

Simple method for frequency locking of an extended-cavity diode laser

Wenge Yang, Amitabh Joshi, Hai Wang, and Min Xiao

We have developed an extended-cavity tunable diode laser system that has a small linewidth and a large output power (more than 90% of the free-running power) whose operating frequency can be conveniently locked to a transition line of Rb atoms. Based on flat-mirror feedback and frequency self-locking and with weak feedback, we have achieved a continuous frequency detuning range greater than 900 MHz and a short-time linewidth stability of better than 0.4%. By using a two-step locking procedure we not only can lock the laser frequency but also can detune the frequency to any desired value. The locking is quite sturdy and rugged. © 2004 Optical Society of America

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1. Introduction

Semiconductor diode lasers are becoming increasingly more versatile tools in atomic physics and spectroscopy research owing to their reliability in giving high power and broad wavelength coverage while they steadily decrease in cost.¹ The light from diode lasers is very bright relative to the sizes of these lasers and of other laser sources. One can easily get several watts or hundreds of milliwatts of power from a laser diode operating under continuous wave conditions. In many cases a narrow linewidth and smooth wavelength tunability are desirable characteristics of an ideal spectroscopic source. Whereas diodes are compact and inexpensive devices, sometimes they do not readily exhibit these required attributes for high-resolution spectroscopy. The free-running diodes have some undesirable properties because of their short semiconductor cavities; e.g., their frequencies are highly sensitive to changes in temperature and injection current, and they have poor tunability. Thus it becomes necessary to improve the performance of diode lasers before they can be used in any atomic spectroscopy experiment to produce reliable

and significant data. Frequency stabilization methods have been developed based on various technologies such as optical feedback,^{2,3} external cavities,^{4,5} injection locking,^{6,7} and electronic feedback.^{8,9} Hybrid systems that use more than one of the methods mentioned above are also possible.¹⁰ Some other methods use spatial mode interference¹¹ and the Zeeman effect.^{12,13} However, the most commonly used method to achieve substantial linewidth reduction and frequency stabilization is to operate the laser in a long external cavity that can provide frequency-selective optical feedback.¹ The number of photons in the cavity of a typical diode laser (100-mW output power; 0.1-mm cavity length operating at near infrared wavelengths) is of the order of 10^5 , whereas for a typical gas laser this number is of the order of 10^7 . Because of the low number of photons inside the cavity, diode lasers are more susceptible to the feedback mechanism than are normal lasers. A particularly simple design uses the feedback from a diffraction grating mounted in the Littrow configuration.¹⁴ Difficulties in such design are related to grating alignment and the need to adjust the distance between the collimating lens and the laser within a few micrometers. Also, diodes must be antireflection coated on the output facet, a highly expensive procedure, to ensure stable operation in the presence of the strong feedback from the grating.¹⁴

In this paper we present a method for constructing an extended-cavity diode laser that uses a flat mirror rather than a diffraction grating to provide the optical feedback. The advantage of this method lies in its simplicity of design and in the narrow linewidth of

W. Yang (yang@uark.edu), A. Joshi, and M. Xiao are with the University of Arkansas, Fayetteville, Arkansas 72701; all are with the Department of Physics and W. Yang and M. Xiao are also with the Microelectronics-Photonics Program. H. Wang is with the Institute of Optoelectronics, Shanxi University, Taiyuan, China 030006.

