \omega}{2} \right)^2 + (\omega - \omega_0)^2} \right) + B, \tag{1}
\]

where \( A \) is a factor proportional to the laser power and the flux of the atomic beam; \( \Delta \omega \) is the full width at half maximum (FWHM) of the spectral line; \( \omega \) is the laser frequency; \( \omega_0 \) is the atomic resonance frequency; \( B \) is the DC background proportional to laser power. Figure 1(b) shows that the laser is not orthogonal to the atomic beam, but tilts by a small angle \( \theta \). Due to Doppler Effect, the resonance frequency between the laser beam and atoms will be displaced. The absorption spectrum with a new center frequency is given by:

\[
G(\omega) = A \left( \frac{1}{\left( \frac{\Delta \omega}{2} \right)^2 + (\omega - \omega_0 + \delta \omega)^2} \right) + B, \quad \delta \omega = \omega_0 \frac{\nu}{c} \sin \theta, \tag{2}
\]
where \( c \) is the velocity of light in vacuum; \( \nu \) is the most probable velocity of atoms; \( \delta \omega \) is the Doppler shift. If we subtract two absorption spectrums with opposite tilt angles [Fig. 1(c)], we will obtain a dispersive signal \( F(\omega, \theta) \) illustrated in Fig. 2.

\[
F(\omega, \theta) = G(\omega, \theta) - G(\omega, -\theta) = A \frac{4(\Omega_0 - \omega) \delta \omega}{[(\Delta \omega)^2 + (\omega - \Omega_0 + \delta \omega)^2][(\Delta \omega)^2 + (\omega - \Omega_0 - \delta \omega)^2]}.
\]

(3)

It shows that the line-width of the dispersive line signal only depends on \( \Delta \omega \) and \( \delta \omega \). However, when we take the residual beam divergence into consideration, the result will be different.

\[
F(\omega, \theta) = \int \int [G(\omega, \theta) - G(\omega, -\theta)] f(\alpha) f(\nu) d\alpha d\nu,
\]

(4)

\[
G(\omega, \theta) = A \frac{1}{(\Delta \omega)^2 + (\omega - \Omega_0 + \delta \omega)^2} + B, \ \delta \omega = \frac{\omega c}{\omega_0} \sin(\theta - \alpha).
\]

(5)

Here \( f(\alpha) \) is the atomic population distribution of horizontal divergence angle \( \alpha \); \( \nu \) is the atom velocity, \( f(\nu) \) is the velocity distribution. We can see that the line-width of the dispersive signal depends on \( \Delta \omega \), \( \nu \) and \( \alpha \).
In our experiments, \( f(\alpha) \) can be approximately taken as uniform distribution as long as the residual beam divergence angle is very small.

\[
f(\alpha) = \frac{1}{\Omega}, \quad (-\frac{\Omega}{2} \leq \alpha \leq \frac{\Omega}{2}),
\]

(6)

where \( \Omega \) is the max horizontal beam divergence angle. And \( f(\nu) \) can be written as [12]:

\[
f(\nu) = \frac{2\nu^3}{\nu^4} e^{-\frac{\nu^2}{2}}, \quad (\nu \geq 0).
\]

(7)

Figure 3 shows that the beam divergence \( \alpha \) has an impact on the dispersive signal \( F(\omega, \theta) \). With \( \alpha \) increasing, the signal amplitude weakens and the signal line-width broadens rapidly. It is necessary to minimize the beam divergence angle, keeping it at least less than 2 degrees.

To generate such a dispersive line signal, we use a beam tube of 30 cm length, which is common in the optically pumped cesium beam frequency standard.

3. Experiment and result

The experimental arrangement is shown in Fig. 4(a). The laser source was a DFB laser diode with 3 MHz line-width, operating at 852 nm. Its frequency can be finely tuned by adjusting the injection current with a rate of 700 kHz/\( \mu \)A. A variable part of the laser power was split for spectroscopy by using a combination of a half-wave plate and a polarizing beam splitter. Passing through an aperture of 2 mm in diameter, the laser beam was divided into two beams of the same power by another combination of a half-wave plate and a polarizing beam splitter. Two lenses were aligned with their focuses overlapped to make two light beams first slightly convergent, and then collimated again. A tube covered by a magnetic shield was kept vacuum inside. In the
tube $^{133}$Cs atoms were sprayed out horizontally from an oven. The oven’s temperature, which determined the atom beam flux and atom speed, was well controlled. At a distance of about 20 cm from the oven along the direction of the atomic propagation, a small aperture of a 5 mm diameter was aligned as a vector filter, insuring the atomic beam was almost collimated with a horizontal divergence less than 1.4 degrees. There were two optical windows on the surface of the tube, which allowed the laser to pass through the tube and interact with atoms. Then the two light beams were detected separately by two self-made balanced photo-diodes (PDs). The difference between the two signals formed a dispersive signal.

