# Frequency-stabilized diode laser at 780 nm with a continuously locked time over 100 h

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Received October 12, 2009

Two extended-cavity diode lasers at 780 nm which are longtime frequency-stabilized to Rb$^{87}$ saturated absorption signals are reported. A high-performance frequency-locking circuit module using a first-harmonic detection technique is designed and achieved. Two lasers are continuously frequency-stabilized for over 100 h in conventional laboratory condition. The Allan standard deviation of either laser is estimated to be $1.3 \times 10^{-11}$ at an integration time of 25 s. The system environment temperature drift is demonstrated to be the main factor affecting long-term stability of the stabilized lasers based on our correlation study between beat frequency and system environment temperature.

*OCIS codes:* 140.2020, 140.3425, 250.5960.
*doi: 10.3788/COL20100805.0496.*

More interest comes to diode lasers frequency-stabilized to atomic or molecular transitions owing to their significant applications in atomic, molecular, and optical (AMO) physics[1], precise measurement[2], and optical communication. The reliability and compactness of diode lasers, as well as their broad tunable frequency range[3], make them attractive for frequency stabilization[4]. In this letter, we present two identical extended-cavity diode lasers (ECDLs) at 780-nm frequency-locked to saturated absorption[5] signals of Rb$^{87}$ D2 hyperfine transitions[6,7].

Continuously locked time of frequency-stabilized ECDL is a vital factor since longtime frequency-locked laser is necessary in many of its applications, such as Bose-Einstein condensate experiments[8] and high-performance atomic clocks. In this letter, we provide a solution for extending continuously locked time. In addition, we develop a miniaturized frequency-stabilizing servo circuit which fits to a compact module box with a friendly operating interface. This technique can be widely used in the labs and commercialized ways.

The whole experimental system consists of three subsystems, which are correspondingly saturated absorption system (SAS), frequency beat system (FBS), and electronic servo system (ESS). Layouts of these subsystems are shown in Fig. 1, in which solid lines represent optical paths while dotted lines illustrate electronic links.

In the SAS, we use our home-made 780-nm ECDL (UQDL100) as laser sources, which are Littrow configurations. Under our laboratory circumstance, the laser current varies below microampere level using an extremely low-noise current supply. The temperature of the laser diode is stabilized at millikelvin level. The source also has a mode-hop free frequency tuning range of 15 GHz, a linewidth of approximately hundreds of kilohertz, a side-mode suppression of 40−50 dB, and a typical output power of 10 mW. The laser beam is generated from an ECDL and then passes through a Faraday optical isolator whose isolation ratio is over 30 dB. After passing through a half-wave plate and a polarizing beam splitter (PBS), a part of laser is used for absorption spectroscopy detection while the other part is coupled out for applications. To obtain absorption spectroscopy, a laser beam is split to two beams after passing through a glass beam splitter (GBS). One beam is 4% reflected from the GBS, then goes through a 5-cm-long rubidium vapor cell and reaches a photoelectric detector, which records the absorption spectroscopy to lock the laser frequency. The other beam is reflected by two mirrors to pump the rubidium atoms in the absorption cell. Both beams are adjusted overlapping in the absorption cell. The whole optical setup of two frequency-stabilized laser systems is limited in a 50×40×12 (cm) space.

In the FBS, the two coupled-out laser beams from the frequency-stabilized laser systems are combined for frequency beat by a PBS. The combined laser beams pass through another PBS together, thus their components in the same propagating direction and in the same polarization are ensured. The beat laser beam is reflected and

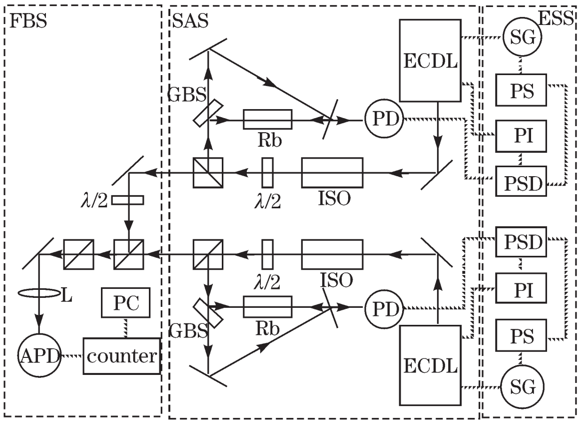

Fig. 1. Experimental setup. ISO: isolator; $\lambda/2$: half-wave plate; GBS: glass beam splitter; Rb: rubidium vapor cell; PD: photoelectric detector; L: convex lens; APD: avalanche photodiode; PC: personal computer; SG: signal generator; PS: phase shifter; PSD: phase-sensitive detector; PI: proportional and integral processor.