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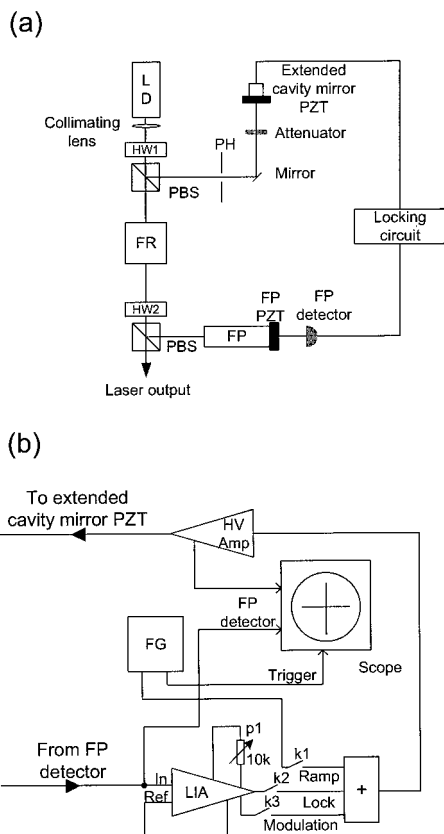


Fig. 1. (a) Schematic diagram of the extended-cavity laser: PBS, polarization beam splitter; FR, Faraday rotator; PH, pinhole; LD, laser diode. (b) Frequency-locking circuit: HV Amp, high-voltage amplifier; FG, function generator; LIA, lock-in amplifier; p1, 10K potentiometer; k1–k3, toggle switches; other abbreviations defined in text.

the laser output. Inasmuch as the mirror provides nondispersive feedback, the gain redistribution feature provided by a grating is absent here.¹⁵ However, as we shall see in what follows, within the limited frequency coverage range of this system we can have continuous frequency tunability over hundreds of megahertz with locking maintained.

2. Design of the System

The experimental setup is shown in Fig. 1(a). The main components of the extended-cavity diode laser design include the laser diode, a confocal Fabry-Perot (FP) cavity, a flat mirror mounted on a piezoelectric transducer (PZT), a collimating lens, and the electronic locking circuit. The diode laser is a Thorlabs HL7851G high-power laser diode with a multiple-quantum-well structure.¹⁶ It is temperature stabilized by a Thorlabs TEC3 thermoelectric cooler. We adjust its operating current and temperature by using homemade current-and-temperature controller such that the lasing wavelength is ~ 795 nm. A collimator lens for a laser diode (Thorlabs C230TM-B aspheric lens) is used to collimate the output laser beam. The distance between the collimating lens and the front facet of the laser diode is

critical and is carefully adjusted. A high-reflection mirror (Thorlabs BB1-E03 broadband dielectric mirror) is used to form the extended cavity. It is mounted on a PZT to provide cavity length scanning.

By rotating the first half-wave plate (HW1) we can adjust the amount of optical feedback. In our experiment, weak optical feedback is required. As the output of the laser diode is not perfectly linearly polarized, there is some residual power in the feedback arm when we rotate the half-wave plate. So a variable attenuator is used to ensure that our locking system works in a weak-feedback regime. This variable attenuator is also useful for study of the dependence of the locking process on the feedback power as well as for fine adjustment of the cavity gain profile. The main mechanism of frequency selection of our system is to adjust the cavity gain profile by controlling the temperature and the injection current, so by carefully adjusting the feedback one can confine the amplification to the central mode only.¹⁷ The injection current to the laser diode is critical for frequency selection, so our current controller has extremely low noise and small fluctuation. The feedback power should be kept low, to within the weak-feedback regime (1–5% of laser output). If the feedback is strong, any change in its intensity will dramatically affect the mode structure of the laser, thus changing the lasing frequency of the diode laser system.

A Faraday rotator is used as an isolator to prevent unwanted feedback from any other optical element. The second half-wave plate (HW2) is used to control the beam intensity in the locking circuit. The stronger this beam is, the stronger the locking capability will be. However, the available output power from the laser becomes smaller when more power goes to the locking system. So, for optimum performance of the whole system, this half-wave plate should be carefully adjusted.