In actual experiments, the oven was heated to 373 Kelvin, with a fluctuation less than 1 Kelvin. So the beam flux could be estimated as $10^{10}$/s, with the relative fluctuation less than 1%. According to the formula of the most probable velocity, we have:

$$\nu = \sqrt{\frac{2RT}{M}} = \sqrt{\frac{2 \times 8.314 \times 373}{0.133}} = 216 \text{ m/s},$$

(8)

where $R = 8.314 \text{ (Jmol}^{-1}\text{K}^{-1})$ is the molar gas constant; $T = 373 \text{ K}$ is the oven temperature; $M = 0.133 \text{ (kgmol}^{-1})$ is the molar mass of Cesium atoms. The wavelength of the laser is $\lambda = 852 \text{ nm}$. So the frequency shift $\delta \omega$ can be calculated, while the tilt angle $\theta$ is equal to 1 degree.

$$\delta \omega = \omega_0 \frac{\nu}{c} \sin \theta = \frac{\nu}{\lambda} \sin \theta = 4.4 \text{ MHz}.$$  

(9)

According to Eq. (3) and Fig. 2, the slope of the dispersive signal get the maximum value...
when $\delta \omega$ is equal to about 0.58 times [5] the line-width $\Delta \omega$. As to the cycling transition (4-5 transition) of the Cesium D2 line, the absorption spectral line width of the resolution limit is determined by twice a natural line-width $\sim 2\Gamma = 10$ MHz. So it is proper to set the tilt angle at about $10 \times 0.58/4.4 = 1.3$ degrees, though the actual line-width of the absorption line is somewhat broader than the resolution limit, due to the power broadening.

Figure 4(b) shows the estimation of the angle. The focal length of lens 1 was $L_1 = 100$ mm, where the distance between the two light was $d_1 = 5$ mm; the focal length of lens 2 was $L_2 = 250$ mm, where the distance between the two light was $d_2 = 12$ mm.

$$\theta = \frac{1}{2} \frac{d_1 + d_2}{L_1 + L_2} = 0.024 \text{ rad} = 1.4 \text{ degrees.} \quad (10)$$

The power of two light beams were both equal to 25 uW after we carefully adjusted the two half-wave plates. Then we gained a dispersive signal with zero background [Fig. 5(b)].

As is shown in Fig. 5(b), three crossover transitions are not contained in the absorption spectrum, because only one light beam interacted with atoms. And the remaining lines were corresponding to the $F = 4 \rightarrow F' = 3, 4$ and 5 transitions of the $^{133}$Cs D2 line. There are two reasons for which the signal of the 4-5 transition line was the largest. Firstly, the strength factor of the 4-5 transition is larger than those of 4-3 and 4-4 transitions. Secondly but more importantly, unlike the 4-3 and 4-4 transitions, the 4-5 line is a cycling transition owing to the electric dipole selection rules and is free from optical pumping [13], which pumps the atoms to $F=3$ level and diminishes the 4-3 and 4-4 transition signals.

For locking the laser frequency, the spectroscopic signal was sent to a PI-controller. Then the PI-controller output was fed back to the injection current of the laser diode. We locked the laser to the 4-5 transition of the $^{133}$Cs D2 line. The fluctuations of laser frequency can be calibrated from the variations of the spectroscopic signal amplitude according to the slope at the zero-crossing point. Figure 6 shows the performance of the stabilized frequency laser. The laser was free-running during the former 500 seconds with a fast fluctuation of about 2 MHz and a frequency drift of about 12 MHz. After locking, the laser frequency fluctuations were suppressed to about 80 kHz peak-peak and 22 kHz rms, which indicated a frequency stability.
of about $6 \times 10^{-11}$ at 1 s. For obtaining the frequency drift after locking, the laser frequency was beaten against another laser stabilized by using saturated absorption spectrum, whose frequency stability in terms of allan deviation was $1 \times 10^{-10}/\sqrt{\tau}$ over integration times $\tau$ from 1 s to 1000 s and less than $5 \times 10^{-11}$ over $10^2 - 10^5$ s. After operating continuously for more than 1 day, the result showed that the long-term drift of the laser frequency was reduced to less than 200 kHz, meaning that the long-term frequency stability was less than $6 \times 10^{-10}$.

