Laser frequency stabilization and shifting by using modulation transfer spectroscopy*

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The stabilizing and shifting of laser frequency are very important for the interaction between the laser and atoms. The modulation transfer spectroscopy for the ^{87}Rb atom with D2 line transition $F = 2 \rightarrow F' = 3$ is used for stabilizing and shifting the frequency of the external cavity grating feedback diode laser. The resonant phase modulator with electro–optical effect is used to generate frequency sideband to lock the laser frequency. In the locking scheme, circularly polarized pump- and probe-beams are used. By optimizing the temperature of the vapor, the pump- and probe-beam intensity, the laser linewidth of 280 kHz is obtained. Furthermore, the magnetic field generated by a solenoid is added into the system. Therefore the system can achieve the frequency locking at any point in a range of hundreds of megahertz frequency shifting with very low power loss.

Keywords: laser stabilization, spectroscopy, diode lasers, line shapes and shifts

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1. Introduction

In the experiment of laser cooling and trapping of atoms, the laser frequency must be well determined and stabilized over time. The natively narrow linewidth lasers such as external cavity grating feedback diode lasers (ECDL) are widely used for these purposes. To enhance the long time frequency stability, the laser frequency is locked to a relatively stable reference level. The locking quality depends on the equivalent reference noise in the feedback bandwidth and the reference quality. The commonly used frequency locking schemes include the saturation absorption dither locking,[1] the dichroic atomic vapor laser lock (DAVLL),[2–4] the polarization spectroscopy,[5–9] the frequency modulation (FM) spectroscopy,[10–12] the modulation transfer spectroscopy (MTS),[13–26] etc.

The phase modulation transfer spectroscopy was proposed by Shirley to lock the laser frequency at one peak of atomic saturation absorption spectroscopy.[14] For the MTS, the external modulation is used by electro–optic modulator (EOM)[13–15] or acousto–optic modulator (AOM),[16,17] instead of direct modulation on the laser source to avoid the extra frequency and intensity noise. The spectroscopy generates dispersive-like line shapes which sit on a flat, zero background with a particular steep slope. MTS has advantages such as possible high response bandwidth, flatter background, and lower noise due to high detecting frequency. Recent work[27] has reported very promising use of MTS as a frequency stabilization method.

In the cold atom experiments, the frequency shifting is necessary besides frequency stabilization. For example, the laser cooling needs a red detuning from resonance to decelerate atom; in the polarization gradient cooling (PGC) process of laser cooling of atoms, larger laser frequency detuning than the natural linewidth of the cooling transition is needed to achieve an expected low temperature of atoms. In many cases, the frequency shift is introduced by changing the driving frequency of AOM. But the diffraction angle changes as the modulation frequency, which leads to the unwanted change of the laser propagation direction. Utilizing the double-passed AOM technique may diminish the effect but the diffraction efficiency is reduced to about 70%. In order to overcome this weakness, we use the transition frequency shifting in a magnetic field as the reference to achieve the laser frequency changing.[28–31] Specifically, this design includes a uniformly wired solenoid added around the vapor cell combining the circular polarization beams used in spectroscopy. The current in the solenoid determines the frequency shifting in both positive and negative directions.

In this paper, we combine the MTS and the solenoid technique to achieve the frequency locking and shifting simultaneously. We report a modulation transfer spectroscopy of ^{87}Rb as a laser frequency locking method for the external cavity grating feedback diode lasers. At the same time, the polarization dependence of the spectrum signal in the magnetic field

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is investigated. The laser frequency shifting of a few hundreds of megahertz is achieved experimentally.

2. Frequency stabilization

2.1. Theory of MTS

The theory of modulation transfer spectroscopy is based on the stimulated four-photon transition, or four-wave mixing. Firstly, the side bands of the pumping light are generated when it is modulated by the phase modulator. When the pumping light and probing light are counter-propagating through the vapor cell, four-photon transition happens, which generates the fourth light co-propagating along the probing light. Then the MTS is generally observed by detecting the beat signal between the probe field and the generated sidebands with a phase sensitive detector. The beat signal on the detector is in the following form:[13,14,27]