The crucial element of this extended-cavity laser design is the confocal FP interferometer. One of its mirrors is mounted on a PZT tube. This FP cavity has two functions here. First, it is used to generate the interference fringes when we apply the scanning ramp signal to the PZT of the extended-cavity mirror. This fringe signal is essentially used to generate the error signal to rectify fluctuations in laser frequency. The second function of this FP cavity is to detune the output frequency of the diode laser by changing the FP cavity length, as we discuss in more detail in what follows. It should be noted that the stability of the length of the FP cavity is important in our experiment; hence the cavity is made from Invar to reduce the effects of variation in ambient temperature. The thermal coefficient of Invar is $\sim 1.4 \times 10^{-6}/^{\circ}\text{C}$, resulting in a 0.8-kHz/ $^{\circ}\text{C}$ frequency shift. We further passively stabilize the FP cavity thermally by maintaining the temperature of the environment and isolating the working table from rest of the room. The length of this FP cavity is 25 cm. The output of this FP cavity is measured by a high-speed photodetector (Thorlabs Det 110) and is sent to a lock-in circuit to generate an error signal.

In our system the circuit shown in Fig. 1(b) is used to generate the error signal. A phase-sensitive detector [Stanford Research System SR510 lock-in amplifier (LIA)] is used to generate the error signal. To lock the diode laser to the cavity's resonant peaks we monitor the photodiode signal on an oscilloscope (LeCroy 9314). The ramp is set to the OFF position, causing the signal seen via the photodiode to be a flat line with small modulations, and the lock-in switch k2 is set to ON, causing the line to stay at the resonance peak. The output frequency of this extended-cavity diode laser is monitored with a saturated-absorption spectroscopy (SAS) setup.¹⁸ We use a Rb-vapor cell in our experiment for SAS.

3. Continuous Detuning of Laser Frequency

In many experiments with atomic spectroscopy, one needs to detune the frequency of the diode laser away from its locked value. In what follows, we describe the mechanism employed in our design to achieve laser frequency detuning. Because of the presence of the lock-in circuit, the laser frequency is initially locked to one of the FP resonance peaks. After the laser frequency is locked, we change the bias voltage applied to the PZT on one of its mirrors to change the cavity length slightly. Because of the variation in cavity length, the normal modes of the FP cavity are shifted away from their starting positions. Meanwhile, the lasing frequency follows the cavity mode that is coincident initially with the diode lasing mode. So the continuous frequency detuning is caused primarily by the self-mode-locking effect in this flat-mirror-feedback diode-laser system. Using this method, one can easily achieve a detuning range of 0.9 GHz. The relatively modest tuning range of our locking method is limited by the low voltage available in our piezo controller. We use a Thorlabs MDT693 piezo controller, which has a 150-V maximum output voltage. According to our experimentally determined calibration of 6 MHz/V, the maximum frequency detuning range available is ~ 900 MHz. Another factor that limits frequency detuning is the feedback ratio, defined as P_B/P_O , where P_O and P_B represent the output power and the feedback power, respectively, of the diode laser. In our experiment, when we increase the feedback ratio from 1% to 5% the detuning range that we achieve increases by $\sim 10\%$. However, in a weak-feedback case, because the change in feedback strength will not greatly affect the mode structure, the frequency detuning range will not change much as the feedback strength changes.

4. Locking Procedure and Experimental Results

From the discussion above, it is clear that we can lock the diode laser's frequency to one of the resonant frequencies of the FP cavity. Sometimes one needs to lock the laser frequency to one of the transition lines of the atomic sample as an absolute frequency reference, which may not necessarily be the same as that of the resonant frequency of the FP cavity. In

