

Attosecond laser station

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Flexible control of semiconductor laser with frequency tunable modulation transfer spectroscopy*

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We introduce a new method of simultaneously implementing frequency stabilization and frequency shift for semiconductor lasers. We name this method the frequency tunable modulation transfer spectroscopy (FTMTS). To realize a stable output of 780 nm semiconductor laser, an FTMTS optical heterodyne frequency stabilization system is constructed. Before entering into the frequency stabilization system, the probe laser passes through an acousto-optical modulator (AOM) twice in advance to achieve tunable frequency while keeping the light path stable. According to the experimental results, the frequency changes from 120 MHz to 190 MHz after the double-pass AOM, and the intensity of laser entering into the system is greatly changed, but there is almost no change in the error signal of the FTMTS spectrum. Using this signal to lock the laser frequency, we can ensure that the frequency of the laser changes with the amount of AOM shift. Therefore, the magneto-optical trap (MOT)-molasses process can be implemented smoothly.

Keywords: semiconductor laser, frequency stabilization, frequency shift, frequency tunable modulation transfer spectroscopy

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1. Introduction

In atom interferometer, narrow linewidth and frequency-stabilized lasers are required to achieve high quality atomic sample and interference.[1] The natural linewidth of alkali atoms is several MHz, but the frequency drift of a free running semiconductor laser could reach up to several GHz per day, so the research on frequency stabilization of semiconductor laser is extremely necessary.[2] In the experiment of laser cooling and trapping of atoms, the frequency is locked onto the transition frequency between the hyperfine energy levels of the atoms. The saturated absorption spectroscopy (SAS),[3] doppler-free dichroic atomic vapor laser lock (DAVLL),[4] frequency modulation spectroscopy (FMS),[5] and modulation transfer spectroscopy (MTS)[6] are often adopted to stabilize the frequency. Among them, MTS is a good candidate for laser frequency stabilization since the signal-to-noise ratio is better and there is no background at all.[7,8] It is simple and robust, and it has potential applications in atomic physics experiments and so on.

Most of the previous methods focus on the frequency stabilization only.[9] The frequency of the output laser cannot be tuned freely while keeping the laser locked. In laser cooling, at magneto-optical trap (MOT) to molasses stage, a double-pass acousto-optical modulator (AOM) is used to shift the frequency with a drawback of intensity control. An alternative approach could be applied, with the cooling laser locked to a reference laser with a tunable frequency offset, but an additional laser is required, thus increasing the complexity of the system.

In this work, we demonstrate a new and simple approach, i.e., a double-pass AOM is inserted into the traditional MTS to form a frequency tunable MTS. It allows us to stabilize and control the frequency of the laser simultaneously, while keeping the output intensity adjusted independently.

2. Theory and experimental setup

In the experiment, the laser frequency is stabilized on the D2 line of ^{87}Rb by the frequency tunable modulation transfer spectroscopy (FTMTS). The pump beam needs to be modulated by an electro-optic modulator (EOM), and it can produce a good class of dispersion line,[10] with a flat over zero background, and the slope at the lock point is very steep.[11]

The FTMTS is based on MTS. The principle of MTS is derived from four-wave mixing in nonlinear medium.[12] The four-wave mixing method is that two beams of light are transmitted relative to each other, and a third beam has the same or a small angle in the direction of the beam of light, which interacts with each other in the medium to produce a fourth beam in a nonlinear medium.[13]

The probe beam detected on the photodiode and the beat

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frequency signal of the side band can be expressed as

$$S(\omega_{\rm m}) = \frac{c}{\sqrt{\Gamma^2+\omega^2}} \sum_{n=-\infty}^{\infty} J_n(\beta) J_{n-1}(\beta) \times \left[\left(L_{\frac{n+1}{2}} + L_{\frac{n-2}{2}} \right) \cos(\omega_{\rm m} t + \varphi) + \left(D_{\frac{n+1}{2}} - D_{\frac{n-2}{2}} \right) \sin(\omega_{\rm m} t + \varphi) \right], \quad (1)$$

where β is the modulation coefficient (phase modulation depth); J is the Bessel function of the n-th order; $\omega_{\rm m}$ is the modulation frequency; φ is the phase of the detector relative to the modulation field applied to the pump beam; the constant c is a parameter that represents the amplitude of the signal, depending mainly on the parameters of the detector and the intensity of the laser; L_n is the Lorenz line type which is the type of absorption line, and D_n is the dispersion line type, the type of in-phase component can be obtained by changing φ, or in-quadrature component. The L_n and D_n are expressed as