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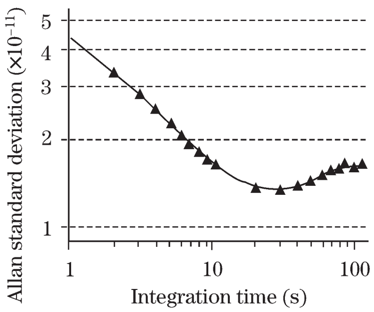

Fig. 2. Relative stability (Allan standard deviation) of the frequency-stabilized ECDL.

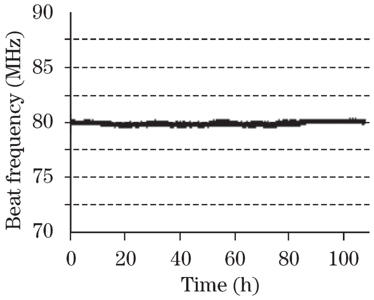

Fig. 3. 110 h beat frequency record.

then focused to the avalanche photodiode (APD) by a convex lens. To study Allan variance of the laser beat, we use an Agilent 53131A counter, a HP 34970A data acquisition unit, and a computer for data recording. Through this way, longtime beat frequency from the APD and simultaneous temperature value from a thermal resistor put in the middle of the two vapor cells can be recorded with a computer.

Inside the ESS box there are two printed circuit boards (PCBs), the first one is used for generating modulation signal and reference signal while the second one is designed for phase discrimination and filter amplification. The first PCB provides both modulation signal and reference signal at the frequency of 2.5 kHz, whose harmonic suppression ratios are both better than 65 dB. The phase difference between the two signals can be continuously adjusted within a 360° range, in order to compensate the phase delay around the servo system. The second PCB serves to lock the laser frequency by phase discrimination. It demodulates the signal from the photoelectric detector by a phase discriminator and gives out the error signal with the aid of filter loop, in which the bandwidth of the low-pass filter is set at 10 Hz.

After turning laser frequency to $\mathrm{Rb}^{87}$ D2 hyperfine transitions and scanning it at a relatively low rate (typically 0.1 Hz), we obtain error signals with high signal-to-noise ratios. After turning off the scan, we feed the error signal back to the laser's piezoelectric transducer (PZT) driver to lock the laser frequency with a proportional and integral processor (PI)[9], in which the proportional processor depresses the short-term frequency noise and the integral processor depresses the long-term frequency drift. The two diode lasers are frequency-locked to different crossover saturated absorption signals of $\mathrm{Rb}^{87}$ D2 hyperfine transitions whose frequency interval is approximately 80 MHz. Then the beat frequency between the two lasers can be recorded by the automatic data recording system.

Relative stability of the beat frequency is calculated to illustrate relative stability of the frequency-stabilized laser in the form of Allan standard deviation[10] $\sigma(\tau)$, which obeys[11]

$$\sigma_1(\tau) = \sigma_2(\tau) = \frac{1}{\sqrt{2}}\sigma_{\mathrm{tot}}(\tau), \tag{1}$$

where $\tau$ is the integration time, and $\sigma_{\mathrm{tot}}\ (\tau)$ represents Allan standard deviation of the beat frequency, while $\sigma_1\ (\tau)$, as well as $\sigma_2\ (\tau)$, represents Allan standard deviation of either laser frequency.