$$S(\omega_{\rm m}) = \frac{c}{\sqrt{\Gamma^2+\omega_{\rm m}^2}} \sum_{n=-\infty}^{\infty} {\rm J}_n(\delta) J_{n-1}(\delta) \times [(L_{(n+1)/2}+L_{(n\text{ - }2)/2})\cos(\omega_{\rm m}t+\varphi) + (D_{(n+1)/2}-D_{(n\text{ - }2)/2})\sin(\omega_{\rm m}t+\varphi)], \quad (1)$$

where δ is the modulation index (phase modulation depth) and ${\rm J}_n(\delta)$ is the Bessel function of order n, $\omega_{\rm m}$ is the modulation frequency, φ is the detector phase with respect to the modulation field applied to the pump beam, c is a constant dependent on the photodiode detection parameter and laser intensity, L_n is the Lorentzian function describing the absorption and D_n is the function describing the dispersion,[13] and they are given by

$$L_n = \frac{\Gamma^2}{\Gamma^2+(\Delta-n\omega_{\rm m})^2}, \quad (2)$$

$$D_n = \frac{\Gamma(\Delta-n\omega_{\rm m})}{\Gamma^2+(\Delta-n\omega_{\rm m})^2}, \quad (3)$$

where Δ is the frequency detuning from line center and Γ is the transition's linewidth. If $\delta < 1$ is applied and only the zeroth and first order of Bessel function are considered, equation (1) is simplified into[13]

$$S(\omega_{\rm m}) = \frac{c}{\sqrt{\Gamma^2+\omega_{\rm m}^2}} {\rm J}_0(\delta){\rm J}_1(\delta) \times [(L_{-1}-L_{-1/2}+L_{1/2}-L_1)\cos(\omega_{\rm m}t+\varphi) \times (D_1-D_{1/2}-D_{-1/2}+D_{-1})\sin(\omega_{\rm m}t+\varphi)]. \quad (4)$$

From Eq. (4), we can find that the spectrum curve can be exchanged between absorption, dispersion, and the combination of two forms by varying the phase shift of the detector. These phenomena can be observed using a phase-sensitive detector.

2.2. Experimental setup of MTS

In our experiment, D2 lines of ^{87}Rb atom are used as frequency reference for the laser. As shown in Fig. 1, a small fraction of the light from ECDL is split into two parts for the pumping light and probing light respectively. The pumping light passes through an EOM, which operates at $\omega_{\rm m}$ = 12.5 MHz and the modulation depth δ is about 0.08 to generate side-bands. The pumping light and probing light after beam expanders counter-propagate and overlap in the Rb vapor cell. The spectrum signal is collected at a high speed PIN photodiode detector followed by an amplifier.

In our MTS scheme, the Rb vapor cell of 150 mm in length is temperature controlled to optimize the spectrum line. For enough optical bench space, longer cell and lower cell temperature will be preferred. The EOM driver is homemade. A low noise crystal oscillator (OX) of 50 MHz is used as a modulation frequency reference. Then the frequency is divided by 4 to generate a 12.5-MHz frequency to drive the EOM. A set of RF electronic components (phase shifter, mixer, and low-pass filter) is used to extract the spectrum signal. According to Eq. (4), the extracted phase shift can be adjusted continuously, in which the magnitude of this phase shift is related to the modulation signal, thereby changing the shape

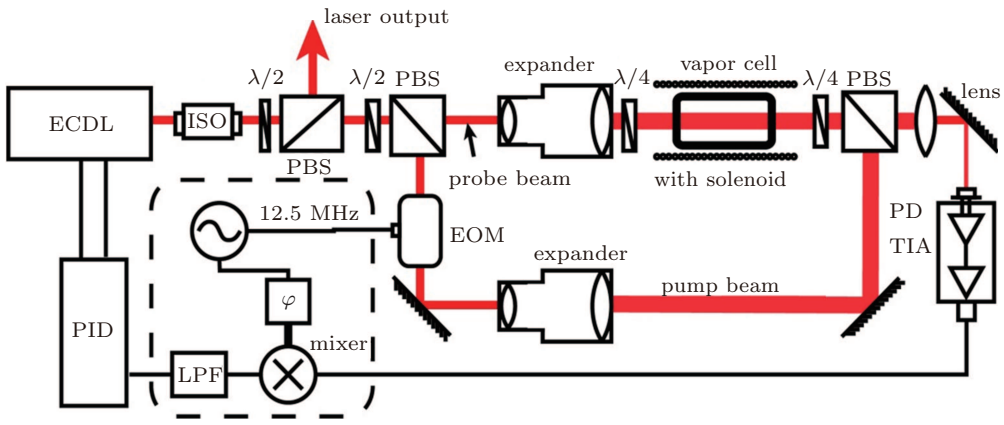


Fig. 1. (color online) Modulation transfer spectroscopy experimental setup. PBS: polarizing beam splitter, PD: photodiode, TIA: trans-impendence amplifier, EOM: electro-optical modulator, LPF: low pass filter.