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

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

where Δ is the frequency detuning between the cooling laser and the transition from $F = 2$ to $F' = 3$ cycle of ^{87}Rb atom, so the formula is simplified, and Γ is the natural linewidth of the atoms. If the phase modulation depth $\beta < 1$, the formula is simplified into

$$S(\omega_{\rm m}) = \frac{c}{\sqrt{\Gamma^2+\omega_{\rm m}^2}} J_0(\beta) J_1(\beta) \times \left[\left(L_{-\frac{1}{2}} - L_{-1} - L_{\frac{1}{2}} + L_1 \right) \cos(\omega_{\rm m} t + \varphi) + \left(D_1 - D_{\frac{1}{2}} - D_{-\frac{1}{2}} + D_{-1} \right) \sin(\omega_{\rm m} t + \varphi) \right]. \quad (4)$$

The cooling laser is used for laser cooling and trapping a large number of ^{87}Rb atoms in a vacuum chamber.[14] In the MOT, the frequency detuning is about 6–20 MHz, i.e., about 1Γ–3Γ. In the optical stage of further cooling, it is necessary to further increase the frequency detuning and reduce the intensity of the laser.[15] In general, the detuning of the cooling laser needs to change in a range of 0–60 MHz or even more. The frequency shift is realized by AOM, and the modulated sound wave is generated by an electro acoustic transducer added to the electrical modulated signal on AOM. The sinusoidal signal of a frequency is generated by the signal source, After RF-signal switching on, it is amplified by the RF-power amplifier and added to AOM, so that the frequency shift of the laser through the AOM is realized.

Figure 1 shows the experimental setup of MTS measurement in our system. An external cavity semiconductor laser (ECDL) is used as the laser source. The output beam passes through the optical isolator first, avoiding the instability of the reflected laser into the laser and the output power of the laser. Most of the laser power passing through PBS1 is used for cooling and trapping the atoms. About 2 mW of the laser power is reflected by PBS1 to the spectroscopy. After shifting frequency through double-pass AOM, the laser beams are reflected by PBS2 and divided into two parts, which are used to produce pump beam and probe beam, respectively. The pump beam is phase modulated at 4.0 MHz by a homemade EOM, whose modulation phase index is ~ 0.1. The probe beam counterpropagates relative to the pump beam inside the Rb vapor cell.