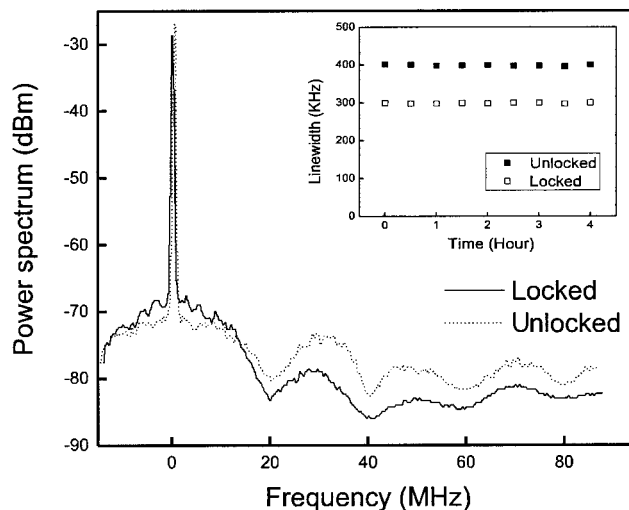


Fig. 2. (a) Linewidth measurement by a delayed self-homodyne technique. The curves represent the photocurrent power spectral density of a locked and an unlocked diode laser. Inset, instantaneous linewidth measured every 30 min for the locked and unlocked diode lasers.

what follows, we discuss the procedure for achieving this goal.

As discussed above in Section 3, with our locking mechanism ON we can tune the laser frequency by simply changing the bias voltage applied to the PZT on the mirror of the FP cavity. Thus we have the potential to lock the diode laser's frequency to any reference value. We use a two-step locking procedure to lock the laser frequency to an atomic transition line. First we lock the laser frequency to any resonant frequency of the FP cavity in the vicinity of an atomic transition line, and then we adjust the FP PZT bias voltage to push the laser frequency to exactly match the atomic transition line.

To characterize a diode laser after it is frequency stabilized, we studied the improvement in our diode laser's linewidth. We used the standard optical self-homodyne technique to measure the linewidth of the diode laser with weak flat-mirror feedback.¹⁹ First the laser output was coupled into a single-mode fiber. The beam was then sent to a fiber Mach-Zehnder interferometer. A 10-m-long standard single-mode fiber was used in one arm to introduce a time delay of $\sim 0.1 \mu\text{s}$. This time delay is short compared with the coherent time of the laser source, so the self-delayed homodyne technique works in the coherent regime.¹⁹ The output of this Mach-Zehnder interferometer was measured with a fast photodetector, and the generated photocurrent was then sent to a rf power spectrum analyzer (Tektronix 2710) for power spectrum analysis. The power spectrum obtained was curve fitted to the theoretical photocurrent power spectral density formula, with laser linewidth $\Delta\nu$ as a free parameter. The measured photocurrent power spectra for the free-running and the frequency-locked diode lasers are shown in Fig. 2, and the corresponding linewidths are 400 kHz and 290 kHz. We can see that