of spectral line. As the feedback loop to the laser, a proportional integral derivative (PID) regulator based on a field programmable gate array (FPGA) is designed and used. The feedbacks are applied to the laser current and cavity grating which is driven by a piezo-electric transducer (PZT).

The quarter wave plates in the setup are used to change the pumping and probing light into the circular polarization. With the solenoid, the frequency shift is measured, which will be described in detail in Section 3.

2.3. Experimental results of MTS

The spectrum curve is measured with laser frequency scanning across the D2 lines of ^{87}Rb and ^{85}Rb atoms as shown in Fig. 2. The feature of the transition line from $5^2S_{1/2}$ F = 2 to $5^2P_{3/2}$ F′ = 3 of ^{87}Rb atom is marked and used for frequency stabilization, which is specially called the MTS signal in the following text. The noise level of the signal is 4 mV rms with a 10-kHz bandwidth. The saturated absorption signal in a low frequency range of the same detector is also shown for comparison. Next, some important parameters affecting the MTS signal are investigated in detail, including the temperature of vapor, the probe beam intensity, the pump beam intensity, and the polarization of the beams.

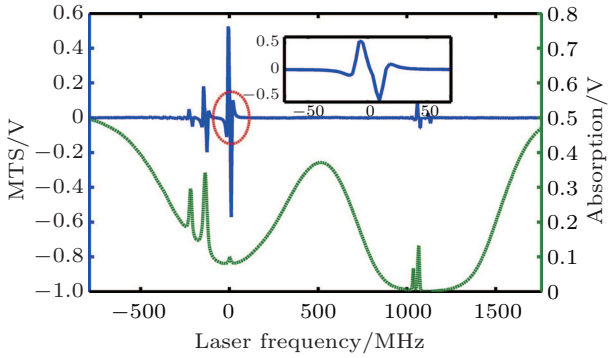


Fig. 2. (color online) A comparison between MTS (solid) and saturated absorption spectrum (dash dot) for the ^{87}Rb F = 2 → F′ transition at a modulation frequency of 12.5 MHz.

Figure 3 shows the dependence of the MTS signal amplitude on cell temperature when the pump light power is 3.8 mW and the probe light power is 3.65 mW. It is shown that the temperature affects greatly the response of the MTS signal. The MTS signal is optimized at a temperature of 44 °C. At lower temperature, there the atom number is insufficiently large since the saturated atom vapor density depends on temperature. At higher temperature, however, the collisions among atoms and between atoms and the cell wall may cause deeper spin destruction and reduce the efficiency of the optical pumping, which will eventually reduce the MTS signal. And also, the absorption of the vapor gas to probe and pump light becomes severe at higher cell temperature.

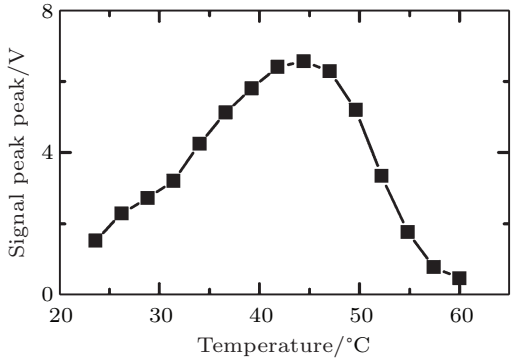


Fig. 3. MTS signal amplitude versus the vapor cell temperature.