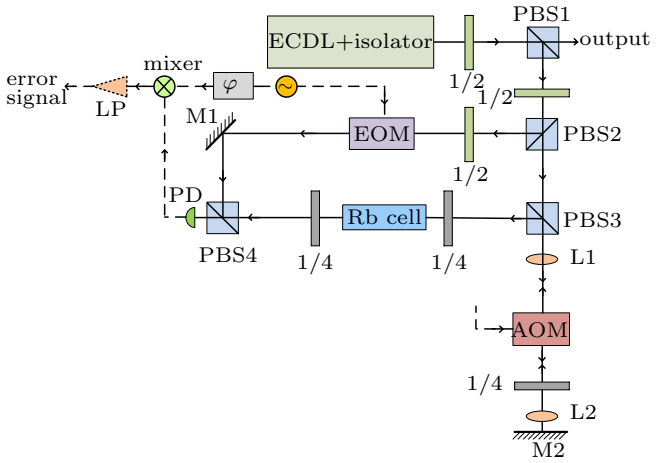
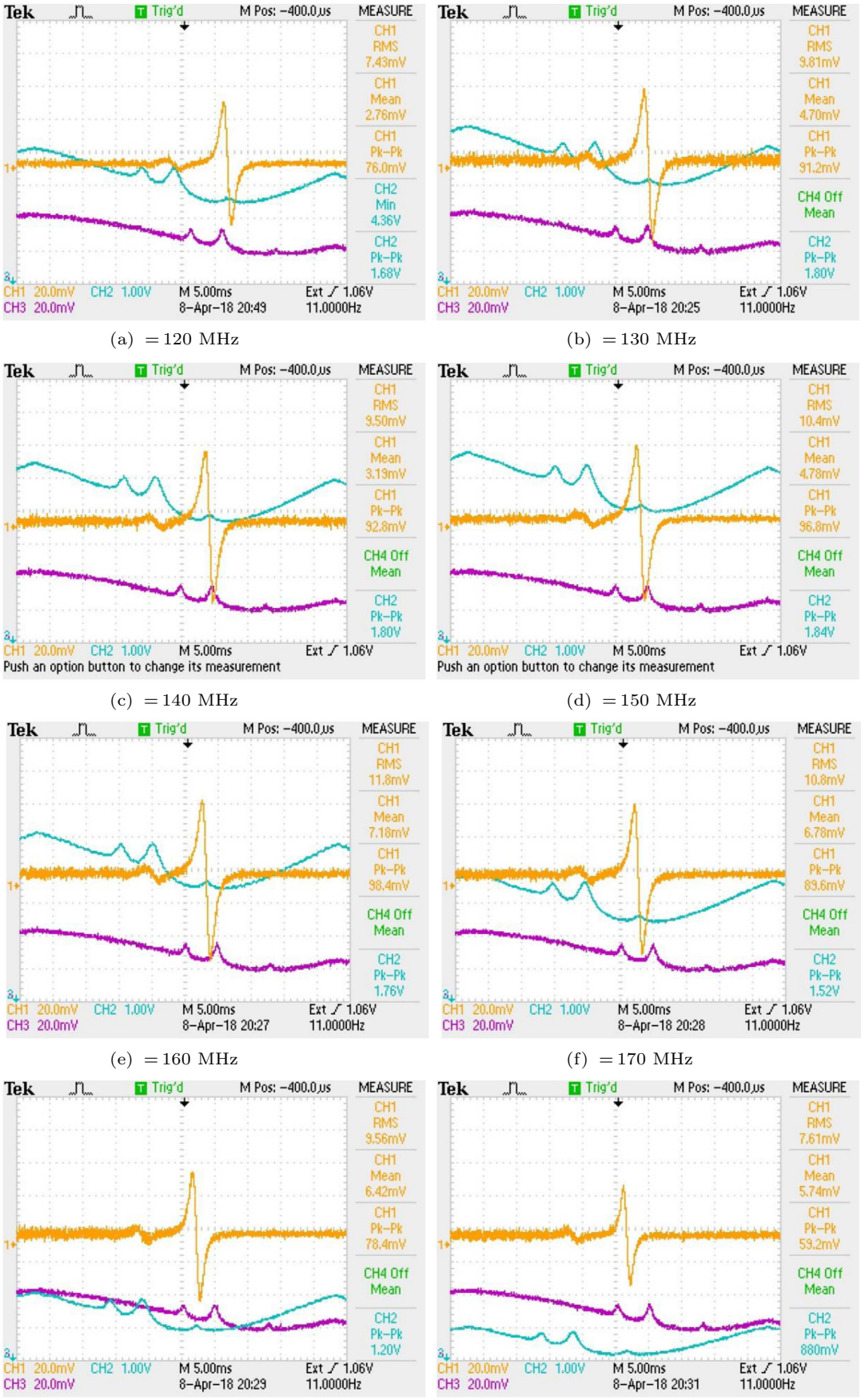


Fig. 1. (color online) (color online) Experimental setup of FTMTS measurement. 1/2, half-wave plate; 1/4, quarter-wave plate; PBS, polarizing beam splitter; L, lens; M, mirrors; EOM, electro-optic modulator; AOM, acousto-optic modulator; PD, photodiode; LP: low pass filter.

The signal of FTMTS is detected by a fast photodiode after PBS3. The opto-electric signal from the photodiode is mixed with the modulated signal with a phase shift, and the linear beat frequency signal is obtained to be $\frac{c}{\sqrt{\Gamma^2+\omega^2}} J_0(\beta)(L_{-\frac{1}{2}} - L_{-1} - L_{\frac{1}{2}} + L_1)$. After going through a low pass filter, the error signal is obtained, which can be sent to the PID feedback circuit to stabilize the laser frequency.

3. Results and discussion

In order to prove that the frequency stabilization can still work after the frequency has been shifted by the double-pass AOM, we adjust the optical path while changing the frequency of the RF-signal to the AOM. The optics in the double pass part is carefully adjusted to make sure that the output beam pointing from the AOM does not change with varying frequency of the RF-signal. In the initial optical path, the modulation frequency of AOM is 75 MHz, and the optical path is set to be along the $+1$ order beams. Before passing through the amplifier, the amplitude of the RF-signal is -8.9 dBm. The adjusted optical path can be in the AOM modulation frequency range of 6–95 MHz. Therefore, the frequency shift is in a range from 12 MHz to 190 MHz though the double-pass AOM. The error signals with different RF-frequencies are shown in Fig. 2.



(a) = 120 MHz (b) = 130 MHz

(c) = 140 MHz (d) = 150 MHz

(e) = 160 MHz (f) = 170 MHz

(g) = 180 MHz (h) = 190 MHz

Fig. 2. (color online) (color online) FTMTS signals with different frequency shifts. Purple curve represents reference spectrum, which marks the output frequency of the laser. Light blue curve denotes spectrum output from photodiode in FTMTS. Yellow curve refers to the error signal from FTMTS.