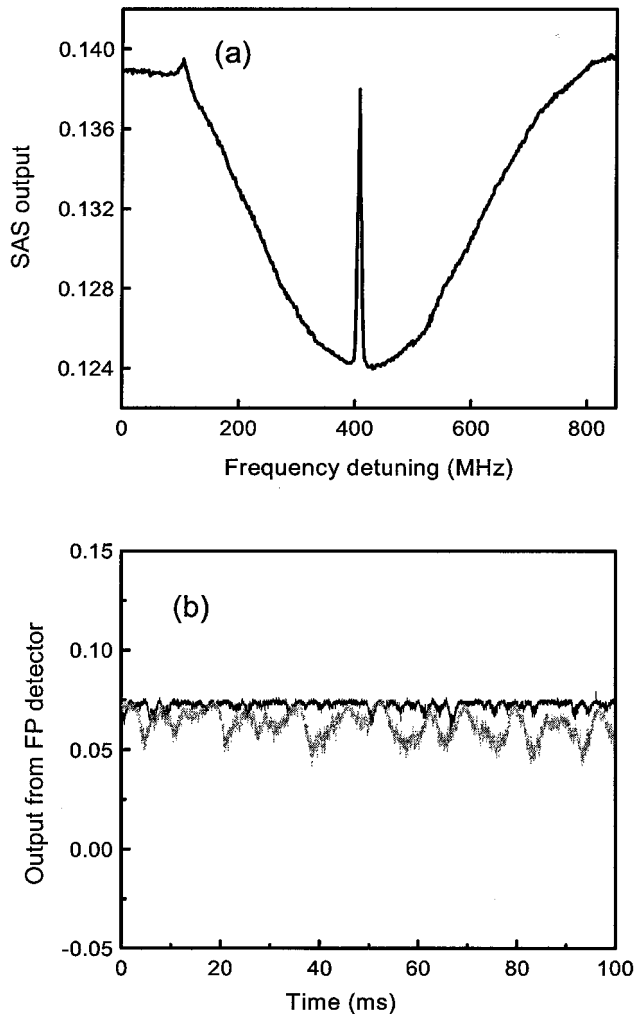


Fig. 3. (a) Saturated-absorption spectrum near the $^{87}\text{Rb } 5^2P_{1/2}, F' = 2-5^2S_{1/2}, F = 1$ transition line. (b) Experimental results. Lower curve, response of the FP detector without locking; upper curve, response after locking.

our lock-in scheme reduces the laser linewidth by $\sim 30\%$.

To study the laser linewidth stability further, we measured the instantaneous (within milliseconds) linewidth of a free-running and frequency-stabilized diode laser every 30 min. The results are shown in the inset of Fig. 2. We can see that the fluctuation of laser linewidth is smaller (less than 0.4%) when the laser frequency is locked than when it is free running; in the latter case it is greater than 1%.

We also studied the frequency tunability of the locked diode laser. After the laser was frequency locked to one of FP cavity modes, we applied a low-frequency ramp signal to its PZT controller while we kept the diode injection current fixed. The laser beam was passed through a Rb cell, and the saturated-absorption spectrum was measured with a photodetector. Figure 3(a) shows the measured SAS spectrum about the $^{87}\text{Rb } 5^2P_{1/2}, F' = 2-5^2S_{1/2}, F = 1$ transition line. As the Doppler-

broadened linewidth at room temperature is ~ 500 MHz, we can infer from Fig. 3 that an ~ 900 -MHz frequency detuning range is achieved in the experiment.

This two-step lock-in procedure is used to lock several diode lasers in our elaborate experiments.²⁰⁻²³ The diode lasers can be continuously locked to the SAS peak for hours. If there is a thermal or injection current drift caused by some disturbance, the fluctuation in the dc level will increase momentarily but will quickly decrease, indicating that our locking is strong and stable. Figure 3(b) shows one such result from our locking experiments. The upper and lower curves represent the FP detector output after and before the diode laser is locked, respectively. We can see that the dc fluctuation becomes much smaller (less than 2%, whereas initially it was more than 10%) after the laser is locked. The potential sources of frequency instability are cavity length fluctuation (because the cavity is not actively thermal stabilized), injection current and PZT driver noise, mechanical vibrations, acoustic disturbances, and rapid changes in the refractive index of air caused by air flow.

5. Conclusions

We have designed and developed a simple system to lock a diode laser to an atomic transition line. For this purpose we employed a two-step locking procedure. The procedure involves locking the laser frequency to one of the resonant frequencies of a FP cavity, followed by tuning the FP cavity by use of FP PZT bias voltage such that the laser frequency gets exactly matched to the atomic transition. At the same time, the diode laser's frequency can be detuned a desired amount away from the atomic transition frequency, which is necessary for an atomic spectroscopy experiment. The continuous frequency detuning is caused by the self-mode-locking effect for a laser-diode system with nondispersive mirror feedback. A large useful output power ($>90\%$ of the free-running power of the diode laser) and a modest frequency detuning range (~ 900 MHz) are achieved by the use of weak flat-mirror feedback. Linewidth improvement (30% lower than in free-running operation) was also demonstrated. The novelty of this locking system is that it is easy to build and that the locking so obtained is quite sturdy, which provide an alternative method for locking and detuning the frequency of a diode laser for atomic physics experiments. We hope that the detailed descriptions of this technique can help other researchers to use this scheme in their work of atomic physics with diode lasers.

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