4. Discussion

Due to the beam tube, the whole system of our scheme is bigger and more complicated compared with other schemes relying on thermal vapor cells. However, the dispersive signal obtained in our scheme exhibits four unique advantages suitable for laser frequency stabilizing.

Firstly, all the three hyperfine transitions hardly have any Doppler background because of using the atomic beam, thus avoid the bad influence, such as altering the zero-crossing point and decreasing the signal-to-noise ratio, on the laser frequency stabilization.

Secondly, for there is no crossover transition, the distances between the three hyperfine transitions are large enough (Fig. 5) to avoid harmful influence from each other.

Thirdly, because the spectroscopic signal is taken from the difference of two absorption lines, all the common-mode noise are greatly suppressed. For example, the power fluctuations of the laser, as an important noise source, can not alter the zero-crossing of the signal but only vary its peak-to-peak amplitude.

Last but not the least, when the system is running, the oven temperature is well controlled to provide a fixed flux of atoms. In addition, the tube is covered by a magnetic shield. In consequence, the spectroscopic signal is very stable and insensitive to parameters fluctuations (room temperature, ambient magnetic field).

The only one drawback of this scheme is that the locking point may be not located at the
F(ω) = G_1(ω, θ_1) - G_2(ω, θ_2)

\[ F(ω) = A_1 \frac{1}{[(Δω)^2 + (ω - ω_0 - δω_1)^2]} - A_2 \frac{1}{[(Δω)^2 + (ω - ω_0 - δω_2)^2]} + B_1 - B_2. \] (11)

When the two light power are equal, but their tilt angles are not opposite, then we can calculate the zero-crossing point:

\[ ω = ω_0 + \frac{1}{2}(δω_1 + δω_2) = ω_0 + \frac{1}{2}ω_0 \frac{υ}{c} \sin(θ_1 + θ_2), \] (12)

where \( υ \) is the most probable velocity, which is very stable according to Eq. (8) owing to the low fluctuation of the oven temperature. According to Eq. (9), the locking point will alter with a rate of 4.4 MHz/deg, here the angle is the average value of the two signed tilt angles. When the angle is equal to 1 degree, the change of the zero-crossing point contributed by the velocity of atoms is calculated to be less than 6 kHz, which is still very small.

As to the other condition that the two light power are not equal, while their tilt angles are exact opposite, we can get the zero-crossing point by solving the equation:

\[ \frac{1}{[(Δω)^2 + (ω - ω_0 - δω)^2]} A_2 \frac{1}{A_1} \frac{1}{[(Δω)^2 + (ω - ω_0 + δω)^2]} + B_1 \frac{A_1}{A_2} \left(1 - \frac{A_2}{A_1} \right) = 0, \] (13)

here, \( A_2/A_1 \) is equal to the ratio of two light power; \( B/A \) depends on the detection efficiency of PDs, the intrinsic property of the Cs atom and the flux of the atomic beam. Owing to the well controlled temperature of the oven, the flux of the atomic is almost invariable. Though the zero-crossing point is related to many factors, we can see that it will keep stable as long as the ratio of two light power keep the same because of dividing from one light beam.
In actual experiment, after carefully adjusting, we observed no significant difference (less than 1 MHz) between the zero-crossing point of the dispersive signal and the center of the corresponding saturated absorption spectrum (see Fig. 5). Of course, we can also use the fluorescence signal to generate the dispersive signal, which has no background B. However, as is shown in Fig. 7, we have to add another pair of optical windows.

5. Conclusion

We demonstrated a simple and robust modulation-free technique to stabilize a laser frequency by using an atomic beam. It produced a pure dispersive signal with a high signal-to-noise ratio and no background. Moreover, the signal we obtained was very stable, and its zero-crossing point was insensitive to the laser power fluctuations and the surrounding environment. Using this method to lock a diode laser, we stabilized the laser frequency for more than 1 day without losing lock. The rms frequency fluctuations are suppressed to 22 kHz and the long-term frequency drift was reduced to less than 200 kHz in a laboratory environment. This method will be a good choice in those areas that require the laser to be locked for long time with low noise and have no demands on the system size, especially in the area of atomic beam frequency standard [14], where this method can be applied conveniently to suppress the laser frequency noise in a wide feedback bandwidth.

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