Figure 4 shows the dependences of the MTS signal amplitude and slope on the pump and probe lights intensity. Here all the light powers are measured before the vapor cell. As the absorption is not negligible at high temperature, the powers at the end of cell will be changed for different laser frequencies. For example from Fig. 2 it follows that the probe light power is only 20% as large as the input power near the transition line from $5^2S_{1/2}$ F = 2 to $5^2P_{3/2}$ F′ = 3 of ^{87}Rb atom. The amplitudes and the slope increase with the increasing of the light intensity in low scattering saturation for both probe light and pump light. The pump light or probe light with high intensity will lead to the broadening of the transition linewidth, which plays an important role in the MTS curve shape. Thus the MTS amplitudes and the slope will decrease as the intensity further increases. When the probe light power is 3.65 mW and the beam size is 3 mm, the real optical power density is

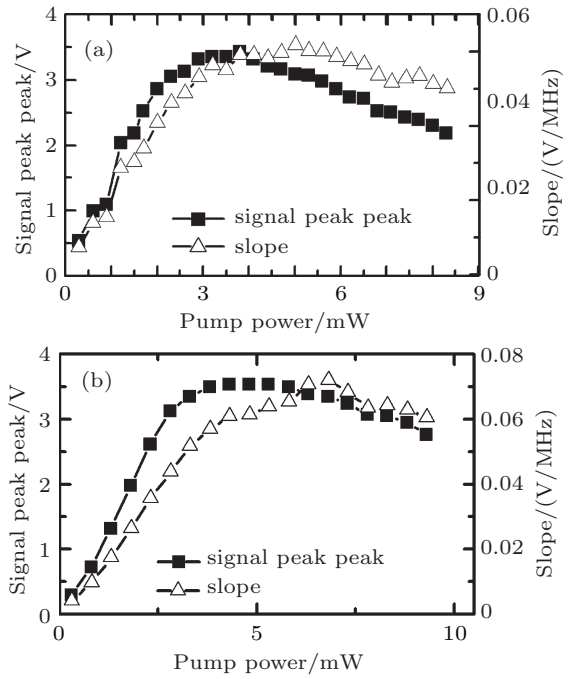


Fig. 4. (a) MTS signals versus pump light power (with probe light power being 3.65 mW). (b) MTS signals versus probe light power (with pump light power being 3.8 mW). The beam sizes are all 3 mm in full width at half maximum (HWHM).

about 10.4 mW/cm^2 for the transition $5^2S_{1/2}$ F = 2 to $5^2P_{3/2}$ F′ = 3, which corresponds to the theoretical broadening of the transition linewidth by about 11.8 MHz.

In the conventional MTS, linearly polarized probe and pump beams are used in order to avoid the transition sensitivity to the surrounding magnetic field.[13,16] The polarization-dependent effects have been investigated for linearly polarized probe and pump beams.[16,22] In our case, in order to shift the laser frequency, the circularly polarized probe and pump beams are applied to the MTS method. Table 1 shows the MTS relative signal peak-to-peak amplitude with linearly and circularly polarized beams respectively. It is shown that the MTS signal with circularly polarized beams has some different amplitudes from the signal with linearly polarized beams. For different polarized combination beams, the case of perpendicular linear polarization light is the optimized one. But with applied magnetic field, the signal amplitude varies as the field strength. These results are provided in Section 3 with shifting spectrum.

Table 1. Spectrum voltage signal amplitude (peak-to-peak) for the combination of pump and probe light with different polarizations.

	σ_+ pump	s-linear pump	σ pump	p-linear pump
σ probe	2.14	1.90	0.74	1.76
p-linear probe	1.90	2.40	1.70	1.80

2.4. Locking result

There are two methods that are usually used for measuring laser frequency stabilities: linewidth and Allan deviation. During an integral of relatively short time interval, we can obtain the linewidth of the laser, which is the deviation from its carrier frequency, and in a specific line shape (for examples, Lorentzian or Gaussian). In another way, the Allan deviation of the laser frequency can be calculated after recording the frequency in a relatively long time period. From the Allan deviation, we can obtain the stability of laser in many average time intervals.

To evaluate the frequency stability, almost identical two sets of lasers and locking loops are used and the frequency difference is measured by their beat note frequency after a frequency shift added by acousto–optic modulator. Because the electronic noise is higher than the light system noise, the beat note signal is well described by the Gaussian line shape, with an FWHM linewidth of 280 kHz at 5-ms scan time, which is shown in Fig. 5(a). The central frequency is averaged and recorded for every 0.5 seconds using an RF spectrometer and the Allan deviations calculated from 14-hours data are shown in Fig. 5(b). The Allan deviation value reaches 3.5 kHz at 400 seconds on average. At longer time, the Allan deviation increases as average time increases because the long time offset drifts in electronic circuit.