The spectrum in purple curve is the saturated absorption signal for reference, which marks the output laser frequency. The yellow differential spectrum gives the MTS error signal after the AOM double pass. For different driving RF frequencies, we can see clearly the frequency variation marked by the error signal according to the reference spectrum.

In the experiment, we optimize the diffraction efficiency of the AOM at a driving RF-frequency of 75 MHz, which corresponds to the laser frequency shift of 150 MHz. When the RF-frequency is changed, the diffraction efficiency will drop as well. This leads the laser intensity to enter into the FTMTS drops also. We can see it from the light blue curve shown in Fig. 2, the direct output from the photodiode in MTS. The amplitude of the spectrum reflects the intensity of the probe laser. At $\Delta = 150$ MHz, the intensity of the probe is maximum, while at $\Delta = 130$ MHz and $\Delta = 190$ MHz, the intensity of the probe laser becomes lower, according to the drop of the diffraction efficiency of the AOM.

Although the intensity of the probe varies significantly with the driving RF-frequency changing from 60 MHz to 95 MHz (from 120 MHz to 190 MHz changing according to the laser frequency), the output error signal (yellow curve in Fig. 2) does not change a lot. We put all the error signals with $\Delta = 130$ MHz, $\Delta = 160$ MHz, and $\Delta = 190$ MHz together to make the comparison as shown in Fig. 3. We observe that the background of the error signals keeps stable and the amplitude only changes a little. The most important thing is that the slope of the center linear part of the error signal has almost no change. The slopes in the linear part of the error signal at $\Delta = 130$ MHz, $\Delta = 160$ MHz, and $\Delta = 190$ MHz are measured to be -91.54 V/MHz, -93.75 V/MHz, and -90.86 V/MHz, respectively. When the laser is in the locking phase, the driving force of the feedback electrons to the laser is proportional to the slope of the error signal. When the driving frequency of the AOM is shifted in the laser locking phase, the output of the feedback will not be much disturbed. This can guarantee that when the laser is locked with the FTMTS error signal, the locking will keep stable even if the output frequency of the laser changes according to different driving RF-frequencies to the AOM.

Furthermore, with this FTMTS setup, we may realize a stable laser lock as well as the frequency output of the laser changing in a range larger than 60 MHz. An additional single AOM could be used at the output of the laser as a switch to realize a function of fast switch on and off. At the same time, the power of the laser output applied to the experiment will keep stable. This is an advantage to perform the MOT-molasses experiment to trap and cool the alkali atoms. The requirement for the laser power will be reduced to ~ 50 mW only. The frequency and amplitude of the laser can be controlled independently during the experiment.

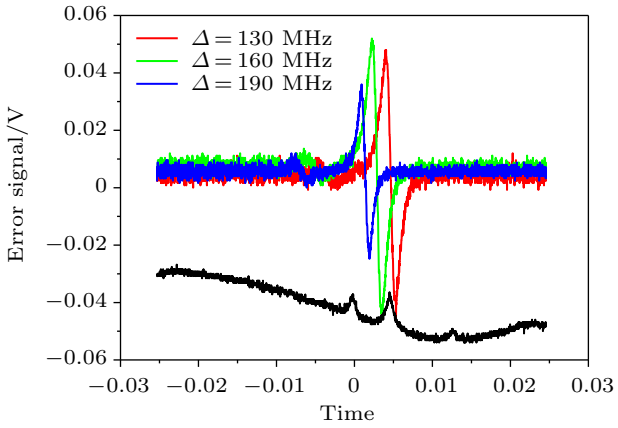


Fig. 3. (color online) Comparison among FTMTS signals at different frequencies.

4. Conclusion

We have demonstrated a novel FTMTS method of stabilizing the laser frequency. By jointly using a double-pass AOM and the EOM in the spectroscopy, a frequency-shift FTMTS error signal is obtained in the experiment. Although the power of the laser to the spectroscopy varies a lot due to the uneven diffraction efficiency of the double-pass AOM with different driving frequencies, the error signal still keeps stable. This allows us to lock the laser with the frequency scanning over the range of 60 MHz, while keeping a large and stable output power. It becomes an advantage to implement the MOT-molasses experiment with only one ECDL laser as the cooling laser, the high power-consuming laser amplifier is not necessary. Our new method can also be applied to precision laser spectroscopy and measurement.

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