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Ultra-Stable Rubidium-Stabilized External-Cavity Diode Laser Based on the Modulation Transfer Spectroscopy Technique

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We construct an ultra-stable external-cavity diode laser via modulation transfer spectroscopy referencing on a hyperfine component of the $^{87}\text{Rb}$ D2 lines at 780 nm. The Doppler-free dispersion-like modulation transfer signal is obtained with high signal-to-noise-ratio. The instability of the laser frequency is measured by beating with an optical frequency comb which is phase-locked to an ultra-stable oven controlled crystal oscillator. The Allan deviation is $3.9 \times 10^{-13}$ at 1 s averaging time and $9.8 \times 10^{-14}$ at 90 s averaging time.

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Frequency-stabilized external cavity diode lasers (ECDLs), benefiting from compactness, low cost and wide tuning range, have been recognized as promising sources not only for metrology applications but also for high-resolution spectroscopy, optical communications, and the rest of fundamental physics. As rubidium atoms have been widely used in atomic physics experiments such as Bose-Einstein condensation, atomic clocks based on coherent population trapping (CPT), frequency-stabilized tunable diode lasers at 780 nm are of great importance. Among the existing techniques to stabilize lasers, the pump-probe schemes are very popular because they can achieve sub-Doppler resolution and thus enhance the frequency discrimination. In particular, the scheme of modulation transfer spectroscopy (MTS) is more significant than other schemes of the saturated absorption spectroscopy (SAS) and frequency modulation spectroscopy (FMS) because of the transfer process. This transfer process can be described as a non-linear four-wave-mixing process, which takes place when the sub-Doppler resonance condition is satisfied. Consequently, the base line of MTS lineshape is completely flat without affection by residual linear-absorption, and the zero points of the modulation transfer signals are precisely corresponding to the transition center. In addition, the closed atomic transition effect dominates greatly to gain high signal-to-noise ratio (SNR) in these transitions in MTS. In fact, there was almost no report on the frequency stabilization of diode lasers at 780 nm by using the MTS technique in the past. A very similar work on Cs-stabilized DBR diode laser reported an instability of $1.5 \times 10^{-11}$ at 1 s averaging time. In addition, a Rh-stabilized ECDL in using FMS technique, constructed for absolute frequency measurements, reported an instability of $3.8 \times 10^{-12}$ at 1 s averaging time. To date, modulation transfer spectroscopy in atomic rubidium for laser locking has been studied exhaustively, and it has shown a significantly improvement in both the MTS signal gradient and peak-to-peak amplitude by expanding the beams using telescopes. In this study, we improve the instability of ECDL through the wonderful technique of MTS, the short term stability of $3.9 \times 10^{-13}$ at 1 s averaging time, and $9.8 \times 10^{-14}$ at 90 s averaging time are achieved respectively.

Fig. 1. Experimental setup for our Rb-stabilized ECDL system. ECDL, extended cavity diode laser; ISO, isolator; AOM, acousto-optic modulator; λ/2, half-wave plate; PMF, polarization maintained fiber; PBS, polarization beam splitter; BS, beam splitter; PD, photo detector; OFC, optical frequency comb.

First, we describe in detail the realization of a saturated-absorption spectrometer by using the modulation transfer spectroscopy technique. A Doppler-
The experimental setup is schematically shown in Fig. 1. The laser source (Vortex 6013, New Focus Inc.) is an external-cavity diode laser with 300 kHz linewidth at 50 ns sweep time. As diode lasers are very sensitive to optical feedback, two 30-dB isolators are necessary for high isolation. The polarization maintained fiber (PMF) can filter the laser beam to be pure fundamental transverse mode, and the output beam of PMF is expanded to 1 mm in diameter by an aspheric lens. One percent power of light is split out by a beam splitter (BS1) and received by a photodiode (PD1). The photocurrent of PD1 is fed back into an intensity servo controlling the input radio frequency power used in our system, according to Fig. 3(b). Here 200 µW of light, split out by PBS2, is beaten with an ultrastable-OCXO-referenced optical frequency comb (OFC) to measure the laser frequency deviation. The homemade electro-optic modulator (EOM) is working at a frequency of 5.5 MHz and a modulation index of 0.4. This modulation frequency 5.5 MHz is chosen to be 0.7 times of the measured linewidth of the transition in our system. The separated pumping beam and probing beam are expanded to 8 mm and 6 mm in diameter, respectively, and counter-propagate into the rubidium vapor cell (CQ19075-RB, Thorlabs) with complete overlapping. The powers of the pumping beam and probing beam are about 0.7 mW and 0.17 mW, respectively, to reach the highest SNR. The temperature of electro-optic crystal, inside the EOM box, is controlled to reduce the effect of the residual amplitude modulation. The rubidium vapor cell is magnetic-shielded by three layers of commercial high-efficiency magnetic-shield product CONETIC AA (Magnetic Shield Corp.), while the magnetic fields in the cell are reduced to be less than 3 µT.