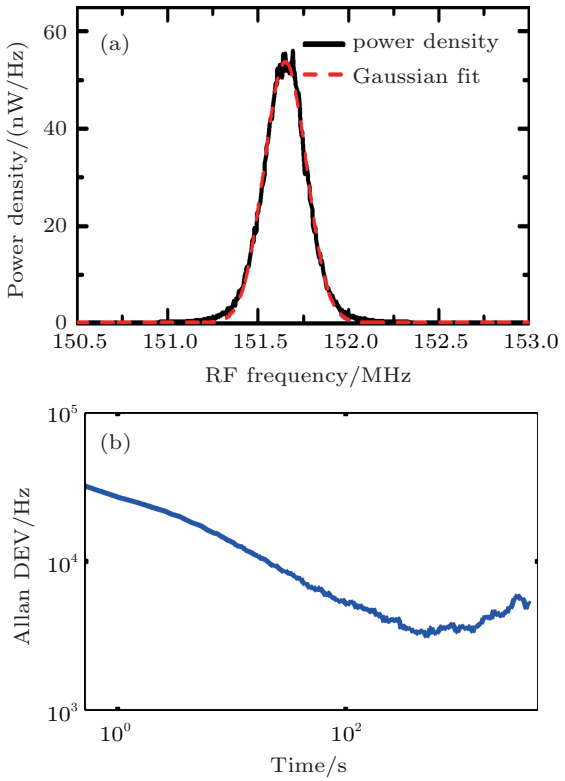


Fig. 5. (color online) (a) Beat signal between the lasers with two MTS locked lasers. (b) Allan deviations of recorded relative frequency drift.

3. Frequency shifting

Due to the Zeeman effect, the interaction between the atom and the external magnetic field leads to the splitting of the atomic resonance lines in the spectrum. In a weak field, the Zeeman shift of a given level can be expressed as

$$\Delta\nu_{\mathrm{F},m\mathrm{F}} = \frac{m_{\mathrm{F}} g_{\mathrm{F}} \mu_{\mathrm{B}} B}{h}, \tag{5}$$

where m_{F} is the magnetic quantum number, g_{F} is the Landé factor, μ_{B} is the Bohr magnetron, and B is the magnetic field. In this magnetic field, the linear frequency shift of the atomic transition is given by

$$\Delta\nu = KB, \tag{6}$$

where $K = (m_{\mathrm{F}} g_{\mathrm{F}} - m_{\mathrm{F}'} g_{\mathrm{F}'})\mu_{\mathrm{B}}/h$.

In the experiment, we enwind uniformly the solenoid around the vapor cell to provide the magnetic field given by $B = CnI$, where C is a geometric factor related to the solenoid shape, I is the current of the solenoid, and n is the number of solenoid turns. Two quarter-wave plates are used to make the pump and probe beams be of right- and left-handed circular polarizations as shown in the setup of Fig. 1. When a right-handed circularly polarized laser beam passes through the atoms, the transition obeys the selection rule $\Delta m_{\mathrm{F}} = 1$. As a result, the atoms are pumped into the $5^2S_{1/2}$ F = 2, $m_{\mathrm{F}} = -2$ state and only the transition $5\,^2S_{1/2}$ F = 2, $m_{\mathrm{F}} = -2$ to $5\,^2P_{3/2}$ F′ = 3, $m_{\mathrm{F}} = -3$ exist. So that the linear frequency shift-coefficient of this transition is $K \approx -14.0$ GHz/T.

The experimental frequency shifting, the linear fit, and the fitting residual versus the current of the solenoid are shown in Figs. 6(a) and 6(b). The linearity of the shifting is better than 1 MHz in the whole range. The fitting equation of this experimental frequency shift is

$$\Delta\nu \approx 47.04\ \text{MHz/A} \times I - 0.17\ \text{MHz}. \quad (7)$$

The residual of frequency shift is caused by changing the locking point, asymmetry of the spectrum curve, and the residual surrounding magnetic field. The magnetic shielding is added at the outside of the solenoid to suppress the fluctuation of the environment magnetic field. The shielding is provided by a three-layer concentric cylindrical shield made of high permeability material (permalloy), which results in the inside magnetic field being lower than 2 μT. Here, we can shift the frequency from −150 MHz to 150 MHz by changing the current from −3.18 A to 3.19 A.