As illustrated in Fig. 2, the relationship presenting relative frequency stability of the stabilized laser, which is based on totally 24-h data, can be approximately described as

$$\begin{aligned}\sigma\ (\tau) = {} & 4.4\times10^{-11}\tau^{-1/2} + 1.5\times10^{-12}\tau^{1/2} \\ & - 2.7\times10^{-12}\ (1 \leq \tau \leq 100\ \mathrm{s}).\end{aligned} \tag{2}$$

The stability at $\tau$=1 s is as low as $4.3 \times 10^{-11}$ and the best stability of $1.3 \times 10^{-11}$ is reached at $\tau$=25 s. The character of frequency noise is very important for frequency stability of a stabilized laser, consequently it is studied in our experiment. In Eq. (2), the $\tau^{-1/2}$ term is introduced by white frequency noise, the $\tau^{1/2}$ term comes from random walk of frequency noise and the constant term originates from flicker frequency noise.

As our most constructive achievement, both diode lasers are simultaneously frequency-locked and maintain their locked state over 100 h, which is illustrated in Fig. 3. It should be noted that we stop locking the two laser frequency after 100 h since we suppose that 100 h has been a sufficiently long time for applications, and in principle, the lasers are able to keep frequency-locked continuously as long as possible when the system environment temperature changes within 2 °C and there is no big vibration around.

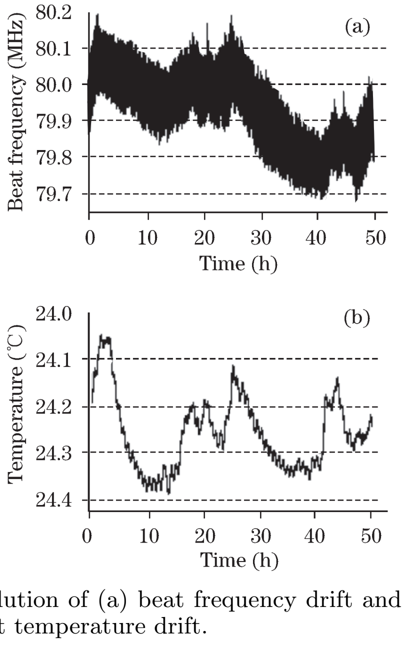

Fig. 4. Evolution of (a) beat frequency drift and (b) system environment temperature drift.

Excellent continuously locked time is achieved due to our particular considerations. Firstly, slow laser frequency drift is the most direct threat to a long locked time, correspondingly the integral part in a PI circuit serves the function to compensate that. Unfortunately on account of nonideal characteristics of electronic components, particularly bleeder resistance of the integral capacitor, the amplitude-frequency response at low-frequency band drops, which leads to a limited compensable range for frequency drift. Thus in our integral circuit we use polytetrafluoroethylene (PTFE) capacitors, which have a rather low bleeder resistance. Secondly, 10-mm-long PZT in ECDL and the high gain of corresponding high-voltage (HV) PZT drivers ensure a maximum 5-GHz compensable range, while the free-running laser frequency drift in our lab environment is approximately 1 GHz based on our observations. Thirdly, we benefit from the well controlled bandwidth of the band-pass filter processing photoelectric signals and bandwidth of the low-pass filter processing error signals in the demodulation circuit.

The system environment temperature drift is demonstrated to be the main factor undermining the long-term frequency stability and limiting continuously locked time of stabilized lasers based on our correlation study between the beat frequency drift and the system environment temperature drift.

The considerable correlation between the beat frequency and the system environment temperature can be discovered in Fig. 4, which is based on a 50-h experimental record. As a consequence, to enhance the long-term frequency stability of a stabilized laser by depressing the frequency drift, efficient temperature controlling solutions should be applied, in which the rubidium vapor cell, as well as the ECDL, should be most concerned.

In conclusion, two identical ECDLs are simultaneously frequency-stabilized to saturated absorption signals of Rb$^{87}$ D2 hyperfine transitions for over 100 h, adopting a first-harmonic detection technique. Particular integral components and high-gain HV PZT drivers are applied to ensure a significantly long continuously locked time. The noise characteristic of the relative frequency stability is analyzed. To improve the long-term stability of a frequency-stabilized laser, the obvious correlation between the beat frequency drift and the temperature drift suggests that the system environment temperature, especially temperatures of the vapor cell and the ECDL, should be well controlled. This long-time continuously frequency-locked ECDL can be widely used in AMO physics, precise measurement, and high-performance atomic clock, etc.

This work was partially supported by the National "973" Program of China (Nos. 2005CB724503, 2006CB921402, and 2006CB921401) and the National Natural Science Foundation of China (Nos. 60490280 and 10874008).

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