The cold finger of the cell is temperature-controlled at 20°C with fluctuation of ±0.001°C, whose contribution to the laser frequency instability can be ignored considering the pressure shift of 2 kHz/°C at 20°C (Fig. 3(c)). The FM sideband of pump beam is transferred to the probing beam on resonance of Rb atoms, and a p-intrinsic-n (PIN) photo-detector, PD2, detects the amplitude-modulation (AM) beat signal between sidebands and carrier of the probing beam. This signal is subsequently demodulated to error signal by a double-balanced mixer (DBM).

The cold-finger temperature of rubidium vapor cell is magnetic-shielded by three layers of commercial high-efficiency magnetic-shield product CONETIC AA (Magnetic Shield Corp.), while the magnetic fields in the cell are reduced to be less than 3 µT.

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![Fig. 2. Optical layout for the frequency instability measurement. APD: avalanche photodiode, MUP: metal-semiconductor-metal ultrafast photodiode, f_r: repetition rate, f_o: carrier-envelope offset, f_b: beat note, f_{780}: optical frequency, n: the number index of the comb component for f - 2f interferometer, m: the number index of the comb component for optical beating, counter: frequency counter.](image-url)

![Fig. 3. (a) Modulation transfer spectrum recorded by a digital oscilloscope. (b) Laser frequency shift vs pump power, about 46 Hz/µW at 700 µW pump power. (c) Laser frequency shift vs temperature of cold finger, about 2 Hz/mK at 20°C.](image-url)
oscillator (Gigajet20) is pumped by a 532 nm solid state laser (Coherent Verdi V6) with an output power of about 600 mW while 4.8 W pumped. The repetition rate \( f_r \) is around 760 MHz and the pulse-width is 25 fs. The signal of \( f_r \) is acquired by injecting the laser into a metal-semiconductor-metal ultrafast photodiode (MUP). Here \( f_r \) is phase-locked to the microwave reference signal from an OCXO (8607BM, Oscilloquartz), whose nominal instability is \( 1 \times 10^{-13} \) at 1–30 s averaging time, by feeding back the phase error into the PZT attached on the cavity mirror to change the cavity length. An \( f - 2f \) nonlinear spectroscopy utilizing the photonic crystal fiber (PCF, Crystal Fiber NL-740-2.0) is used to acquire an octave spectrum. The supercontinuum is generated by the hydrogen atomic clock, as the reference for the OFC, will be evaluated in the future.

We also recorded the modulation transfer spectrum of \(^{87}\text{Rb} \) D2 line with a digital oscilloscope. As shown in Fig. 3(a), the signal of hyperfine transition \( 5^2S_{1/2}(F = 2) \rightarrow 5^2P_{3/2}(F' = 3) \) is obviously stronger than the others because of closed atomic transition and therefore we lock the laser to this component. The Allan deviation is shown in Fig. 4. The laser frequency instability is \( 3.9 \times 10^{-13} \) at 1 s averaging time, and \( 9.8 \times 10^{-14} \) at 90 s averaging time. The instability of the OCXO is slightly better than its nominal values the manufacturer declaimed, which was confirmed by calibration with the higher stability standard. The real instability of the stabilized ECDL should be better than the measured one in a certain extent. Furthermore, the long-term stability is mainly limited by the drift of the high-performance oscillator OCXO. The ultimate instability of the stabilized laser, usually measured by comparing two identical facilities or employing a higher-stability frequency source, such as the hydrogen atomic clock, as the reference for the OFC, will be evaluated in the future.

In summary, we have constructed a Rb D2 saturated-absorption spectrometer, using the modulation transfer spectroscopy technique to lock an external-cavity diode laser to hyperfine component \( 5^2S_{1/2}(F = 2) \rightarrow 5^2P_{3/2}(F' = 3) \) of \(^{87}\text{Rb} \) D2 lines. The light power fluctuation is kept within 0.2%, and the temperature of the cold finger of rubidium vapor cell is controlled to \( 20 \pm 0.001 \)°C. The maximum variations of the laser frequency caused by these two factors are 65 Hz and 4 Hz, respectively, according to the light shift and pressure shift measured in our system (Figs. 3(b) and 3(c)). The frequency instability is measured by using an OCXO-referenced optical frequency comb, to be \( 3.9 \times 10^{-13} \) at 1 s averaging time, and reduced to \( 9.8 \times 10^{-14} \) at 90 s averaging time.

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