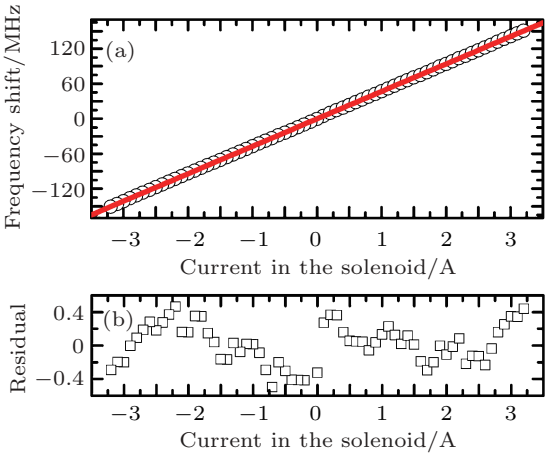


Fig. 6. (color online) (a) Experimental frequency shift (open circles) and the linear fit (solid line) and (b) the residual of frequency shift versus current.

The amplitude of the spectrum signals changes with the applied magnetic field. This is due to the field being nonuniform, and its direction being unparallel to the light beams. The measured data are shown in Fig. 7, which include different polarization configurations. During the shifting, the noise level of signal remains unchanged, and the laser linewidth is not increasing. In applications where large frequency shifting is needed, the gain in the feedback loop should be optimized with respect to the change of signal amplitude.

In the case of the pump and probe beams along the magnetic field, they will interact only with transitions with $\Delta m_{\rm F} = \pm 1$. As the linear polarization light is the combination of left-hand and right-hand circular polarization light, with the linear probe light and the circular pump light, there will be half of the probe light power used in MTS process in the large magnetic case, thus causing the drop of the signal amplitude. With both linear probe and pump lights, there will be two sets of spectrum features splitting from the center of the transition line, and these features are much weak due to half of the optical power in one feature and lack of the optical pumping. These split light beams will not interfere with each other only in the large magnetic field.

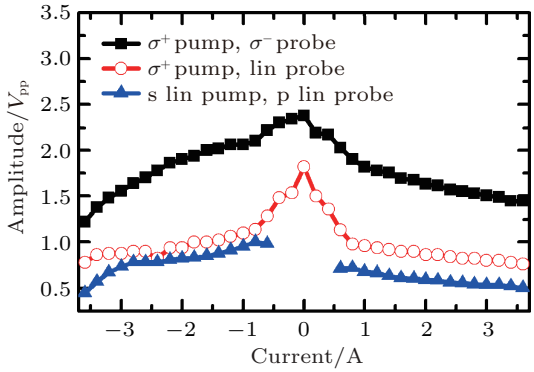


Fig. 7. (color online) Variations of experimental spectrum amplitude the applied current for three cases of circular or linear (lin) polarization pump and probe light.

Combining the MTS and the frequency shifting, we can lock the laser frequency at any point in a range of hundreds of megahertz frequency shifting, which means that we can obtain one laser frequency detuning in a range of hundreds of megahertz from the atomic transition by using MTS and solenoid enwinding the atomic cell. With this method, by adjusting the current in the solenoid, the laser frequency can be easily modulated. This is very useful in the polarization gradient cooling,[32] where the frequency shifting of about several tenths of MHz and the rapid tuning of the frequency are required, but the high shifting precision is not necessary. For the limit of tuning speed, the coil current driven bandwidth and the laser feedback bandwidth should be considered. In our case, the current can be increased to 0.2 A within 0.1 ms and the laser feedback bandwidth is 10 kHz, which means that the frequency shifting can reach about 10 MHz within 0.1 ms.

4. Conclusions

In this paper, we put forward and achieved experimentally a modulation transfer laser spectroscopy using EOM with a resonant frequency of 12.5 MHz. The spectral width of the beat signal between the two locked lasers is 280 kHz in FWHM. Also, through the Zeeman effect, we can realize the frequency shifting up to hundreds of megahertz by adding the magnetic solenoid enwinding around the vapor cell. Combining the MTS and the solenoid-assisted Zeeman effect, the stabilizing, shifting, and tuning of the frequency can be obtained. Compared with the tunable AOM method, this system can provide continuous frequency shift including red and blue detuning. Furthermore, this technique will not cause additional laser power loss, which may be widely applied to laser cooling systems.

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